Wind and Windblown Sand Damage to Pearl Millet

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ABSTRACT

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is grown worldwide in areas affected by wind erosion, but no data on associated damage to millet are available. Laboratory wind tunnel experiments were conducted to determine the kind and extent of damage to millet caused by wind, sandblasting, and burial. In Exp. 1, millet was exposed for 15 min to wind (8, 11, or 14 m s^{-1}) or wind + sand (8.3, 25.0, or 41.7 g m^{-1} s^{-1} sand abrader flux) at 8 and/or 16 d after emergence (DAE). Viable leaf area, leaf net photosynthesis, and NO_3 content were measured through 21 DAE and dry matter production through 57 DAE. In Exp. 2, millet was seeded as three single seeds or in tufts, exposed to 25 g m^{-1} s^{-1} sand flux for 15 min at the 1-, 2-, or 3-leaf stage, and then manually covered by 15 mm sand. Survival was monitored weekly; dry matter was determined 70 DAE. In Exp. 1, survival was uniformly 100%. Wind alone or low sand flux had no effect on viable leaf area. High sand flux decreased viable leaf area by 74% at 2 d after the 8-DAE exposure and 42% at 5 d after the 16-DAE exposure. Photosynthesis of the remaining leaf area was reduced up to 88% immediately after exposure compared with the control, and NO_3 content of sandblasted millet was increased up to six times. Dry weight was reduced 40% at 21 DAE by the highest sand flux, but 9.7% at 57 DAE. In Exp. 2, burial decreased millet survival and dry weight. Buried tufts had a higher survival rate and 35% more dry weight than buried single plants. Millet buried at the 1-leaf stage had 28% higher survival than plants treated later. Sandblasting reduced dry matter of buried millet only. Regression analyses between calculated total kinetic effects and growth parameters showed low r^2 values. Millet can survive short-term sandblasting at any growth stage, but growth is reduced by strong sand flux, a sequence of wind erosion events during early growth, or by combinations of abrasion with burial by blown sand.

WIND EROSION affects 430 million hectares worldwide, or 8% of the susceptible dryland areas (UNEP, 1992). Dust loads in the Sahara and the U.S. Great Plains regions are estimated between 97 million to 750 million tonnes per year, but most of the material is moving from one location to another at the soil's surface (Fryrear, 1990). Regions suffering from particularly acute wind erosion problems are the Sahel, the Maghreb, the U.S. Great Plains, parts of the Commonwealth of Independent States, China, Mongolia, Iraq, India, Paraguay, and Australia (UNEP, 1992). Pearl millet is one of the most important staple food grains in several of these regions. India, China, Niger, and Sudan have a total of 26 million hectares cropped with millets (FAO, 1992). In the southern USA, pearl millet is used for forage, but there is growing interest in the grain types in the U.S. Great Plains (Mohammed and Clegg, 1993). Annually, an average of 1.7 million hectares of land are damaged in the Great Plains region by wind erosion (estimates from the Soil Conservation Service, cited in Fryrear, 1981).

Effects of windblown sand on many plants have been investigated since the fifties, mostly by the use of wind tunnels: winter wheat (*Triticum aestivum* L.) (Woodruff, 1956; Armbrust et al., 1974; Armbrust, 1984); alfalfa (*Medicago sativa* L.) and different grasses (Lyles and Woodruff, 1960; Fryrear et al., 1973); bean (*Phaseolus vulgaris* L.) and pea (*Pisum sativum* L.) (Skidmore, 1966; Bubenzer and Weis, 1974); cotton (*Gossypium hirsutum* L.) (Armbrust, 1968; Fryrear, 1971); tomato (*Lycopersicon lycopersicum* Mill.) (Armbrust et al., 1969; Greig et al., 1974; Precheur et al., 1978); soybean [*Glycine max* (L.) Merr.] (Armbrust, 1972, 1984; Armbrust and Paulsen, 1973); different vegetable crops (Downes et al., 1977); tobacco (*Nicotiana tabacum* L.) (Armbrust, 1979); and sorghum [*Sorghum bicolor* (L.) Moench] (Armbrust, 1982, 1984). However, no reports were found on wind erosion damage to millet.

When plants were subjected to wind and windblown sand, reported injuries consisted of abraded leaves, decreased survival rate, slower development, and lower yields. Factors influencing the extent of damage to plants are species; their shape and age; wind speed; amount and kind (i.e., size, shape, and density) of abrasive material; storm duration and frequency; and environmental conditions after exposure (water and nutrient availability, air, and soil temperatures). Only a few papers focused on physiological responses to sandblasting. Experiments with soybean indicated that NO_3 content in plants increased after exposure to blown sand (Armbrust and Paulsen, 1973). Whole-plant photosynthesis of sorghum decreased after sandblasting, but increased when calculated on a live-leaf-area basis (Armbrust, 1982). High NO_3 content in forage millet may create problems for grazing animals.

