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Wind and Sandblast Damage to Growing Vegetation

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Abstract: Wind erosion is a major problem on agricultural lands in much of North Africa, the Near East, parts of Asia, Australia, southern South America, and portions of North America. Particles moving in the wind stream damage plants by impact, burial, and exposure of plant roots. Reported effects of wind and sandblast damage are: reduced dry weight, leaf area, plant height, survival, photosynthesis, and quality and quantity of yield. Additional effects include increased respiration, delayed maturity, plant disease transmission, morphological, and anatomical changes. Future challenges to research on wind damage effects are: quantifying plant sandblast damage under field conditions, while including additional factors such as burial or removal of soil from around roots. Improved transducers are also needed for measuring the energy of windblown particle impacts.

Keywords: Wind damage, plant characters, factors of damage, research needs.

Large aeolian deposits from past eras present evidence that wind erosion is not a recent phenomenon. Satellite photographs have revealed much about the origin and extent of dust storms occurring around the world (Idso, 1976).

Major areas susceptible to wind erosion on agricultural land include much of North Africa and the Near East, parts of southern and eastern Asia, Australia, southern South America, and the semi-arid and arid portions of North America (FAO, 1960). Also, agricultural areas in the Siberian Plain and other areas of the Russian Republic have a potential for wind erosion.

Wind erosion is the dominant problem on about 30 million ha area in the United States (USDA, 1965). About 2 million ha are moderately to severely damaged each year. Wind erosion can occur when the following soil, vegetative, and climate conditions exist: (a) the soil is loose, dry, and finely divided; (b) the soil surface is smooth and vegetative cover is absent or sparse; (c) the field is large; and (d) the wind is strong enough to move soil.

Wind erosion occurs when the wind exerts enough force on the soil surface that soil particles or sand grains dislodge and are transported by the wind. Lyles and Krauss (1971) observed that as the threshold velocity was approached, some particles began to vibrate or rock back and forth. Erodible particles vibrated with increasing intensity as wind velocity increased and then left the surface as if ejected. Saltation-size particles (0.1 to 0.5 mm in diameter) rise almost vertically (75 to 90 degrees from the horizontal), travel 10 to 15 times their height of rise, and return to the surface with an angle of decent of about 6 to 12 degrees from the horizontal (Chepil and Woodruff, 1963). Upon returning to the surface, the particles strike the soil surface or vegetative materials and either rebound and continue downwind or embed themselves and initiate movement of other particles. The bulk of total transport, roughly 50 to 80%, is by saltation. Saltating particles rise less than 120 cm; most rise less than 30 cm. The impact of saltating particles on leaves and stems of growing plants causes damage, often referred to as sandblast damage.

Particles larger than 0.5 mm roll or slide along the surface by being impacted by the saltating particles. Bagnold (1943) observed that at low wind speed, sand grains moved in jerks a few millimeters at a time, and at high wind speeds, the whole surface appeared to be moving forward. Particles smaller than 0.1 mm are carried in suspension to great heights by the wind. Suspension is the most spectacular mode of transport and easily recognized from a distance, forming rolling clouds of dust.

The objectives of this paper are to review the literature on the effects of wind alone or wind laden with soil or sand particles (sandblasting) on growing plants determined in laboratory and field wind tunnel studies and to present future challenges in quantifying the effects of wind and sandblast damage on growing plants.

Wind Damage

Evidence of the wind's effect on the growth, morphology, and anatomy of growing plants can be observed where winds blow from a predominate direction for most of the year. Trees demonstrate altered shapes, with more growth toward the downwind direction, and plants exposed to windy environments, like alpine meadows, are shorter; have smaller leaves; and have thicker, shorter stems than plants growing in protected areas.

Morphological changes caused by exposure to wind velocities ranging from 0.4 to 14.8 m sec^{-1} have been reported for marigold (Finnell, 1928); sunflower (Martin and Clements, 1935; Whitehead, 1962); sweet corn (Whitehead and Luti, 1962); and barley, pea, and rape (Wadsworth, 1959, 1960). In all these wind-exposed plants, the leaves were shorter, broader, and thicker with less total area than unexposed plants. Stem diameters were smaller in sunflower (Martin and Clements, 1935), but larger in sweet corn (Whitehead and Luti, 1962). Plants were shorter than unexposed plants, because of shorter internodes. These morphological changes were evident within 24 hours (Finnell, 1928) and led to gnarled leaves and deformed stems.

