DIVISION S-6—SOIL AND WATER MANAGEMENT AND CONSERVATION

Soil Mulch Effects on Seedbed Temperature and Water During Fallow in Eastern Washington[1]

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ABSTRACT

Depth of dry soil mulch affected summer soil temperatures and seed-bed water at the end of fallow in the dryland wheat region of eastern Washington. Increasing the depth of the tillage mulch from 6 to 11 cm reduced summertime seed zone drying sufficiently to benefit wheat emergence. Reduction of drying was greatest when the seed zone had good capillary continuity with the deeper soil layers. Drying depth and intensity was greater with a cloddy soil mulch than with a fine mulch.

The seed zone water-conserving effect of a fine soil mulch was related to the lowered temperatures and temperature gradients across the seed zone associated with the increased mulch depth. The deeper soil mulch conserved seedbed water through increased resistance to water flow from moist layers to the atmosphere, and through increased thermal insulation of the moist soil below the dry mulch. Surface-applied straw (4,000 kg/ha) decreased seed-zone temperatures under the shallow mulch only.

The key factor in conserving seedbed water through extended periods of hot, dry weather is that the loss rates from the seed zone be balanced by upward unsaturated flow from deeper layers. As the soil dries, the relative importance of loss rates through evaporative loss across the dry layer and thermally induced flow downward increases because of decreasing return flow from the deeper layers along matric potential gradients. Under these dryland conditions, it appears that seedbed water could be best conserved through using a soil mulch of maximum resistance to vapor and liquid water flow, and maximum thermal insulation, overlying a seed zone having good

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capillary continuity with the deeper soil layers. The stratification produced by moderately deep rod-weeding appears to provide such a mulch.

Additional Index Words: winter wheat, tillage, temperature gradient, thermal insulation, unsaturated flow, evaporation.

EARLY ESTABLISHMENT of winter wheat (*Triticum aestivum* L.) on fallow in much of the Northwest USA wheat region has a major influence on wind and water erosion. Stands established in late summer or early fall protect soil against wintertime erosion, and also increase the crop production potential as compared with stands from late fall emergence (6). Moreover, the increased residue from moderately early stands provides added protection against soil erosion by both wind and water during subsequent fallow.

Inadequate seedbed water at planting is a major limitation to early establishment of wheat in this region. Because of the rainfall pattern, successful stands usually depend on reaching carryover water from the previous winter. Field observations indicate that the seed zone water content at the end of fallow is strongly influenced by method of fallow tillage. In particular, many farmers in this wheat region are convinced that a moderately deep, dry soil mulch formed by secondary fallow tillage conserves seedbed water.

The use of the water-conserving properties of soil mulches has been a subject of numerous investigations. Benefits where noted are generally attributed to reducing evaporation through disrupting capillary flow, thereby hastening the formation of a surface dry layer, which reduces both liquid and vapor flow to the atmosphere (1, 7, 12, 15, 16, 22). McCall (15) concluded that for dryland eastern Washington, a soil mulch was detrimental to absorption of overwinter precipitation but reduced evaporation of stored water during the summer as compared with unmulched soil. He also noted a slight increase in water retention oversummer in the upper 90 cm of soil when the mulch depth was increased from 10 cm to 15 cm. In the Great Plains and certain other regions, the dust mulch has generally been discredited as a water conservation practice in dryland agriculture, except possibly under certain conditions (3, 5, 7, 13, 19). In most studies, attention was given mainly to effects on total water storage rather than to effects on depth distribution of water.

Climatic differences are undoubtedly an important aspect in water conservation with soil mulches. In the Great Plains, much of the precipitation occurs during the period of high potential evaporation. Conversely, the Northwest has high winter precipitation and low summer rainfall. Thus, in the Great Plains it is necessary to consider evaporation and infiltration as concurrent processes when evaluating the effect of tillage on water storage and distribution in the profile. In the Northwest, infiltration is of little concern during the period of high potential evaporation.

The following study was developed because many of the prevailing concepts about soil mulches for water conservation were inconsistent with the prevalent and persistent use of fine mulches during fallow in the Northwest dryland regions. The primary concern here was effects on seedbed water for early fall establishment of winter wheat. This paper reports soil temperatures and seed zone water contents at seeding time as influenced by tillage, effects on wheat emergence, and evaluates factors controlling water loss and water distribution in this layer during the summer.