Crop losses in the field, however, cannot be attributed to abrasive action alone, but also to the burial of plants by blown sand. Effects of covering by moving sand were not included in previous studies. The extent of damage to plants in the field caused by soil covering may depend on the plant age, the crop growth form, the previous abrasion damage, subsequent surface crust building, and surface soil temperatures (Michels et al., 1993). Furthermore, seeding tufts (i.e., putting more than 10 millet seeds in one planting hole), as done by Sahelian farmers, is assumed to protect the inner plants against abrasion and burial.

Data on crop damage by wind erosion are also needed in wind erosion modeling. At present (early 1990s), crop growth models are incorporated into the new Wind Erosion Prediction System (Hagen, 1991; Bilbro, 1992), and further improvements of models such as the Erosion Productivity Impact Calculator (Williams, 1990) and the Windbreak Economic Model (Kort et al., 1993) may also require such data. For modeling purposes, it is desirable to put all exposure parameters (sand flux, wind speed, exposure duration, and plant age) together into a single expression for treatment severity. Attempts have been made by Fryrear and Downes (1975a,b), who established a con-

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Abbreviations: DAE, days after emergence; TKe, total kinetic effect.

cept by calculating a total kinetic effect (TKe) for vegetables. Regression analyses described well the relationship between TKe and vegetable growth parameters such as plant height and dry weight (Downes et al., 1977). Thus it appeared worthy to validate the TKe concept with our millet data.

The objectives of Exp. 1 were to determine the effects of plant age, wind speed, and sand flux on photosynthesis, NO_3 content, and growth of pearl millet plants. In Exp. 2, the objectives were to quantify the effects of burial by sand at different plant growth stages, with and without previous abrasive injury and with different sowing systems. The millet cultivar, the sand mixture, and the sowing systems were selected to simulate millet growth conditions in the Sahelian zone.

MATERIALS AND METHODS

Experiment 1

Pearl millet (cv. CIVT, Composite Inter-Variétal de Tarna, from West Africa) was seeded in 18-cm-diam. plastic pots filled with Kansas river sand (sieved to remove all particles > 2 mm) and thinned to five plants in a row across the pot at 3 d after emergence (DAE). Plants were grown in a growth chamber with cool-white fluorescent and incandescent light; the photoperiod was 14 h day and 10 h night, with an abrupt change. Night and day air temperatures were 25 and 32°C, respectively. Plants were watered daily with Hoagland solution. Millet plants were exposed for 15 min to wind or wind plus sand in a wind tunnel as described by Armbrust (1984). The sand was composed of a sieved Kansas river sand mixture similar to a typical Sahelian Arenosol: 8% coarse sand (2.0-0.47 mm), 29% medium sand (0.47-0.25 mm), 45% fine sand (0.25-0.1 mm), and 18% very fine sand, silt, and clay (<0.1 mm). The sand mixture was introduced into the windstream at the floor of the wind tunnel 6.7 m upstream of the plants. The wind in the tunnel was at ambient room temperature (≈ 25°C). Wind speed was measured in the center of the wind tunnel 0.3 m upwind of the plants with a pitot-static tube and inclined-gage manometer. Treatment variables were plant age at exposure (once at 8 or 16 DAE, or at both ages); wind speed (8, 11, 14 m s^{-1}); and sand flux (0, 8.3, 25.0, 41.7 g m^{-1} s^{-1}). The zero sand flux levels are later referred to as *wind only* treatments. Millet rows within pots were oriented perpendicular to the windstream in the wind tunnel. The surface of the soil in the pots was flush with the surface of the wind tunnel floor. Plants had three visible leaves at 8 DAE and five to six leaves at 16 DAE. The experimental design, consisting of a factorial arrangement of treatments plus an unexposed control, was completely randomized and replicated three times. Pots were returned to the growth chamber immediately after exposure. Because of space limitations, plants were moved to a greenhouse at 28 DAE. Temperature in the greenhouse was maintained between 25 and 30°C and daylight extended to 14 h with a mixture of fluorescent and incandescent lights.