Dry weights of roots and shoots were reduced as the wind velocities increased, but the root to shoot ratio increased (Whitehead, 1962; Whitehead and Luti, 1962). The longest roots were found on the wind-exposed plants. These adaptive changes were attributed to water stress caused by higher transpiration losses from the wind. Finnell (1928) measured increased water use in marigold, but sunflower transpiration rates went down as the wind speed increased (Martin and Clements, 1935). Grace (1974) found increased transpiration rates in tall fescue seedlings and attributed it to increased leaf-to-leaf collisions that damaged the surface. Epicuticular wax was abraded away and epidermal cells next to guard cells were

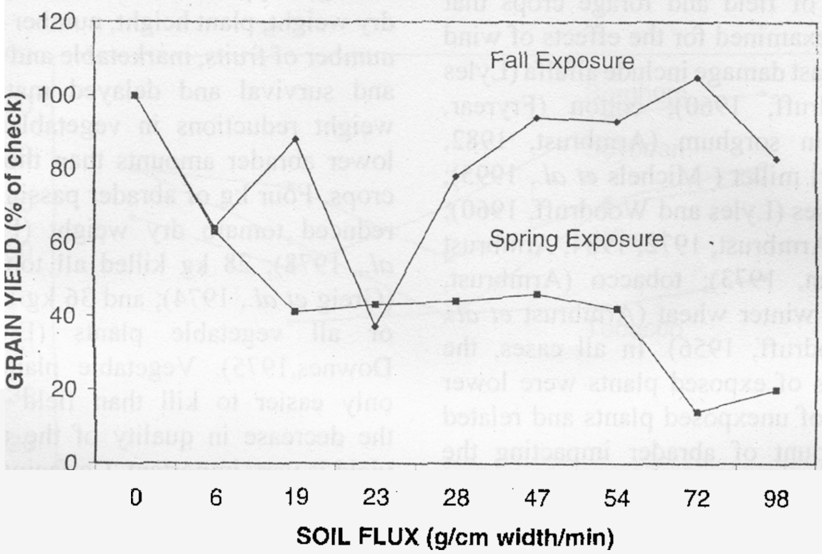

Fig. 1. Effect of exposure to soil flux in fall and spring on grain yield of winter wheat (Woodruff, 1956).

punctured, allowing the guard cells to expand and open the stomata.

Decreased dry weight and reduced growth rates were reported in all studies, and a delay in maturity of 10 days was reported for marigold (Finnel, 1928). Grace and Thompson (1973) measured reduced photosynthesis rates in tall fescue because of higher mesophyll resistance in the wind-exposed plants caused by reduced water content. Plants of barley, pea, and rape grown in water culture indicated no effect of wind on net assimilation (Wadsworth, 1960).

Mechanical damage, in the form of fold lines, was observed in tall fescue seedlings exposed to a 3.5 m sec^{-1} wind speed for 7 weeks (Thompson, 1974). The number of fold lines per leaf and percent of plants with fold lines were greater in the wind-exposed plants than the controls. Once a transverse fold line was formed on a leaf, the tissue beyond showed signs of wilting, chlorosis, and sometimes necrosis. In extreme cases of leaf fluttering, the tissue beyond the fold line was removed from the plant.

These studies showed that wind reduces plant growth by several mechanisms. At low wind speeds, the effect seems to be an increase in transpiration, which results in water stress. This stress causes the plant to adapt by decreasing leaf area and internode length, while increasing root growth and stem diameter. As the wind speed increases further, cell and cuticular damage occurs, followed by death of plant tissue, and a gnarled appearance becomes more apparent.