MATERIALS AND METHODS

Field studies were conducted in the wheat-fallow area of eastern Washington. The climate and soils at the Washington State University Dryland Research Unit near Lind are representative of a large portion of the dryland area. Mean annual precipitation at the station is 24 cm, with about 6 cm of this occurring between initiation of spring tillage (April 1) and wheat planting (early to mid-September). Maximum air temperatures during July and August range between 30 to 38C with lows of 10 to 13C. Experimental sites were on either Ritzville silt loam or Ritzville fine sandy loam soils which are typical of the loessial types found extensively in the transitional arid-semiarid climatic zone in south-central Washington and north-central Oregon (9). Generally, the soils are over 150 cm deep to underlying basalt bedrock.

1967 Experiment—Four tillage treatments were established on Ritzville silt loam near Lind in early April. Wheat stubble was tilled initially about 15 cm deep with a sweep cultivator after the soil surface dried. One week later, the following rod-weedings were imposed on the sweep tillage: "shallow" (6 cm), or "deep" (11 cm) which, in this area, generally covers the range used in conventional practice. Hereafter, these treatments will be referred to as "bare surface," even though some residue remained on the surface during the remainder of the experiment. Two additional treatments were provided by duplicating the tillages and placing 4,000 kg of straw/ha on the surface in mid-June. Three replications of a randomized complete block design were used. Three additional rod-weedings at the selected depths were made with the last on July 20 to further establish the soil mulch, and to control weeds.

In late July, thermocouples were installed in all plots at depths of 2.5, 13, 18, and 30 cm and at the depth of rod-weeding, using the soil surface as reference. Three thermocouples wired in parallel were used at the two upper depths; two in parallel were used at the remaining lower depths. Maximum and minimum temperatures were recorded daily with an electronic recorder until September 20, except for the week August 16–22, when the equipment malfunctioned. Hourly measurements were made on July 31–August 2, August 28, and September 3.

Soil water distribution in the surface 30 cm was measured in core samples taken in all plots in mid-September. In addition, undisturbed rectangular cores 15 by 20 by 33 cm deep were obtained from one replication of each treatment for water content and bulk density measurements by gamma ray attenuation (8). After soil sampling, the site was furrow-drill seeded to winter wheat (variety 'Wanser') at the 13- to 15-cm soil depth. Percentage of emergence (based on seeding rate) was determined in late September, and again in mid-January, 1968.

1968 Experiment—Four tillage treatments were established on Ritzville fine sandy loam near Connell, where precipitation amount and monthly distribution are similar, and mean summer temperatures are 2 to 4C higher than at Lind. The treatments were a factorial combination of: "shallow" (5 to 8 cm), or "deep" (13 to 15 cm) rod-weeding superimposed on "shallow" (13 to 15 cm), or "deep" (18 to 22 cm) sweep tillage. A randomized complete block design with three replications was used. Initial tillage in late March was followed by four rod-weedings—the first, 3 days after initial tillage; the last, in late July. Soil temperature was not measured. Soil cores were obtained from each plot in early September (just prior to seeding) for water content and bulk density measurements by gamma ray attenuation; after which 'Wanser' wheat was seeded with a furrow drill. Samples of soil close to the wheat seeds were taken 2 days after seeding, and the percentage of emergence was estimated 3 weeks later.

1969 Experiment—Two tillage treatments were established at Lind to compare seed zone water conservation with a coarsely

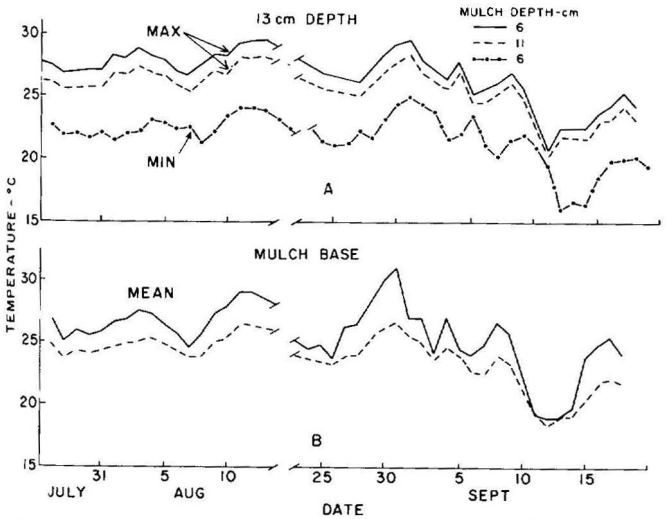

Fig. 1—Daily maximum (max) and minimum (min) soil temperatures at the 13-cm depth (*A*), and daily mean temperature at the mulch base (*B*) for two depths of soil mulch under a bare surface at Lind, 1967. Values are means of three replications. Minimum temperatures for the two mulch depths were similar.