Plant survival, number of leaves, and plant height were recorded weekly. One plant per pot was harvested at 10 and 21 DAE and viable and dead leaf areas were measured (Model LI-3000 portable area meter, LI-COR, Lincoln, NE).[1] Plants were dried at 70°C for 48 h and dry matter was determined. Nitrate concentrations in whole-plant millet tissues was determined at 10 and 21 DAE using the method of Woolley et al. (1960). Photosynthesis was measured at 1 h, 2 d, and 4 d after exposure with a LI-COR 6200 CO_2 analyzer. Photon flux density during CO_2 measurements was kept nearly constant at 1300 µmol m^{-2} s^{-1}. The net exchange rates of CO_2 between the leaf and atmosphere were determined by averaging five subsamples per leaf, on three wind- or sand-exposed leaves per plant, and two plants per pot. Dead leaf tissue was excluded from the leaf area estimation of the photosynthesis measurements. Technical problems precluded the 18 DAE measurements. Final dry matter of the remaining three plants per pot was determined at 57 DAE.

Experiment 2

Millet was seeded and grown under similar conditions as in Exp. 1. A completely randomized, factorial arrangement of treatments with three replications was applied to test the four factors: (i) seeding system (three single plants per pot, or one tuft of 15 seedlings per pot that was thinned to three plants after 3 wk); (ii) exposure treatment (11 m s^{-1} wind speed and 25 g m^{-1} s^{-1} sand flux for 15 min); (iii) burial (manually cover millet plants with 15 mm of sand immediately after the exposure to simulate burying by blown sand); (iv) millet growth stage (one-leaf stage, 2 DAE; two-leaf, 5 DAE; three-leaf, 8 DAE). For the burial treatment, pot rims were raised by 15 mm using a strip of polyethylene, to allow for adding the 15 mm of sand to pots originally flush with the tunnel floor. Plant survival, number of leaves, and plant height were recorded weekly. Final harvest was done at 70 DAE to determine total dry matter.

Total Kinetic Effect

The total kinetic effect for each treatment combination of Exp. 1 was calculated as (following Fryrear and Downes, 1975a,b),

$$\text{TKe} = \frac{1}{2}\frac{MV^2T^2}{A} \qquad [1]$$

where TKe is the total kinetic effect (mJ m^{-1} width), M is the mass flux of the sand (g m^{-1} s^{-1}), V is the wind speed (m s^{-1}) minus the threshold velocity (6.7 m s^{-1}), T is the duration of the exposure, and A is the plant age of seedlings from emergence to time of exposure, both in seconds. Linear and nonlinear regression analyses were performed for correlations between TKe and millet leaf area, NO_3 content, and dry weight. For comparison, calculations were also done to relate sand flux alone to these parameters. Analyses were based on the means of three replications.

Data Analysis

Statistical analysis of variance and orthogonal contrasts of interest were performed using the general linear model (GLM) procedure of the SAS software (SAS Inst., 1988). A probability level of $P \leq 0.05$ was used in the F-test to indicate significant treatment effects, and Fisher's protected LSD (0.05) was applied for comparisons of means. Regression analyses for the TKe concept were done using the REG and NLIN procedures of the SAS software (SAS Inst., 1988). The r^2 for the nonlinear regression was obtained by dividing the sum of squares due to regression by the corrected total sum of squares.

RESULTS AND DISCUSSION

Experiment 1

Plant Survival and Leaf Damage

Millet survival was 100% in all treatments, indicating a higher resistance against sandblasting damage than seen in other species. Cotton exposed to a sand flux of 50 g m^{-1} s^{-1} for 10 min had 63% survival when treated at an age of 3 d, and 71% survival when treated at an age of

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[1] Mention of brand names does not indicate an endorsement by the USDA-ARS.

9 d (Fryrear, 1971). Survival rates of 75% for seven vegetable species were calculated for exposure times between 3 min (for peppers, *Capsicum* sp.) and 16 min [for cowpea, *Vigna unguiculata* (L.) Walp. subsp. *unguiculata*] with 50 g m^{-1} s^{-1} sand flux and 15 m s^{-1} wind at an age of 6 d (Fryrear and Downes, 1975a). These results support the categorization of millet as a crop tolerant against wind erosion damage by Finch (1988). Under field conditions, however, millet survival after wind erosion events can be reduced by up to 90% or even more when burial, surface crusts, high temperatures, and lack of rainfall inhibit plant recovery (Michels et al., 1993). Furthermore, insect and disease pressure may reduce plant survival in the field.