Windblown Soil Damage

Species of field and forage crops that have been examined for the effects of wind and sand-blast damage include alfalfa (Lyles and Woodruff, 1960); cotton (Fryrear, 1971); grain sorghum (Armbrust, 1982, 1984); pearl millet (Michels *et al.*, 1995); native grasses (Lyles and Woodruff, 1960); soybeans (Armbrust, 1972, 1984; Armbrust and Paulsen, 1973); tobacco (Armbrust, 1972); and winter wheat (Armbrust *et al.*, 1974; Woodruff, 1956). In all cases, the dry weights of exposed plants were lower than those of unexposed plants and related to the amount of abrader impacting the plants (Fig. 1). In studies using the same wind speed and similar sand amounts, the amounts of abrader passing the plant needed to reduce dry weight were 40 kg for grain sorghum (Armbrust, 1984); 15 kg for winter wheat (Armbrust *et al.*, 1974); and 10 kg for soybean (Armbrust, 1972), indicating that different species can tolerate different amounts of abrasion damage before dry weight production is influenced.

Other plant parameters decreased by wind erosion damage were leaf area, plant height, survival, and yield. Maturity was delayed 10 days in winter wheat (Woodruff, 1956) and 7 to 10 days in grain sorghum, soybean, and winter wheat (Armbrust, 1984), and cotton growth was delayed 8 to 25 days (Fryrear, 1971). Yield of undamaged tobacco leaves was reduced 19 to 84% (Armbrust, 1979).

Vegetables species including cabbage, carrot, cucumber, onion, pepper, and southern pea (Fryrear and Downes, 1975); tomato (Armbrust *et al.*, 1969, Precheur *et al.*, 1978, Greig *et al.*, 1974); and green bean (Skidmore, 1966) also have been evaluated for their tolerance to wind erosion damage. Typical effects were decreases in dry weight, plant height, number of flowers, number of fruits, marketable and total yield, and survival and delayed maturity. Dry weight reductions in vegetables occur at lower abrader amounts than those in field crops. Four kg of abrader passing the plant reduced tomato dry weight (Precheur *et al.*, 1978); 28 kg killed all tomato plants (Greig *et al.*, 1974); and 36 kg killed some or all vegetable plants (Fryrear and Downes,1975). Vegetable plants are not only easier to kill than field crops, but the decrease in quality of the marketable yield is very important. Catfacing, a quality factor that makes tomatoes unmarketable, was increased from 6% of the yield of unexposed plants to 30% of the yield of wind-damaged plants (Precheur *et al.*, 1978).

Anatomical changes also have been recorded for cotton (Fryrear, 1971) and tomato (Precheur *et al.*, 1978; Greig *et al.*, 1974). Tomato leaves damaged by windblown sand had longer and wider palisade cells, increased midrib thickness, increased adaxial cuticle thickness, and more stomates per mm^2 on the lower epidermis. Secondary endodermis was formed under the wounded areas in 2 days. The epidermis and underlying cortical layer of tomato stems were destroyed where sand impacts were concentrated. Peripheral endodermis was produced under the wound and reduced the stem diameter by approximately 1 mm (Greig *et al.*, 1974). Fryrear (1971) reported that cotton stems were compressed, but not eroded away.