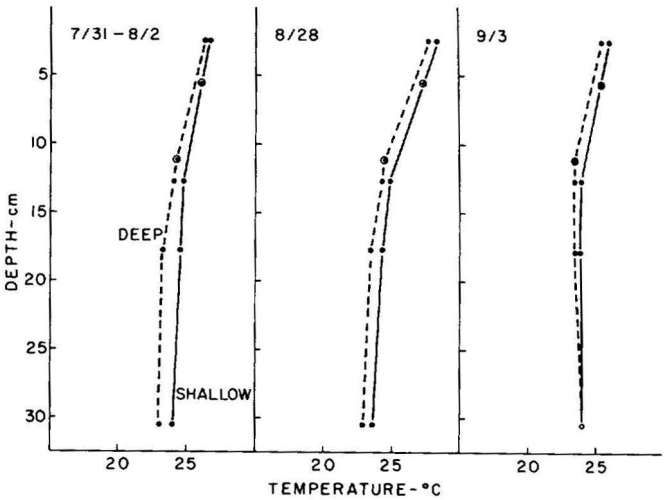

Fig. 2—Mean daily soil temperatures in the surface 30-cm layer on different dates for two soil mulch depths at Lind, 1967. The bullseye indicates the mulch base. Values are means of three replications.

aggregated vs. a fine mulch. Wheat stubble was initially tilled with a sweep cultivator in early April when the soil was relatively wet, resulting in a layer 15 to 17 cm deep having a large proportion of clods with effective diameters ranging from 5 to 10 cm. Subsequent tillage was none or rod-weeding (12- to 14-cm depth). The rod-weeded plots were first skew-treaded to reduce clod size, after which several rod-weedings produced a fine soil mulch by early summer. The experimental design and procedure for temperature measurements were similar to those for the 1967 experiment except that temperatures were measured hourly over three selected intervals of several days during August, in two replications at the 2-, 15-, and 20-cm depths, and at the base of the tillage mulch. Soil cores were obtained from each plot in mid-September for water and bulk density determinations by gamma ray attenuation. Wheat emergence was not studied in this experiment.

Precipitation at Lind during the 1966–67 winter season was slightly above normal. A 1.6-cm rain in mid-June was the last measurable precipitation before seeding on September 20. The 1967–68 winter precipitation in the Connell area was about 40% below normal resulting in low soil profile water content throughout the fallow season. There was less than 3 cm rain between initial spring tillage and early September, all as small showers. The 1968–69 winter and 1969 summer precipitation at Lind were near normal. Mean air temperatures during July and August 1969 were about 4C lower than in 1967.

RESULTS

Soil Temperature

During much of the 1967 summer, daily maximum temperatures at the 13-cm depth of the bare surface treatment were 1 to 2C lower under the deep than under the shallow soil mulch (Fig. 1*A*). With the shallow soil mulch, maximum temperatures at the 13-cm depth during late July and August were about 1C lower where surface residues were applied as compared with the bare surface (not shown). At the same depth under the deep soil mulch there was no temperature difference between the straw-covered and bare surface treatments (not shown). Maximum temperatures at the 13-cm depth under the bare surface deep mulch were generally lower than those at this depth under the straw-covered shallow mulch. Treatment differences were most pronounced during hot weather. Neither residue application nor difference in mulch depth materially affected the daily minimum temperatures.

Daily mean temperatures at the base of the soil mulch for both bare surface mulch depths are presented in Fig. 1*B*. Temperatures below the shallow mulch were higher (as much as 4C) than those below the deep mulch during most of the measurement period. Again, temperature differences were most pronounced during hot weather. Figure 2 shows the integrated mean temperature at different depths for the two bare surface mulch treatments on selected days in 1967. On these days, mean temperatures at the mulch base where there was liquid water continuity with the deeper soil layers were 2 to 3C higher under the shallow mulch than under the deep mulch. Temperatures at other depths were generally higher under the shallow mulch. In all cases, the temperature gradient indicates net downward heat flow which undoubtedly occurs much of the summer, including some days in September.

