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INFLUENCE OF WIND ON WATER VAPOR TRANSFER THROUGH SOIL, GRAVEL, AND STRAW MULCHES

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The influence of wind on evaporation from a wet soil surface has been studied extensively (6), but little information is available on this influence once the soil surface has dried and evaporation becomes limited to water vapor transfer through the dry surface soil. This paper represents an attempt to elucidate the influence of wind on water vapor transfer through dry soil, gravel, and straw mulches.

Fukuda (1), in his study of the influence of wind gustiness on air and vapor movement in soils, concluded that wind gustiness had little influence on the water vapor transfer rate. His conclusions were based entirely on mathematical considerations and assumed that water vapor transfer would be influenced only in proportion to the total amount of air moving out of the soil. That is, he assumed that water vapor transfer was related to wind gustiness only to the extent that water vapor was associated with the mass volume of air leaving the soil. He did not consider the total influence of wind on the water vapor transfer process.

Since diffusion is a slow process involving movement of the various gases in the air in response to concentration gradients of the particular gas, any force or disturbance causing mass movement of air would be expected to influence the rate of transfer of the various gases. Fluctuation of wind at the soil surface, while not necessarily causing a large amount of air to be removed from the soil, logically would be expected to speed up gaseous movement because of greater mixing of gases within the soil due to pressure changes. Thus it seems logical to expect that water vapor transfer (or transfer of any gas) would be influenced by wind speed. The measurements reported herein were made to determine this influence.

Measurements made on soil were of primary interest. Gravel and straw mulches were used for comparative purposes and because they have been widely studied with regard to evaporation (4).

THEORETICAL CONSIDERATIONS

Measurements of the influence of wind speed on pressure fluctuation at the soil surface have not been made as far as the authors are aware. Fukuda (1) quoted a figure of 0.1 mm. Hg for the magnitude of the fluctuations but he gave no wind speed. White (7), using water as a fluid, measured maximum velocity variations of twice the mean. Measurements are few because of instrumentation difficulties. Standard methods for measuring of wind speed (actually pressure measurements in most cases) are not suitable because, since the inertia of the measuring system damps out the fluctuations, only an average is measured. Based on present knowledge, it can be concluded that wind speed does have an influence on pressure changes at the soil surface; this influence is manifest in the magnitude and period of the pressure fluctuations. Based upon the data of White (7), the magnitude of the pressure fluctuation is a direct function of wind speed.

Estimations of the influence of pressure fluctuations at the soil surface (due to wind fluctuations or other causes, such as changes in barometric pressure) on pressure fluctuations within the soil can be made from theoretical considerations. Kirkham (5) has shown that the relationship of air pressure to time and depth is given by

$$\frac{\partial p}{\partial t} = \alpha \frac{\partial^2 p}{\partial z^2} \qquad (1)$$

where p is pressure with respect to a reference such as atmospheric, t time, z depth of soil, and

$$\alpha = \frac{KP_a}{\mu f}$$

where K is permeability of soil to air, Pa atmospheric pressure, u viscosity of the air, and f

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porosity of the soil. Equation (*1*) is similar to the heat flow equation of which many solutions for different boundary conditions are known (3).

For a homogeneous soil of infinite depth and for pressure fluctuating periodically at the soil surface the solution of equation (*1*) is

$$p_{z,t} = P_0 e^{-z\sqrt{\omega/2\alpha}} \sin\left(\omega t - z\sqrt{\omega/2\alpha}\right) \qquad (2)$$

where P_0 is the amplitude or half range of the pressure fluctuations at the soil surface, $\omega = 2\pi/T$, and T is the period of fluctuations. In equation (*2*) the first part, $P_0 e^{-z\sqrt{\omega/2\alpha}}$, gives the magnitude of the pressure change at any depth z, and the second part, $\sin(\omega t - z\sqrt{\omega/2\alpha})$, gives the time lag. Equation (*2*) is similar to equation (*5*) derived by Fukuda (1).