The studies discussed above indicated the plants' response to being struck by

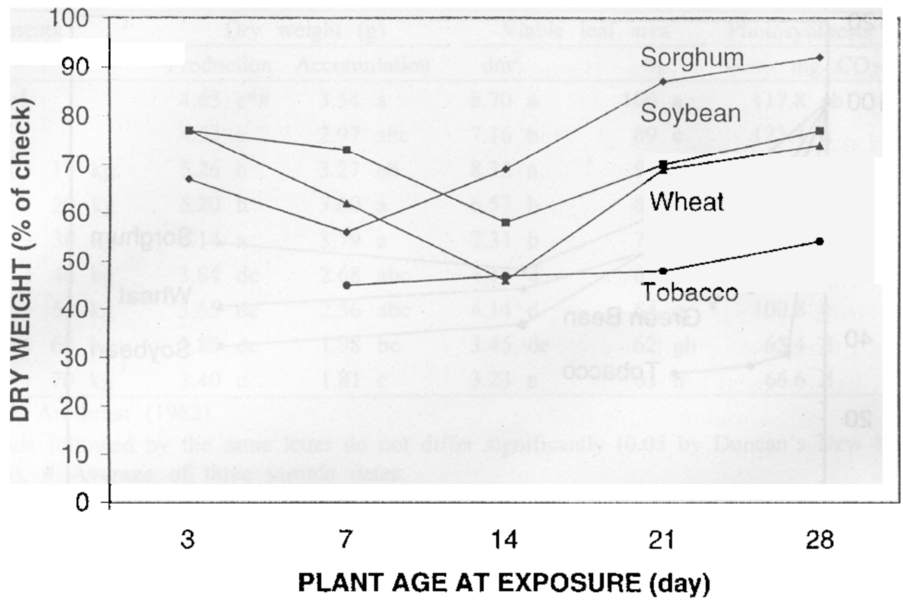

Fig. 2 Effect of plant age at exposure on dry weight production of grain sorghum, soybean, tobacco, and winter wheat (Armbrust, 1979, 1984).

windblown particles, but not those events that occur within the plant, i.e., physiological changes. Photosynthesis and respiration of tomato (Precheur *et al.*, 1978); grain sorghum (Armbrust, 1982); and winter wheat (Armbrust *et al.*, 1974) were measured after exposure to sandblasting. In all crops, photosynthesis was reduced, but then recovered to the normal rate in 5 to 7 days. Respiration was increased by damage in wheat and grain sorghum, but not in tomato. Changes in photosynthesis were due to loss of viable leaf area and moisture stress from cells being ruptured by abrading particles, which allowed rapid drying.

Activity of nitrate reductase enzyme in soybean was reduced immediately after exposure, but then increased above the control level and remained higher for 40 days (Armbrust and Paulsen, 1973). The decrease in enzyme activity was due to short-term, high-intensity, water stress, and the increase was due to higher nitrate concentrations in the tissue of the damaged plants. Soybean shoots contained higher nitrate concentrations after exposure to wind and wind plus sand, even when dry weight was not reduced (Armbrust, 1972). Concentrations of iron in the shoots were increased. Pearl millet also accumulated nitrate nitrogen in plant shoots after exposure to wind erosion damage (Michels *et al.*, 1995).

The effects of soil moisture before and after exposure to sandblast damage have been studied with cotton (Fryrear, 1971) and tomato (Armbrust *et al.*, 1969). Cotton

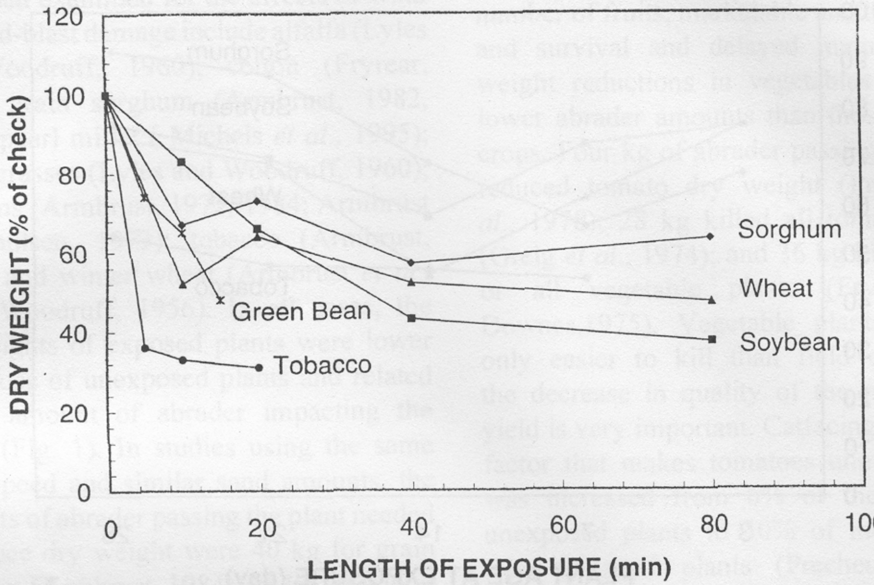

Fig. 3. Effect of length of exposure on dry weight production of grain sorghum, green bean, soybean, tobacco, and winter wheat (Armbrust, 1979, 1984; Skidmore, 1966).

exposed at 3 days of age when soil moisture was high had reduced survival when soil moisture was reduced at 9 or 27 days after exposure. However, plants exposed at 9 days of age, under the same soil moisture conditions, had greater survival when soil moisture was reduced. Tomato survival was increased when soil moisture was increased after exposure.