Visible leaf damage ranged from damaged tips (due to flapping in the wind and whipping on the tunnel floor) with wind alone, to necrotic leaf edges, yellow spots, and complete loss of leaves 2 to 3 d after treatment, depending on treatment severity. Orthogonal contrasts indicated that at the first and second harvest, millet treated with wind only was not different from the unexposed control (Table 1). Sandblasted millet, however, had significantly less viable leaf area than millet treated with wind alone. The significant wind speed × sand flux interaction at the first harvest (10 DAE) indicated a high variability of responses to different wind speeds within each sand flux level. Overall reductions in viable leaf area of 34 and 19% for exposed plants compared with the control were found at 10 DAE and 21 DAE, respectively (Table 1). A sand flux higher than 8.3 g m^{-1} s^{-1} resulted in leaf area decreases of 49 to 74% at 10 DAE and fluxes of 41.7 g m^{-1} s^{-1} resulted in 42% less viable leaf area at 21 DAE, compared with the control. New leaves appeared to grow rapidly after sandblast exposure. Nevertheless, at 21 DAE, the early-exposed and twice-exposed plants still had 14 and 29% less viable leaf area, respectively, than late-exposed mil-

Table 1. Viable leaf area, photosynthesis, nitrate content, and dry matter of millet at different days after emergence (DAE) as affected by wind speed, sand flux, and plant age at exposure.

	Viable leaf area		Photosynthesis					NO_3 content		Dry matter‡	
	DAE		DAE					DAE		DAE	
Treatment†	10	21‡	8§	10	12	16§	20	10	21	21	57
	cm^2		μmol CO_2 m^{-2} s^{-1}					g kg^{-1}		g pot^{-1}	
Control	17.5	122.2	21.4	14.0	22.3	16.9	18.9	0.233	0.288	0.452	30.03
Sand flux, g m^{-1} s^{-1}											
0 (W.o.)	16.5	119.9	21.4	13.2	22.2	10.0	13.2	0.616	0.375	0.420	28.57
8.3	15.2	111.2	18.4	9.8	19.7	10.2	15.3	0.847	0.405	0.390	29.16
25.0	8.4	94.3	7.7	7.9	14.0	8.2	14.5	0.984	0.482	0.354	28.06
41.7	4.6	70.8	2.6	7.3	14.5	4.4	16.0	1.351	0.596	0.270	27.12
LSD	4.2	20.4	4.1	3.5	4.3	1.8	3.3	0.059	0.028	0.080	1.34
Wind speed, m s^{-1}											
8	12.8	99.5	15.9	9.4	17.0	12.1	14.8	0.869	0.418	0.359	28.49
11	11.3	100.0	11.2	9.2	17.1	6.9	13.4	0.973	0.487	0.358	28.26
14	9.5	97.6	10.4	10.0	18.7	5.5	16.0	1.007	0.489	0.358	27.93
LSD	3.6	17.6	3.5	4.1	3.7	1.5	2.9	0.051	0.024	0.067	1.14
Plant age, DAE											
8	11.6	99.8	13.2	9.5	18.0			0.895		0.322	28.51
16		115.5				7.9	11.7		0.451	0.467	28.84
8 + 16		81.8				8.5	17.8			0.287	27.34
LSD		17.5				1.3	2.3			0.068	1.14
Sand × Wind, g m^{-1} s^{-1} × m s^{-1}											
0 × 8	13.9	60.2	26.6	10.9	19.0	14.0	10.7	0.491	0.358	0.357	29.12
0 × 11	18.4	84.4	18.3	17.0	24.9	8.4	10.1	0.801	0.341	0.491	28.30
0 × 14	17.4	61.7	19.2	11.7	22.8	7.7	10.1	0.556	0.425	0.413	28.22
8.3 × 8	24.1	58.1	19.3	7.0	17.9	12.3	16.5	0.688	0.376	0.411	30.23
8.3 × 11	12.7	52.5	20.1	7.0	20.0	8.9	14.2	0.938	0.411	0.360	28.91
8.3 × 14	9.0	62.8	15.7	15.5	21.3	9.2	15.2	0.916	0.427	0.400	28.35
25.0 × 8	7.2	47.3	12.6	12.4	17.0	13.6	15.1	0.689	0.407	0.391	27.69
25.0 × 11	11.0	6.2	5.5	7.0	10.9	7.5	13.0	1.067	0.577	0.337	27.97
25.0 × 14	6.9	17.3	5.0	4.3	14.0	3.5	15.4	1.196	0.463	0.334	28.51
41.7 × 8	6.0	25.2	5.2	7.3	14.4	8.7	16.9	1.609	0.531	0.279	26.86
41.7 × 11	3.0	40.4	1.0	6.0	12.5	2.8	16.3	1.087	0.619	0.246	27.85
41.7 × 14	4.6	20.2	1.6	8.5	16.7	1.6	14.7	1.357	0.639	0.285	26.64
						ANOVA, $P > F$					
Sand (S)	<0.001	<0.001	<0.001	0.027	0.001	<0.001	0.391	<0.001	<0.001	0.002	0.022
Wind (W)	0.189	0.958	0.007	0.898	0.586	<0.001	0.187	<0.001	<0.001	0.999	0.612
Age¶		0.001				0.313	<0.001			<0.001	0.025
S × W	0.014	0.507	0.596	0.024	0.391	0.097	0.133	<0.001	<0.001	0.440	0.611
Contrasts											
Ctrl vs. W.o.	0.733	0.872	0.995	0.782	0.974	<0.001	0.019	<0.001	<0.001	0.555	0.119
Ctrl vs. S	0.005	0.022	<0.001	0.037	0.030	<0.001	0.093	<0.001	<0.001	0.024	0.026
W.o. vs. S	<0.001	<0.014	<0.001	0.006	0.001	<0.001	0.141	<0.001	<0.001	0.013	0.394
CV, %	37	36	32	43	25	30	33	7	6	38	9