Mean soil temperatures at comparable depths for the cloddy and fine mulch treatments in 1969 were similar (not shown). Temperature at the 15-cm depth averaged over the three time intervals was less than the means at this depth given in Fig. 2 for representative days in 1967. The temperature gradient from warm to cool was directed downward for all three intervals but was less steep than in 1967, a reflection of the cooler summer in 1969.

Seedbed Water Content and Bulk Density

Figure 3 illustrates the seed zone water content (determined gravimetrically) for the shallow and deep soil mulches at Lind in mid-September 1967, just before seeding. Averages of the straw-covered and bare surfaces were used because differences between these treatments were not discernible. Soil water potentials (determined by thermocouple psychrometry) corresponding to some of the water contents are shown. The soil water is more evenly distrib-

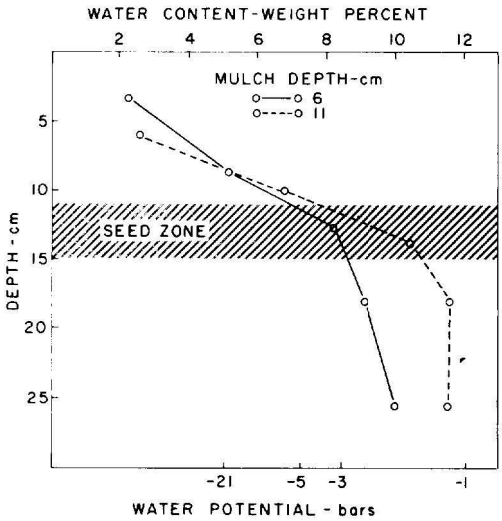

Fig. 3—Water content (determined gravimetrically) and water potential profiles for two soil mulch depths at Lind in mid-September 1967. Values are averages of the bare surface and straw cover treatments. Sample standard deviation, 1.0; coefficient of variation, 12.0%.

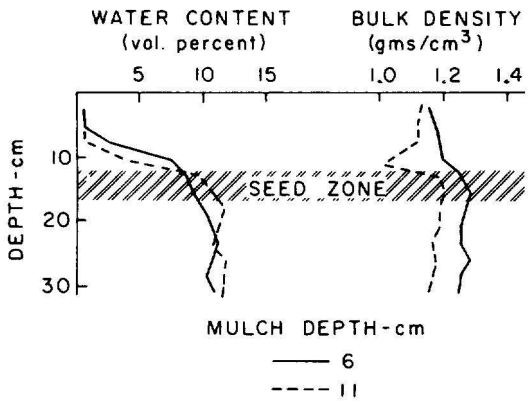

Fig. 4—Water content and bulk density (determined by gamma attenuation) profiles for two soil mulch depths at Lind in mid-September 1967. Values are means of two cores from each treatment, bare surface only.

uted under the shallow mulch, but is generally at a higher content in the seed zone under the deep mulch (Fig. 3). The water potential at the 15-cm depth under the shallow dust mulch was nearly —3 bars compared with —1.4 bars under the deep mulch. Moreover, any subsequent slight decrease in water content caused by evaporation or plant extraction would lower the water potential of the drier soil (shallow mulch treatment) considerably more than that of the wetter soil.

Figures 4 and 5 show the water contents and bulk densities in the upper 30-cm layer for the two mulch depths at Lind in 1967, and the coarse and fine mulches at Lind in 1969, respectively (determined by gamma attenuation). Figure 6 illustrates similar data for the four tillages at Connell, 1968. Figure 4 shows that the seed-zone water content was higher with deep than with the shallow mulch which substantiates further the gravimetric results of Fig. 3. The seed zone is considerably drier with the coarse mulch as com-

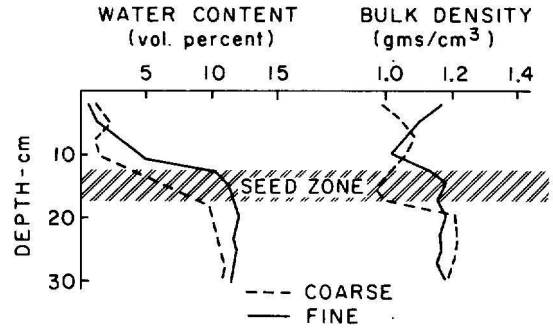

Fig. 5—Water content and bulk density profiles for two types of tillage mulch at Lind, 1969. With the fine mulch, compact soil was nearer the surface as a result of rod weeding as compared with the nonrod-weeded or undisturbed coarse mulch. Values are means of two replications.