Transmission of plant pathogens by wind and windborne soil has been studied using wind tunnels. Wheat streak-mosaic virus was not transmitted to healthy plants when they were abraded by soil particles artificially infested with the virus (Sill *et al.*, 1954). However, transmission occurred when leaves of infected plants came in contact with leaves of uninfected plants. Incidence of bacterial leaf spot of alfalfa increased by 6 to 26% when seedlings were abraded by naturally infested soil or artificially infested sand (Claflin *et al.*,1973). Incidence of common blight of bean in healthy seedlings increased by 25 to 55% under the same conditions in that study.

Factors Affecting Severity of Damage

The major factors that influence the severity of sandblast damage to plants are: (i) age of plant when damage occurs; (ii) wind speed at the time of exposure; (iii) length of time over which the exposure occurs; and (iv) the flux rate of abrader in the wind stream. Each factor will be discussed in the following sections.

Table 1. Total dry weight production, dry weight accumulation from 1 to 7 days after treatment, viable leaf area, percentage of viable leaf area, photosynthesis, and respiration of grain sorghum exposed to wind and wind plus sand

Treatments	Dry weight (g)		Viable leaf area		Photosynthesis	Respiration
	Production	Accumulation	dm^2	%	------ mg CO_2/pot/hr ------	
Control	4.65 c*#	3.54 a	8.70 a	100 a	117.8 ab	36.7 ab
Wind	4.53 c	2.97 abc	7.16 b	89 c	123.4 a	34.4 abc
Wind + 10 kg	5.26 b	3.27 ab	8.32 a	93 b	102.6 bc	39.4 a
Wind + 20 kg	5.20 b	3.60 a	6.57 b	80 d	113.1 bc	38.5 ab
Wind + 30 kg	6.14 a	3.79 a	7.31 b	74 e	105.0 bc	41.7 a
Wind + 40 kg	3.84 de	2.68 abc	4.14 d	68 f	98.8 c	28.6 cd
Wind + 50 kg	3.65 de	2.56 abc	4.14 d	64 g	100.8 c	30.7 c
Wind + 60 kg	3.80 de	1.98 bc	3.45 de	62 gh	65.4 d	22.8 d
Wind + 70 kg	3.40 d	1.81 c	3.23 e	61 h	66.6 d	22.2 d

Source: Armbrust (1982).

* Means followed by the same letter do not differ significantly (0.05 by Duncan's New Multiple Range Test), # Average of three sample dates

Plant age

Exposing 3-day-old cotton seedlings to abrasive injury resulted in a loss of 36% of the plants, whereas the same treatments to 9-day-old plants resulted in 30% loss (Fryrear, 1971). Tomato plants 5 and 12 cm tall exposed to sandblast damage had better survival when they were older, i.e., 12 cm (Greig *et al.*, 1974). Grain sorghum, soybean, and winter wheat plants had the greatest dry weight reduction when they were exposed at 7 to 14 days of age than at younger or older ages (Armbrust, 1984) (Fig. 2). Tobacco leaf dry weight was reduced the most when plants were exposed 7 days after transplanting (Armbrust, 1979) (Fig. 2).

Plants 7 to 14 days of age had exhausted the energy supply in the seed and were becoming totally dependent on their own ability to produce photosynthate. Any loss of photosynthetic tissue at this time places an added burden on the plant's energy supply, because energy must be diverted from growth to repair of tissue damaged by sandblasting.