† W.o., wind only.

‡ Due to missing values, least-squares means are presented.

§ Measurements at 1 h after exposure.

¶ Interactions with plant age were not significant.

let. At 57 DAE, twice-exposed plants had one leaf less than the control, however, the difference was not significant.

Damages to millet seedlings in the field by violent sand storms were reported by Brenner (1991). After a reduction of early leaf area and dry matter, the crop had recovered 46 d after sowing. For grain sorghum, an 18% reduced leaf area was found after treatments of 60 min of wind alone (13.5 m s^{-1}) at the nine-leaf stage, and decreases up to 60% were reported with blown sand, both measured 7 d after exposure (Armbrust, 1982). Viable leaf area of winter wheat decreased up to 37% under similar conditions (Armbrust et al., 1974). In a study with cotton, leaf area of plants exposed to abrasive injury at an age of 3 d was reduced and delayed about 10 d. For plants exposed at an age of 9 d, the delay was between 10 and 17 d (Fryrear, 1971). Grace (1977), however, concluded that plants can tolerate and even benefit from leaf damage and partial loss of leaf area, when extensive surface abrasion does not influence stomatal behavior and leaf water relations over a long period. In a study with tomato plants, wind alone caused no anatomical changes, but tissue destruction was extensive when sand was added (Precheur et al., 1978). In many plants, however, wind can alter the wax structure of leaf surfaces, decrease cuticular resistance, and rupture epidermal cells beyond the epicuticular wax (Grace, 1977). Furthermore, shaking by wind may induce plasmolysis of cells.

Net Photosynthetic Rate

Wind without sand had no significant effect on photosynthesis compared with the control, except for a decrease 1 h after the exposure at 16 DAE, as indicated by contrasts (Table 1). A response to different wind speeds was found only immediately after exposure. Wind speeds of 11 and 14 m s^{-1} decreased photosynthesis at 1 h after the 8 DAE exposure by 30 and 35%, respectively, and at 1 h after the 16 DAE exposure by 43 and 55%, compared with the 8 m s^{-1} treatment (Table 1). When millet was exposed at 8 DAE, significant effects of sand flux on photosynthesis were found up to 4 d after exposure. Compared with the control, the overall assimilation rate of sandblasted leaves was 55% lower at 1 h, 37% lower at 2 d, and 28% lower at 4 d after the 8 DAE treatment. The maximum reduction of 88% was measured at 1 h after exposure (8 DAE) for the 41.7 g m^{-1} s^{-1} sand flux. When exposed at 16 DAE, the photosynthetic rate of sandblasted leaves at 1 h after exposure was 53% lower than that of control plants. The wind-only treatments showed a lower photosynthesis up to 4 d after the 16 DAE-exposure, whereas the reduction due to sandblasting was not significant. The reasons for a higher photosynthesis of twice-exposed plants at 20 DAE compared with those exposed only at 16 DAE were not apparent.

Short-term water stress in leaves with broken cells was assumed to account for decreasing photosynthesis by reducing the activity of carboxylating enzymes (Armbrust, 1982). Reduction in photosynthesis can also be attributed to an increase in stomatal resistance by wind (Grace, 1977). However, our results do not agree totally with data reported for other crops. Whole-plant photosynthesis of sorghum remained unchanged after exposure to wind alone and was decreased for 7 d after sandblasting. When calculated on a live-leaf-area basis, however, the photosynthetic rates increased by 48 to 85% after sandblasting (Armbrust, 1982). Similar results have been found for wheat; Armbrust et al. (1974) reported a higher chlorophyll concentration after sandblasting, but no increase in ribulose-1,5-diphosphate (RUDP) carboxylase activity. For wheat, wind alone resulted in significant higher RUDP carboxylase activity, but lower photosynthesis compared with wind plus sand or the control. Positive correlations between leaf area and photosynthesis were reported for grain sorghum (Peng and Krieg, 1992), but negative relationships were documented for other crops (Bhagsari and Brown, 1986).