If pressure changes are significant at a specified depth it seems logical that vapor transfer would be increased at that depth. Table 1, which was calculated from equation 2, shows the magnitude of the pressure changes at various depths for two soils with three periods of wind fluctuation. Values of α for the two soils were taken from Kirkham (5). The data show large pressure changes within the soil. Thus the following predictions could be made, assuming that air pressure fluctuations within the soil influence vapor transfer: (*a*) that wind would influence vapor transfer through the soil; (*b*) that changing the wind characteristics of period and amplitude of fluctuations would influence vapor transfer; and (*c*) that increasing α by increasing permeability, such as with gravel or straw mulch, would increase vapor transfer. The data show also that the smaller the period the smaller the pressure change at any depth, and the greater the value of α the greater the change of pressure within the soil.

TABLE 1

The relative magnitude of pressure fluctuations at depth z with three periods of pressure fluctuation at the soil surface

Depth (z)	Surface Pressure Fluctuation at Depth z for Various Time Periods		
	1 sec.	10 sec.	30 sec.
cm.	%	%	%
	Sand α = 9153		
0	100	100	100
1	98	100	100
4	88	98	99
8	78	95	97
16	61	91	95
32	38	83	90
64	14	69	80
128	2	47	65
256	0	22	42
	Silt loam α = 1056		
0	100	100	100
1	95	98	99
4	80	93	96
8	64	87	92
16	42	76	85
32	19	57	72
64	4	32	52
128	0	11	27
256	0	1	7

The solution of equation (*1*) for boundary conditions where there is a boundary impermeable to air at some depth below the surface is not known, but apparently vapor transfer would not be influenced as much where a boundary layer exists as it would where one does not exist, because in the latter instance more total air movement would take place within the soil. Increased rates of air flow would be required to realize the same pressure in the large volumes associated with no boundary layer than in the smaller volumes associated with a boundary layer; and by the same reasoning, vapor transfer would be expected to be greater for a deep, air-impermeable layer than for a shallow one. Examples of impermeable boundary layers would be a water table in a field or, as in the case of this experiment, a cylinder closed at the bottom.

EXPERIMENTAL PROCEDURE

The experiment was conducted in a wind tunnel where wind speed could be varied and controlled (8). Plastic cylinders, 1.75 inches inside diameter and with heights ranging from ¼ to 1½ inches were used to contain the soil, gravel, or straw mulch. A mulch is defined here as a medium which transports water only in the vapor phase. Attached to the bottom of the plastic cylinders, but with capillary separation of the soil water by means of three 16-mesh screens, was an aluminum moisture can 1 inch high and of the same diameter as the plastic cylinders filled with soil at about the saturation percentage. The only purpose of the saturated soil was to provide a reservoir of water vapor at a specific depth from the surface. Tests were made only as long as the soil in the aluminum cans was well above permanent wilting percentage, which thus assured a relative humidity near 100 per cent and one therefore constant for all treatments. The cans were attached to the plastic containers with cellophane tape to assure a vapor seal.

The soil mulch in the plastic containers was treated with a waterproofing agent (Arquad 2HT—Armour and Co., Chicago, Ill.), which has been found to stop liquid flow of water in soils (2), in order to be certain that it would classify as a mulch. The soil mulch (Geary silt loam) was formed into a single mass in the cylinder by compacting in a moist condition to a bulk density of 1.45 g./cm.^{3} for all treatments. It was then air-dried before subjecting it to the wind, to prevent loss of soil from wind erosion.

The samples were placed in the wind tunnel with the surfaces level with the tunnel floor. Evaporation was measured gravimetrically. Weighings were made quickly while the wind was blowing. The samples were out of the wind while being weighed for about 1 per cent of total exposure time. Weighings were made about every half hour. Four measurements of evaporation were made at every wind speed on duplicate samples of all treatments. The data reported are averages of four measurements with two replications.