Length of exposure

Increasing the length of exposure to wind-blown particles reduced the dry weight of green beans (Skidmore, 1966); grain sorghum, soybean, and winter wheat (Armbrust, 1984); and tobacco (Armbrust, 1979; Fig. 3). The longer a plant is exposed to blowing soil, the more particles will strike the plant, rupturing more cells, causing more stress, and lowering dry weight production (Table 1).

Wind velocity

Increasing the wind velocity increased the yield reduction of green beans (Skidmore, 1966) (Fig. 4). Saltating particles descend back to the soil surface close to the speed of the wind that has entrained them (Chepil and Woodruff, 1963), so the higher the wind speed, the faster the particles are moving and the more energy is available to impart to the object they strike.

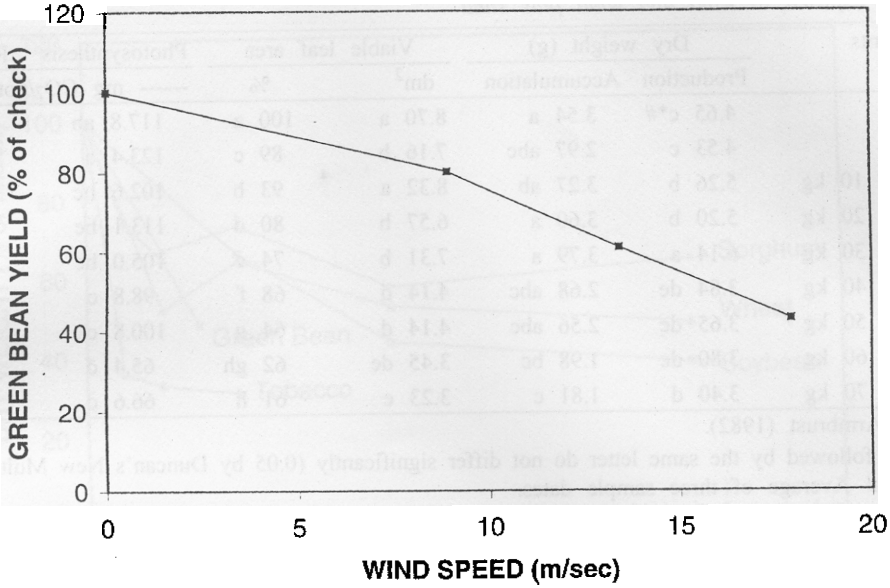

Fig. 4. Effect of wind speed on the yield of green bean (Skidmore, 1966).

Amount of abrader

The more abrader carried by the wind stream, the greater the reduction in green bean yield was (Skidmore, 1966) (Fig. 5). Under natural wind erosion events, the amount of soil moving with the wind stream is related directly to the velocity of the wind. The wind has a natural carrying capacity for saltation and creep size particles, which is determined by wind velocity, the surface conditions, and length of the eroding area down the wind direction (Chepil and Woodruff, 1963).

Assessment of wind erosion damage

Fryrear and Downes (1975) developed a relationship called total kinetic effect (TKe) which was well related to survival of several vegetable species and cotton seedlings. The relationship is:

$$TKe = MV^2T^2(2880A)^{-1} \quad .....[1]$$

where M is the sand flux rate in g (cm width)$^{-1}$ sec^{-1}; V is the velocity of the wind in cm sec^{-1} minus 670 (670 is the threshold velocity); T is the duration of exposure in min; A is the age of the crop seedling in days after emergence; and 2880 is a factor to convert plant age to minutes. Although TKe was related to survival (Fryrear and Downes, 1975), it was not related to leaf area, nitrate content, or dry weight of sandblasted millet seedlings (Michels *et al.*, 1995). Cole (1985) proposed that the appropriate measure of plant damage by wind erosion is particle momentum flux.