pared with the fine mulch (Fig. 5). Note specifically the tillage effect on bulk density in Fig. 4, a trend shown by repeated measurements to be a distinct effect of rod-weeding depth. With deep rod-weeding a very loose soil layer occurs just above a more dense rod pan, and the dry soil above the loose layer grades into a more dense layer extending to the soil surface. This characteristic layering is less conspicuous or absent with shallow rod-weeding but does occur with both mulch treatments of Fig. 5.

The data in Fig. 6 obtained under relatively dry conditions indicate that seedbed water was improved most by shallow initial tillage in combination with rod-weeding to the sweep tillage depth. With this coarse-textured soil and low soil water content no distinct secondary rod pan with either rod-weeding depth is apparent in contrast to the Lind sites where the soils were wetter (Fig. 4 and 5).

Although not studied in detail, there was no apparent effect of mulch treatments on the total profile water content at the end of fallow in these experiments.

Wheat Emergence

Wheat emergence rates were markedly influenced by tillage-induced differences in seed zone water. At Lind, 1967, emergence 8 days after planting was 18 and 57% for the shallow and deep mulch treatments, respectively (refer to Fig. 3 for seed zone water status). By late fall, emergence was relatively uniform on all plots but the plants that emerged late were smaller in size and had fewer tillers than the plants that emerged early.

Table 1 shows percent emergence and related information on soil water associated with the different tillages at Connell. In this relatively dry soil, a small increase in water content produced a marked increase in wheat emergence rate. Water potentials of soil adjacent to the seeds were highest where initial tillage and subsequent rod-weeding were deepest. This result concerning initial sweep tillage depth appears contradictory to the water content data of Fig. 6, which showed that the water content in the hypothetical seed zone was higher with shallow initial tillage. The discrepancy results because the actual seeding depth in the deep sweep-tilled plots was at least 5 cm deeper than in the shallow-tilled plots. The loose soil in the deep-tilled plots allowed the furrow drill to penetrate deeper, and thus

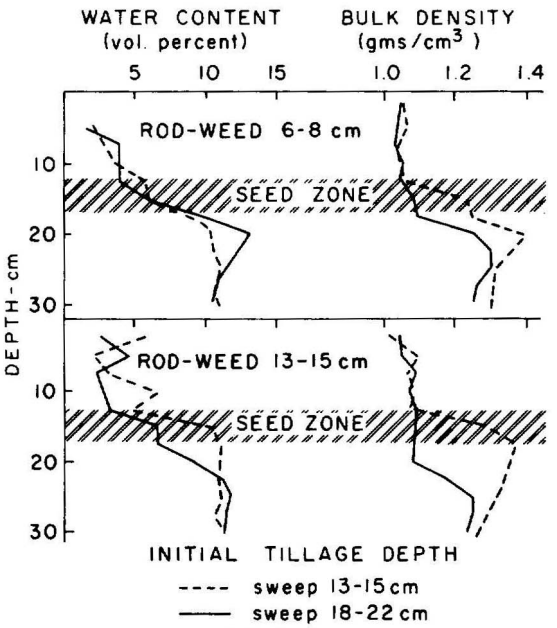

Fig. 6—Water content and bulk density profiles for different tillage combinations at the end of fallow near Connell. Values are means of two replications.

place the seed in wetter soil. This experience points out still an additional practical factor, namely, seeding depth control caused by the early operations of fallow tillage.