Nitrate Content

Nitrate content at both harvests was significantly affected by an interaction of sand flux and wind speed (Table 1). The content increased with increasing sand flux and increasing wind speed, but response to wind speed within different sand flux levels was inconsistent (Table 1). This may reflect a high variability within the data because of complex treatment-effect mechanisms rather than systematic physiological reactions. Compared with the control plants, wind alone increased NO_3 content of millet by 160 and 30% at 10 and 21 DAE, respectively. Plants exposed to the highest sand flux had NO_3 contents that were 5.8 and 2 times more than that of the control at the first and second harvest, respectively.

Similar effects of sandblast damage on NO_3 content have also been reported for soybean; Armbrust and Paulsen (1973) found increased NO_3 content for 40 d after an exposure of 40 min to wind (13 m s^{-1}) or to wind plus sand (5 g m^{-1} s^{-1}). A significant increase after a 5-min exposure to wind alone was found 21 d after exposure, and 15-min exposures to wind and to wind plus sand increased NO_3-N 120% in soybean (Armbrust, 1972). Except for immediately after treatment, higher activity of the nitrate reductase enzyme and higher NO_3 content have been found for 40 d after exposure (Armbrust and Paulsen, 1973); this was attributed to a possible alteration or disruption of amino acid and protein synthesis.

Sandblasted millet can be considered safe forage for consumption by cattle. Up to 6 g kg^{-1}, NO_3 is expected to have no negative effect (Corah, 1988). However, stems would have higher contents, and lower stem parts would have still higher contents, than our whole-plant samples. Nitrate content can easily exceed 9 g kg^{-1} because of other stress factors, such as low light intensities, drought, phosphorus shortage, or high N fertilization (Corah, 1988). Corah also stated that 30 g kg^{-1} NO_3 is possible for forage sorghum. Thus, wind erosion may be only a secondary factor in increasing the likelihood of NO_3 poisoning in cattle.

Dry Matter

Wind alone did not significantly affect millet dry matter at the second or the final harvest, and the effects of different wind speeds on dry matter production were not significant (Table 1). Exposure to blown sand and the plant age at exposure, however, had significant effects. Blown sand reduced dry matter by an average of 25% (at 21 DAE) and 6.4% (at 57 DAE) compared with unexposed plants (Table 1). The highest sand flux level resulted in 40% less dry matter at 21 DAE and 9.7% less at the final harvest compared with the control. The lowest sand flux, however, resulted in a higher dry weight than wind-only treatments. Millet exposed once at 8 DAE and twice (at 8 and 16 DAE) had, at 21 DAE, 31 and 39% less dry matter, respectively, than millet exposed once at 16 DAE. At the final harvest (57 DAE), no difference occurred in dry matter between 8 DAE and 16 DAE single exposures, whereas twice-exposed millet had 5% less dry matter than once-exposed millet.

The decrease in millet dry matter at 21 DAE observed in our research reflects the losses of viable leaf area and the decrease in the photosynthetic rates from blown sand at that date. Through the final harvest, millet showed a good ability to recover and to reduce the early effects of leaf area loss and photosynthesis reductions on final dry matter. A similar pattern was found by Leihner et al. (1993), where a positive early effect of wind protection on millet dry weight disappeared at later growth stages. Unfortunately, the effects of different wind speeds and sand fluxes on grain yields of millet have not yet been ascertained. An increase of dry weight at low sand flux levels was also found for grain sorghum sandblasted at the nine-leaf stage, when measured at 7 d after treatment (Armbrust, 1982). Possible reasons could be an increased translocation of stored carbohydrates at low sand flux levels. The stored energy may not have been sufficient at higher sand flux levels to compensate for the decrease in photosynthesis (Armbrust, 1982).

Long-term responses of other crops indicated higher sensitivities than millet. Cotton dry matter at 50 d of age was reduced by 70% after sandblasting at ages of 3 or 9 d (50 g m^{-1} s^{-1} sand flux and 13.5 m s^{-1} wind speed for 10 min) (Fryrear, 1971). Increasing sand fluxes caused dry matter and yield depressions in wheat of up to 40%, and ripening of grain was delayed up to 10 d on severely exposed plants (Woodruff, 1956). Pod yields of bean decreased almost linearly with increasing wind speed, abrasive flux and duration of exposure (Skidmore, 1966). Yield losses of bean were 42% after exposure to 13.4 m s^{-1} and 20 g m^{-1} s^{-1} for 5 to 15 min.