The factors of length of exposure and amount of abrader can be combined to obtain a parameter that can be a measure

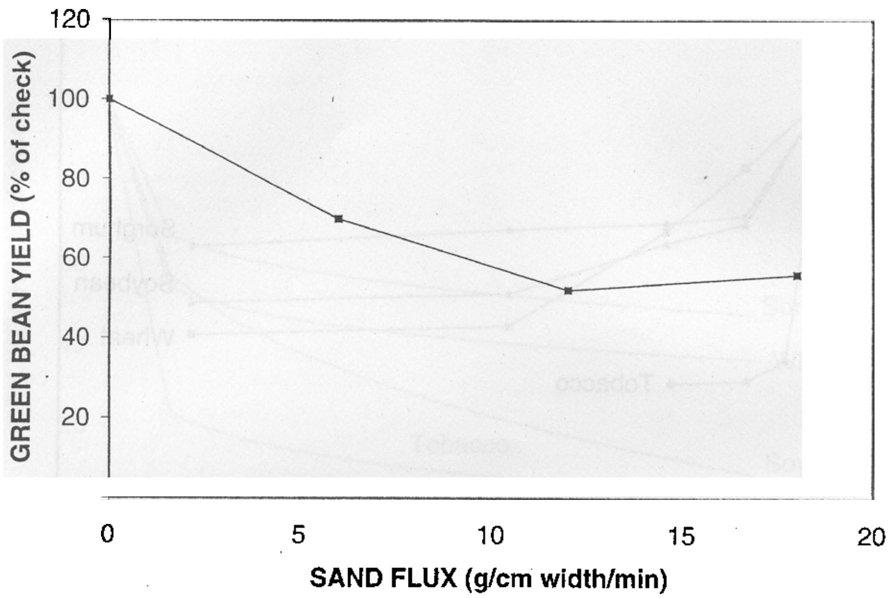

Fig. 5. Effect of sand flux on the yield of green bean (Skidmore, 1966)

of the energy of the particles striking the plant (Fig. 6). Dividing this parameter by the age of the plant at time of exposure results in a new parameter, which can be used as an indicator of wind erosion stress. It is a way to compare plant damage results conducted with different amounts of abrader, lengths of exposure, and plant ages (Fig. 7). All the relationships shown in Fig. 7 are of the form:

$$DW = a\text{-}bX^{c} \qquad .....[2]$$

where, DW is the dry weight as per cent of the control; a, b, and c are crop specific coefficients; and X is the amount of sand passing a plant divided by plant age at exposure. If the mass of an individual particle and the wind speed were known, an energy relationship could be developed. Figure 7 shows the differences in crop species' tolerance to sandblast damage; grain sorghum is the most tolerant, and tobacco the least tolerant.

Research needs

Further research is needed on plants grown under natural conditions in the field. One of the main obstacles to conducting field experiments of sandblast damage is that the climatic conditions cannot be controlled. Precipitation before, during, or after exposing plants can negate the effect of sandblast damage. Winter wheat that was emerging from dormancy had 50% of its leaf area damaged by simulated wind erosion damage 1 week after exposure, but subsequent abundant rainfall negated that condition by 2 weeks after exposure (Armbrust, unpublished results). Because plant damage by wind erosion under natural