Wind speed was measured at 6 inches from the tunnel floor. Wet and dry bulb temperatures were measured at 3 and 6 inches. The vapor conductivity was computed from measurements of evaporation rate and vapor pressure gradient (2). The vapor pressure at the soil surface was extrapolated from the vapor pressure at 3 and 6 inches, which was determined from the wet- and dry-bulb measurements. The vapor pressure at the bottom of the mulch (top of wet soil) was determined from measurements of the temperature at that point with the assumption of a 100 per cent relative humidity. Since the soil moisture content was maintained well above permanent wilting percentage throughout the tests this should be a safe assumption (2). All temperature measurements were made with thermocouples and were recorded on a Brown "Electronik" recorder. A complete cycle of temperatures was completed every 10 minutes.

The gravel size ranged from 2.0 to 6.4 mm.; the density of the straw mulch was maintained constant and amounted to 3000 lbs./acre as a mulch ¼ inch thick (6000 lbs./acre as a ½-inch mulch etc.). A screen was placed over the straw to prevent its movement by wind. The straw used was wheat stubble cut into ¼-inch lengths.

RESULTS AND DISCUSSION

Figures 1 and 2 show the influence of wind and of depth and type of mulch on evaporation rate. The data show that evaporation rate increases in all cases with an increase in wind speed. This increase for the soil mulch is much greater with no mulch than with a mulch. Evaporation was increased about 10 times by increasing the wind speed from 0 to 25.4 miles/hour with no mulch and only 2 to 6 times where a mulch was present.

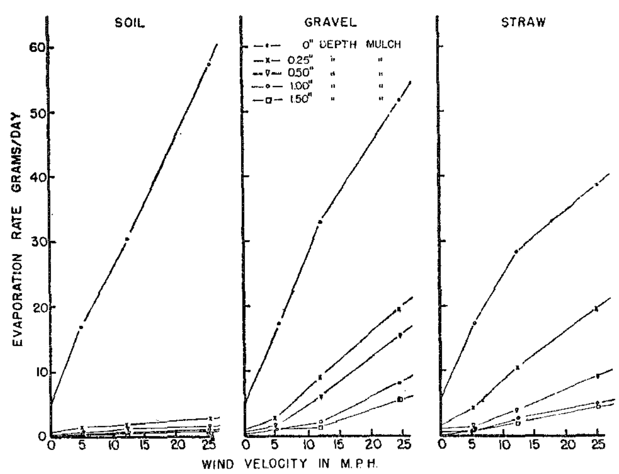

FIG. 1. Influence of wind speed on evaporation rate

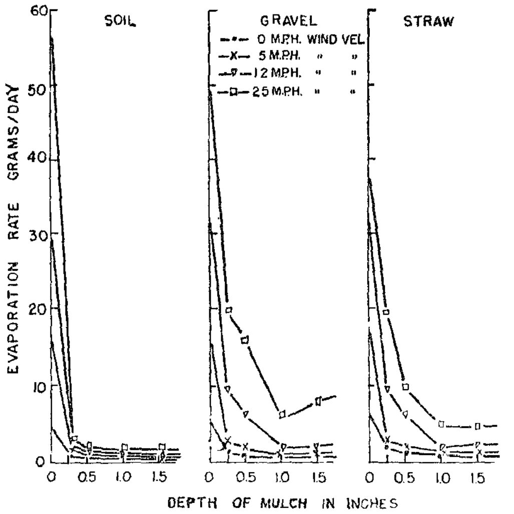

FIG. 2. Influence of depth of mulch on evaporation rate.

Thus it appears that a soil mulch "buffers" the relative influence of wind on evaporation. For the gravel and straw, evaporation was increased about 10 to 15 times by increasing the wind speed from 0 to 25 miles/hour.

In general, evaporation rate at all wind speeds decreased as the depth of mulch increased. The decrease was much greater, however, between 0 and ¼ inch mulch depth than from ¼ inch depth to successive depths. For example, at a wind speed of 12.5 miles/hour the evaporation rate was reduced from 30.5 to 0.7 g./day with the soil mulch by increasing the depth from 0 to 1½ inches. However, 96 per cent of this reduction was brought about by increasing the depth of mulch from 0 to ¼ inch. Thus a ¼-inch mulch appears to be about as efficient as a 1½-inch mulch.