DISCUSSION

Temperature Effects

The lowering of seed-zone temperature with increasing depth of soil mulch relates to thermal insulation afforded by the loose, dry tillage layer. Several workers have shown that loosening and drying of the surface layers reduces heat flow downward because the soil thermal conductivity is decreased (20, 23). The theory illustrated by van Wijk (21, Chapter 6) for heat conduction in a layered soil was applied to provide more detail on the effect of soil mulch depth on temperatures at the soil surface and below the tillage depth. The soil is assumed to consist of two distinct layers, a tilled layer overlying untilled soil, each with constant thermal properties. The theory assumes that turbulent heat transfer in air can be described by the differential equation for heat conduction. Although this introduces an element of uncertainty in the partitioning of heat between air and soil, the calculations should serve as a first approximation to illustrate temperature effects. Soil porosity and water content measurements were used to determine the thermal conductivity and heat capacity of the tilled and of the underlying untilled soil, by the dielectric analogue method of de Vries as described by van Wijk (21). Calculated thermal conductivities, and heat capacities of the tilled and underlying untilled soils, were 0.9×10^{-3} and 2.7×10^{-3} cal cm^{-2} sec^{-1}°C^{-1}, and 0.22 and 0.35 cal cm^{-3}, respectively.

With these constants, the procedure was first to compute the diurnal temperature change at the soil surface as a function of mulch depth, based on the amplitudes and phase changes of heat fluxes in air and soil. In this computation, it was assumed there was equal net radiation over all surfaces and no evaporation. These results are graphed in Fig. 7*A*. From this graph, the temperature change at the mulch base and then at the 13-cm depth were computed as a function of soil mulch depth and are compared with the mean fluctuations for the period July 31 to August 2, 1967 (Fig. 7*B*). These were sunny days with low wind and low humidity. Using van Wijk's symbols and terminology, the heat capacity of air, C_{ai}, was taken as 2.9×10^{-4} cal cm^{-3}; z_0, the surface roughness parameter as 0.1 cm (a fairly smooth surface with irregularities less than 1 cm high); b, an empirical constant depending on the surface roughness and wind velocity as 2×10^{-3} cal cm^{-2} sec^{-1}°C^{-1} (light wind, 1–2 mph); and the amplitude of net radiation as 6×10^{-3} cal cm^{-2} sec^{-1}.

The agreement with experiment is reasonable and could possibly be improved by using different thermal, wind, and soil parameters. The theory tends to underestimate the amplitudes near the soil surface (by nearly 4C at the soil surface based on measurements with an infrared thermometer) and to overestimate amplitudes at the lower depths. Never-

Table 1—Water content and corresponding water potential of soil adjacent to the wheat seeds two days after planting, and percent emergence 19 days after planting as affected by two depths of initial sweep cultivation and two rod-weeding depths

Tillage				
Sweep-cultivation depth	Rod-weeding depth	Water content*	Water potential	Emergence
cm		weight %	bars	%
12-15	6-8	6.5	-8.8	10
	13-15	7.5	-4.5	25
18-22	6-8	7.5	-4.5	20
	13-15	8.7	-2.0	40

* Water content values are averages of three replications. Sample standard deviation, 0.5; coefficient of variation, 6.6%. Water potential was inferred from a soil-moisture characteristic curve determined by thermocouple psychrometry.

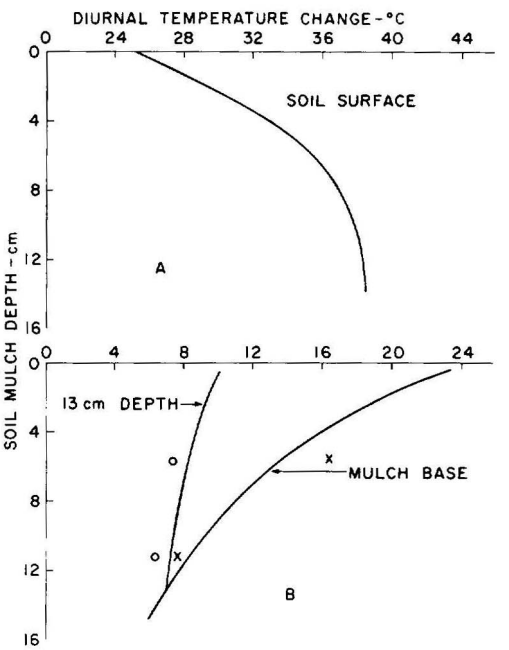

Fig. 7—Calculated diurinal temperature change (max - min) at the soil surface (*A*); and at the soil mulch base, and 13-cm depth (*B*) as a function of soil mulch depth. Mean experimental values for the period July 31–August 2, 1964 at the mulch base (X) and at the 13-cm depth (O) are compared with the calculated curves in (*B*).