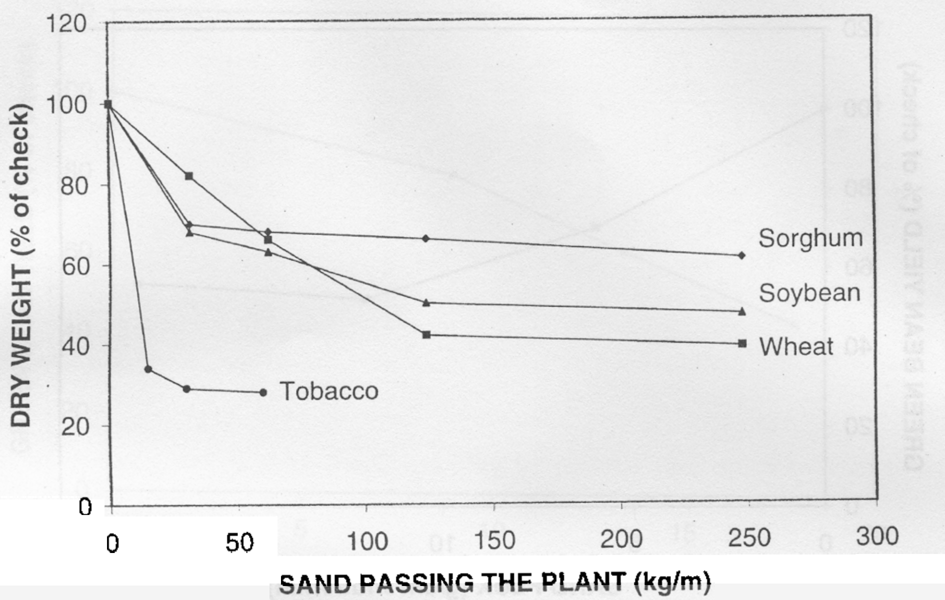

Fig. 6. Effect of the amount of sand passing the plant in kg m^{-1} on the dry weight production of grain sorghum, soybean, tobacco, and winter wheat.

conditions usually occurs when plants are exposed to water and temperature stress, duplicating those conditions is nearly impossible without some way to control the climate, such as a large shelter against rain or choosing an area where rainfall is sparse. Field experiments were carried out successfully in Big Spring, Texas, USA, where rainfall averages about 46 cm per year (Armbrust, 1968).

Growing plants are damaged not only by being impacted by windborne particles, but also by being buried partially or totally by those particles or having the roots partially or totally uncovered. Studies of artificial or natural burial of millet indicated that all measures of growth are reduced by plants being covered by wind-blown particles (Michels *et al.*, 1993, 1995). No studies of soil removed from around the roots by wind erosion have been conducted.

A very important area of future research is measuring the energy of impact of wind-blown particles at the plant surface and relating that energy to decreases in leaf area, growth rate, and quality and quantity of crop yield.

Field observations of natural wind erosion events indicate that plants on the extreme upwind edge of the field suffer more damage than plants further downwind. All past wind tunnel experiments on plant sandblast have been simulations of the upwind edge of the field without the upwind canopy to help protect plants from the impact of saltating particles. Therefore, all future work should be conducted with some form of upwind canopy in place.

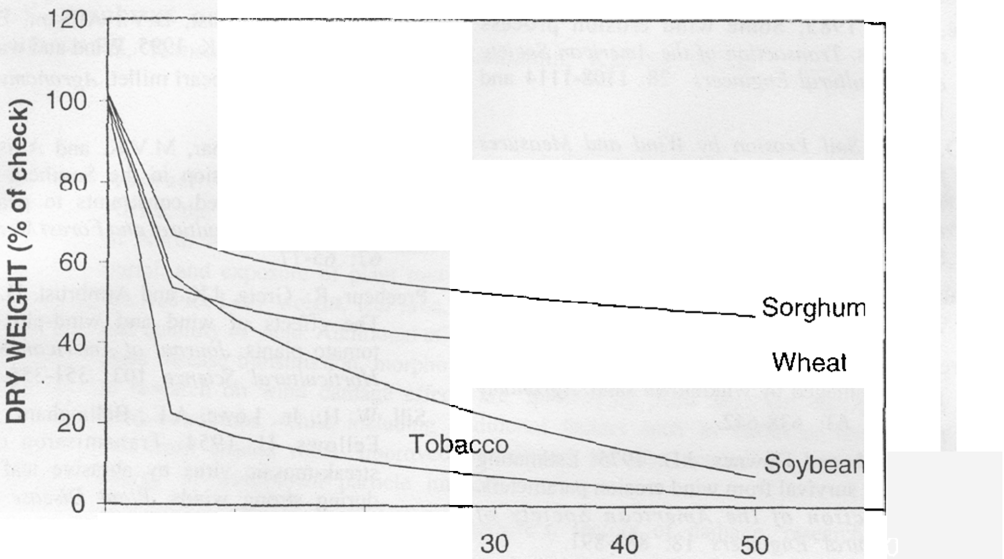

Fig. 7. Relationship of wind erosion stress in kg m⁻¹ (age at exposure)⁻¹ on the dry weight production of grain sorghum, soybean, tobacco, and winter wheat

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