The soil mulch appeared to reduce the evaporation rate much more than the gravel or straw mulch, especially at the higher wind speeds. At zero wind speed, evaporation from gravel and straw averaged about 1.3 times as much as from the soil. At 25 miles/hour, evaporation from the gravel and straw averaged 6.3 times as much as from the soil. There appear to be no outstanding differences between gravel and straw.

Table 2 shows the influence of treatment, depth of treatment, and wind speed on the diffusive conductivity of the mulch. If the movement of water vapor through a mulch was influenced solely by factors other than wind the vapor conductivity would be the same for all wind speeds and depths. Since the data show this not to be the case, the measured vapor transfer is not pure diffusion, and air mixing due to wind movement is indicated.

For all treatments and depths of mulch the vapor conductivity increased with an increase in wind speed. This increase was much more evident for the gravel and straw than for the soil.

The vapor conductivity for this soil increased 1.2, 5.0, and 4.5 times for the soil, gravel, and straw, respectively, with an increase in wind speed from 5 to 25 miles/hour. This is evidence, as was predicted from mathematical considerations presented herein, that the higher permeability of the straw and gravel permitted a greater influence of wind on vapor conductivity. The fact that the vapor conductivity was greater than 1 where the wind speed was over 12 miles/hour for the straw and gravel is indicative of diffusion being surplanted by some other process. This might explain, in part, why straw mulch has not been so effective with regard to moisture conservation in the windy Great Plains as would be

TABLE 2

Influence of treatment, depth of treatment, and wind speed on water vapor transfer

Wind Speed	Computed Vapor Conductivity at Various Treatment Depths*			
	¼ in.	½ in.	1 in.	1½ in.
m.p.h.				
	Dry soil			
5	0.30	0.37	0.54	0.70
12.7	0.33	0.38	0.60	0.80
25.4	0.35	0.39	0.62	0.87
	Gravel			
5.8	0.56	0.78	0.68	1.55
12.0	1.67	2.05	1.08	1.92
24.9	2.82	4.72	3.14	6.48
	Straw			
5.2	0.76	0.60	0.60	0.91
12.0	2.25	1.52	1.54	2.38
25.0	3.40	2.89	2.72	3.96

* Diffusive conductivity is defined as the ratio of diffusion rate through a porous media to the diffusion rate through still air. In the notation of Hanks (2) it is equal to $\phi\alpha$ of equation (*1*).

predicted from the laboratory experiments where wind speeds are low.

The dry soil mulch data of table 2 also indicate an increase in the value of vapor conductivity with an increase in depth of mulch. This result would tend to substantiate the prediction made in the theoretical discussion to that effect. The data for gravel and straw however are not as conclusive in this regard with several unexplainable inconsistencies.

SUMMARY

Data presented indicate that wind has a definite influence on water vapor transfer in soil, gravel, and straw mulches, and that this influence was much greater for gravel and straw mulches than for soil. Evaporation rates were increased 2 to 6 times where soil mulches were used, and 10 to 15 times where gravel or straw was used, when the wind speed was increased from 0 to 25 miles/hour.

Increased depths of mulches, in general, decreased evaporation rates. Most of this reduction was brought about, however, by increasing the depth of mulch from 0 to 0.25 inch.

Soil was a more effective mulch in reducing evaporation than was gravel or straw. Evaporation rates for gravel and straw were 1.3 times greater than for soil at zero wind speed and were 6.3 times greater for 25 miles/hour wind speeds.

The data show that the vapor conductivity of water vapor is increased with increased wind speed, and that diffusive conductivity is increased for a dry soil mulch as the depth to an impermeable layer is increased; the data also suggest, but are not conclusive, that this occurs in gravel and straw.

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