The effects of plant age on dry weight after single exposures were more pronounced for other crops than for millet. For sorghum, dry weight reduction was highest after exposures at 7 DAE, compared with earlier and later treatments; for soybean and wheat maximum reduction occurred after exposures at 14 DAE (Armbrust, 1984). Similar to the dry weight decrease of twice-exposed millet, yields of cotton decreased, as the number of exposures increased (Armbrust, 1968). It should be noted, that recovery of sandblasted crops in the field under harsh climatic conditions is more difficult than in this laboratory study.

Experiment 2

Survival

Millet plants that were not buried showed 100% survival. Survival of buried millet was affected strongly by interactions with both sowing system and growth stage at treatment (Table 2). We observed that most of the buried plants survived and recovered once their leaves had emerged again. Highest survival rates of buried millet occurred with treatments at the one-leaf stage and with planting in tufts. These effects may have been caused by higher food reserves in seeds in early stages and by the shape of tufts facilitating recovering. Furthermore, the higher seedling numbers in tufts at burial resulted in higher probabilities that at least some seedlings would recover and survive.

Dry Matter

Dry matter production at 70 DAE was affected significantly by interactions of burial with sowing system, growth stage, and sandblast treatment (Table 2). Unburied single stands had 4.9% more dry matter than unburied plants in tufts. Sandblasting had no significant effect on dry matter production of unburied plants. However, exposures of nonburied plants to sandblasting at the one-leaf or two-leaf stage resulted in slightly less dry matter compared with an exposure at the three-leaf growth stage (data not shown). Most growth reductions occurred with combinations of burial with single stands or with sandblasting. Among buried millet, plants in tufts had nearly a five times higher dry matter production than single plants, due mainly to an increased survival rate (Table 2). Exposure to sandblasting before burial reduced dry matter by 47% compared with unexposed buried millet. Dry matter production of millet buried at the one-leaf stage was 2.8 times more than that of later treatments, due to a higher survival rate.

These results and those from an exploratory trial in combination with Exp. 1 disprove the assumption that planting in tufts provides natural protection against abrasion damage. Recovering after burial was improved by tufts, and this may be one reason that farmers in Southwest Niger traditionally sow their millet first in tufts and thin the plants after several weeks. The possible protection against sandblasting, however, was negligible compared with growth reductions due to early competition. Millet appears to be most sensible to abrasion damages within the first days after emergence. However, the ability to recover after burial decreases at later stages. Field experiments with portable wind tunnels and subsequent artificial burial of different crops could provide useful data on the ability to recover under a range of agroclimatic environments.

Total Kinetic Effect

Correlations between calculated TKe and measured leaf area, NO_3 content, and dry weight were in general poor, as indicated by low coefficients of determination. As is shown in Fig. 1, the complexity of a nonlinear equation was rarely justified. There was large variation in the data at low TKe levels. This was partly due to the fact that the TKe is zero for both the control and the wind-only treatments, but growth reductions and increases in NO_3 content compared with the control were observed with wind alone (Table 1). However, the elimination of the zero values of TKe did not substantially improve the regression (data not shown).

Table 2. Millet plant survival and dry matter 70 d after emergence as affected by sand burial, sowing system, sandblasting, and the growth stage at treatment, with ANOVA results for the 14 factors and combinations.

Treatment	$P > F$	Survival	$P > F$	Dry matter
		plants pot^{-1}		g pot^{-1}
Burial (B)	<0.001		<0.001	
No burial		3.0		50.0
15-mm cover		0.9		17.3
Sowing system (Sow)	<0.001		<0.001	
Single stands		1.6		28.6
Tufts		2.3		38.7
Growth stage (GS)	0.002		0.005	
One-leaf		2.3		39.2
Two-leaf		1.8		30.5
Three-leaf		1.8		31.3
Sandblasting (SB)	0.418		0.014	
No sandblast		2.0		36.6
15-min sandblast		1.9		30.7
B × Sow	<0.001		<0.001	
No burial				
Single stands		3.0		51.2
Tufts		3.0		48.8
15-mm cover				
Single stands		0.3		6.0
Tufts		1.6		28.6
B × GS	0.002		<0.001	
No burial				
One-leaf		3.0		48.2
Two-leaf		3.0		50.1
Three-leaf		3.0		51.8
15-mm cover				
One-leaf		1.7		30.3
Two-leaf		0.5		10.8
Three-leaf		0.7		10.8
B × SB	0.418		0.044	
No burial				
No sandblast		3.0		50.6
15-min sandblast		3.0		49.5
15-mm cover				
No sandblast		1.1		22.6
15-min sandblast		0.8		12.0
GS × Sow	0.610		0.913	
GS × SB	0.126		0.620	
Sow × SB	0.685		0.357	
GS × Sow × SB	0.051		0.015	
GS × Sow × B	0.610		0.783	
GS × SB × B	0.126		0.270	
GS × SB × B × Sow	0.104		0.088	
CV, %	29		29	