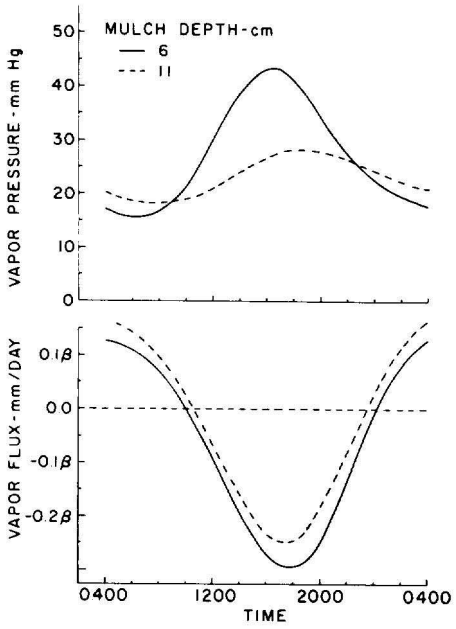

Fig. 8—Saturated water vapor pressure at the soil mulch base (*A*), and thermally induced vapor flux across the 13-cm depth (*B*) for two soil mulch depths on August 1, 1967. Saturated vapor pressure are handbook values using the recorded temperatures. Vapor flux was estimated using Cary's (4) method. Negative values indicate downward flux. According to Cary, β is a dimensionless factor accounting for pore geometry, cross sectional area of voids, and microscopic temperature discontinuities.

theless, the effect of soil mulch depth on temperature is obvious. During hot weather, the incoming heat progressively concentrates in the surface layers to some maximum as the mulch depth is increased, and the deeper layers remain cooler than in uniformly compacted soil. Energy exchange between the soil and atmosphere must increase with increase in mulch depth because with higher surface temperatures the convective transfer is greater. This real effect of the mulch may at least partially explain the noted discrepancy between theory and experiment. Figure 7 shows that the tillage mulch affects the temperature amplitude most with the moderate to shallow mulch depths, and that the effect is considerably reduced after the mulch depth exceeds 11 cm.

Water Loss Effects

The water-conserving effect of mulching, particularly of a fine soil mulch, presumably relates in part to the lowered temperature and temperature gradients across the seed zone associated with the increased mulch depth. Evaporative loss across a dry soil layer occurs primarily as vapor flow and is inversely related to the thickness of the layer. The dry layer reduces water loss by lowering the rate of energy exchange between the atmosphere and the underlying moist soil, and by increasing the resistance to liquid water flow to the soil surface. The resistance effect of a porous material to vapor transfer usually attenuates rapidly after the diffusion path length exceeds several centimeters (14). Thermally induced water flow (17) can also contribute to seed zone drying.

Both vapor flow across the dry soil layer and thermally induced water flow rates are strongly temperature dependent. Increasing the temperature at the evaporation sites increases the water vapor-pressure gradient from the moist soil to the atmosphere, and hence the evaporation rate. Small temperature changes comparable to those induced by soil mulch differences (Fig. 1) can produce a marked effect on the water vapor pressure. For example, at 28C, a 2C decrease in temperature decreases the saturation vapor pressure of water by 11%. During hot weather, thermally induced downward flow may also be appreciable, particularly near the surface where under the field environment, temperature gradients are steepest (4, 18). Such flow can occur as liquid or vapor; however, in the lower range of soil water contents vapor flow predominates (11, 18). Thus, at times water can flow both upward (evaporative loss to the atmosphere) and downward (thermally induced flow) simultaneously from the zone of vapor pressure maximum that occurs in moist soil below the dry soil mulch. Both processes, particularly when these occur over extended periods, can contribute to desiccating this layer even though the water moved downward is subject to eventual upward movement along a matric potential gradient.

The curves in Fig. 8 were obtained from calculations using hourly temperatures for August 1, 1967, and are used to evaluate the relative effect of mulch depth on vapor loss at a practical seed zone depth. The vapor pressures are at the mulch bases and are approximated by using values for saturated air. The thermally-induced vapor flux across the 13-cm depth is estimated from Cary's (4) equation [4]. On this date, the upper fringe of moist soil was at the base of the shallow mulch, but extended nearly 1 cm into the deep mulch. From the area under the vapor pressure curves, evaporative loss across the deep mulch should average, for the day, 15% less than from the shallow mulch, owing to a temperature effect alone. Taking into account both the vapor pressure and depth of the dry layer and following the calculation procedure of Hanks (10), evaporative loss across the deep mulch averaged, for the day, 60% less than from the shallow mulch. Using a dry layer porosity of 60% and taking the vapor pressure of the air above the soil surface as 6 mbars, the mean evaporation rates across the shallow and deep mulches are 0.36 and 0.15 mm per day, respectively.

An analysis of the thermally-induced vapor flux curves of Fig. 8 reveals that the net daily flux across the 13-cm depth is downward, and that the flux under the deep mulch is about half that under the shallow mulch. Absolute values depend on Cary's (4) β, which must be determined experimentally for a given soil. According to Cary, β would probably not exceed 2 for the relatively dry soils here indicating that the net daily downward vapor flux at the 13-cm depth would approach 0.1 mm under the shallow mulch and about half this under the deep mulch. The magnitude of flow and mulch depth effect would be even greater if the very upper fringe of moist soil were considered.

Under the field conditions here, seed zone water must be conserved by maintaining the loss rate from this zone in balance with or less than the replenishment rate by unsaturated flow from moist soil below. Thus, a higher unsaturated

conductivity (as with higher water contents and more dense soil) would sustain a higher loss rate without incurring a decrease in the seed zone water content. As the soil dries, the unsaturated conductivity decreases markedly and the loss rate becomes more critical for seed zone water retention. A dry front will penetrate downward until the dry layer is sufficiently thick to reduce the loss rate such that it is balanced by upward unsaturated flow. This places a depth limit, depending on soil and climatic conditions, beyond which increased mulch depth would no longer be effective in conserving water. Thus, we observed that the lower part of the 11-cm mulch remained moist throughout the summer indicating that deeper tillage would have been of little value in improving seedbed water. With the coarse mulch (Fig. 5) drying was deeper than with the fine mulch presumably because of increased turbulent air exchange as the number of large continuous pore spaces is increased. With cooler weather and finer pore structure, the mulch depth could be decreased, which may help explain yearly and location variations in the effectiveness of a soil mulch in conserving seedbed water.

Others have shown that small differences on soil temperature during fallow significantly affect water storage and distribution in the profile. Black and Greb (2) reported a high negative correlation between average soil temperature at the 7.6-cm depth and soil water storage during fallow in eastern Colorado. A 1C decrease in average temperature during a dry summer resulted in a gain of approximately 5 cm of water and decreased the depth to seedbed water. Hillel (12) showed that chalk dusting a field plot markedly reduced daily maxima of soil temperature at 4 cm and that over a 2-week period the chalk-dusted plot evaporated only 46% as much water as the control.

In evaluating the potential effectiveness of tillage for conserving seedbed water where infiltration is of no concern, the resistance to water flow and the thermal properties of the tillage layer must be considered simultaneously. Resistance to water flow is largely a function of the soil porosity and pore size distribution which also affect the soil thermal properties. Decreasing the soil porosity to increase the diffusion resistance may increase the soil thermal conductivity, which could negate any benefit of the former. Increasing the soil porosity would lower the soil thermal conductivity, but at some point heat flow and vapor exchange would be enhanced through increased turbulent air flow. Ideally, the tillage should increase both thermal insulation and resistance to water transport to the atmosphere. The stratification produced by "deep" rod-weeding may do both (Fig. 4). The high porosity layer immediately above the compact soil at the rod-weeding depth would thermally insulate the underlying soil and greatly limit upward transmission of liquid water. The denser and poorly aggregated dry soil just above this loose layer increases resistance to diffusive flow in the vapor phase. The compact rod pan below increases the unsaturated conductivity for replacing lost water.

From Fig. 6 it appears that the deep initial spring tillage resulted in lower seedbed water content at the end of fallow than where the tillage was comparatively shallow. Some of the foregoing principles discussed may offer an explanation for this result. The 1967–68 fallow season was abnormally dry, and the loosened soil below the rod-weeding depth did not compact to the extent it would under wetter conditions. Good capillary continuity with the deeper layers is essential for replenishing water lost by whatever process. Decreasing the soil bulk density below the seed zone by deep cultivation would decrease the unsaturated conductivity particularly in the drier soil causing the dry front to penetrate deeper than with shallow initial tillage where the density was higher. In other words, some sacrifice of water from the deeper layers may be required to maintain adequate water in the shallow layers for germination and emergence of winter wheat under these dryland conditions.

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