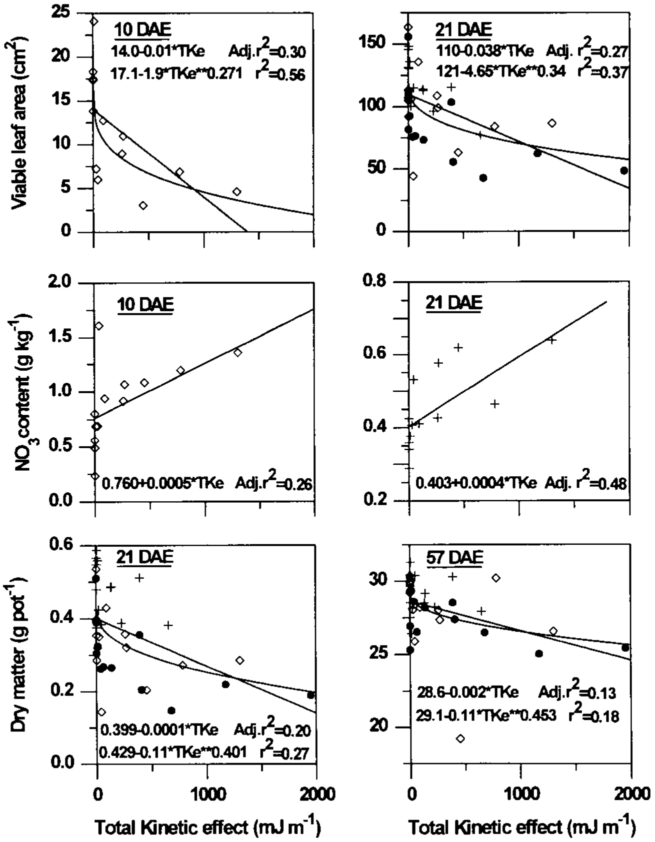

Fig. 1. Relationship at two dates between total kinetic effect and leaf area, NO_3 content, and dry weight of pearl millet exposed to wind plus sand at 8, 16, or 8 and 16 days after emergence (DAE). No nonlinear regression was found for NO_3. Open symbols, 8 DAE exposure; solid symbols, both 8 and 16 DAE; crosses, 16 DAE.

When the TKe term in the regression was replaced by sand flux, coefficients of determination were usually higher. This is in contrast to published results for vegetables and cotton (Fryrear and Downes, 1975a), and indicates the need to adapt the TKe concept to different crops. Distinct analyses for each plant age group increased the coefficient of determination of the twice-exposed treatments (up to 0.58 for the leaf area at 21 DAE). It is thus unlikely that calculated TKe values from distinct erosion events may be summed and compared with those from single exposures. Wind speed as a factor had no significant effects on measured millet leaf area and dry matter (Table 1). Furthermore, it did not improve correlation coefficients of plant survival (Fryrear and Downes, 1975a). Thus it is not needed in the TKe term. Including age at exposure into the regression with sand flux did not increase the variation explained by the equations.

The calculation of a stress index for wind erosion damages of a given crop requires more detailed data. It should also include effects of burial by blown sand. Trials under field conditions with portable wind tunnels could help to determine the effects of a sequence of erosive events. Since the exposure time component was not a variable in our trial, it should also be included in future research.

CONCLUSIONS

Exposing millet seedlings to wind and windblown sand will reduce leaf area, photosynthesis, and dry matter production, but will increase NO_3 content. Effects get smaller a few days after the exposure. Growth is most reduced by sandblasting at the one-leaf stage, by high sand flux levels, by a sequence of wind erosion events during early growth, or by combination of sandblasting with burial and other agroclimatic growth constraints. Millet can withstand sandblasting without a reduction in survival rate. Wind speed during erosion events is less important for leaf area losses and dry matter production than the sand flux level. Wind erosion is only a secondary factor in increasing the likelihood of NO_3 poisoning in cattle. The TKe concept needs more detailed data sets for further improvement.

Further research is needed to obtain field data under a range of natural environments. The use of portable wind tunnels combined with physiological measurements should be emphasized. Measurements of transpiration after exposure could provide supplemental information, because transpiration affects both NO_3 assimilation and photosynthesis (Huffaker et al., 1970). In order to determine if uptake or metabolism of N is affected by wind and sandblasting, the total N content should be investigated. Furthermore, NO_3 content should be measured through final harvest, especially for vegetables. Experiments with artificial burial of many crops can be easily conducted under field conditions in regions affected by wind erosion. The effects of crop cultivars on recovering and growth after sandblasting or burial also need further investigation.

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