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Time of stand establishment is a critical factor affecting yields of winter wheat and barley in the fallow-crop rotation areas of the Pacific Northwest. Farmers in this winter-rainfall region are dependent on residual moisture in the seed zone for germination, because significant precipitation does not usually occur until after the optimum planting dates. Moisture is maintained near the soil surface through the summer of the fallow period by the use of a soil or stubble mulch. The rate of moisture loss is relatively low during the summer, but seems to accelerate in late August and September. This loss dries the seed zone and forces either deeper planting to reach adequate moisture or delayed seeding until precipitation rewets the seed zone. Both practices can result in late, less vigorous stands which have lower yield potential and provide less protection from erosion.

The objectives of this study were to: 1) quantify changes in seed zone water content prior to seeding; 2) determine the cause of the accelerated loss; 3) substantiate the effect of planting date on the yield of one variety of winter wheat and one variety of winter barley; 4) investigate the effect of soil temperature on the rate of first and 70% emergence of these species in the field; and 5) develop a means of predicting the average last date of planting after which stand establishment is excessively delayed at one location in eastern Oregon.

Although both years were abnormally wet in late summer and fall, significant losses of seed zone water content occurred in 1976. At 6 cm, the loss period occurred in early September; at 9, 12, 15, and 18 cm, the losses occurred in late September. The measured losses were not as great as expected. No significant losses were observed in 1977 because of frequent precipitation. My hypothesis was that increasing nighttime vapor pressure gradients from the moist seed zone to the soil surface develop because of the combination of warm days and cool, clear nights characteristic of late August and September in this area. Larger vapor pressure gradients would cause increased water losses from the profile. However, no correlation was found with calculated vapor pressure gradients, the occurrence of low surface temperatures at night, or average temperature gradients in the upper soil profile. Computer simulation of isothermal liquid flow was used to discern

the relative contributions of evaporative losses and of long-term redistribution of water in response to gravitational and potential gradients in the profile. Redistribution accounted for 60% of the water loss in the soil beneath the seed zone from mid-July to early August, and accounted for none of the loss from early August to early September.

Planting date had a significant effect on yield of both wheat and barley; the optimum planting dates were late September to early October. On each planting date, the seeds were placed in moist soil and covered with approximately 5 cm of soil with a deep furrow drill, so temperature was the primary factor affecting rate of first and 70% emergence. Regression equations of rate of emergence on average 10-cm soil temperature from planting to emergence were highly significant. The degree days needed for first and 70% emergence for wheat were 149 and 210 using a base temperature of 0.7 and 0.4 C, respectively, and for barley were 92 and 159 using base temperatures of 6.1 and 3.5 C, respectively. Soil temperatures from 1963 to 1977 were used to develop a means of predicting average daily 10-cm soil temperature. Using this long-term average and the regression equations of rate of emergence and stand establishment versus temperature, the average last date to plant and still obtain 70% stand in 14 days was 25 September. If seeding is delayed until 15 October, lower soil temperatures will cause the average days to 70% stand of wheat to approach 22-24 days, while barley will require 24-29 days to reach 70% stand at these temperatures.

Soil Moisture and Temperature Relationships under Fallow in Eastern Oregon

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SOIL MOISTURE AND TEMPERATURE RELATIONSHIPS UNDER FALLOW IN EASTERN OREGON

INTRODUCTION

The Pacific Northwest is a region of diverse climatic conditions. A predominantly winter rainfall pattern is found throughout the area, and average annual precipitation amounts range from 20 to 320 cm in Oregon alone. In the lower precipitation areas of eastern Oregon, eastern Washington, and Idaho, fallow-crop rotations are used by farmers to stabilize and sometimes increase cereal yields. The rotation generally consists of a 14-month fallow period, which begins after harvest in July or August, and a 10-month crop period, which begins at planting in September or October. From a given field, only one crop is harvested every two years. Although this rotation has been criticized as wasteful and unproductive compared with annual cropping, there are several reasons such a rotation has been adopted.

First, the establishment of an adequate stand early in the fall is important in maximizing potential yielding ability of winter wheat (Triticum aestivum L.) and barley (Hordeum vulgare L.). Significant rainfall does not generally begin in this area until October, and since little available moisture is left in the soil after harvest, seed germination and stand establishment in annual cropping depend on this precipitation to rewet the seed zone. Late or infrequent rains cause poor, spotty stands, consequently reducing the potential yield and increasing the erosion hazard. In the fallow-crop rotation, residual moisture stored from the previous winter is held near the soil surface so that seeding can take place at an earlier, more optimum date.

Precipitation is highly variable, especially in the drier areas. In those regions with sufficiently high average annual precipitation for cropping every year, rainfall often greatly exceeds and often falls far short of the mean. Annual cropping yields are therefore quite variable. Under a fallow-crop rotation, a portion of the rainfall from the previous 14 months is stored in the soil profile, and this moisture reserve tends to stabilize the yields. As a consequence, even though the average annual yield from the fallow cropping areas is not twice that of annual cropping, the farmers can rely on a much more stable source of income, and have to face fewer crop failures.

Third, fallowing allows a longer period for the breakdown of organic matter and the release of nutrients for plant use. The seasonal precipitation pattern plays a large part in the actual amounts of nitrogen, for example, released each year (Aktan, 1976).

Fourth, fallowing provides an extended span of time in which a farmer can control weed and volunteer infestations. Ideally, no plants should be allowed to grow in a fallow field, since they would utilize moisture which is needed for maximum production of the crop. At present, weed control is accomplished with the use of a rodweeder or other implements which can be pulled rapidly over the large acreages. Chemical methods of weed control are as yet too expensive to be incorporated into the management of the fallow.

There is one primary disadvantage of fallowing in the Pacific Northwest: the increased problem of erosion. Both wind and water erosion are serious problems in this area (Papendick and Miller, 1977). The soils typically have low infiltration rates and are subject to crusting. If the fields are moldboard plowed in the fall after harvest, the unprotected, weak soil structure offers little resistance to the forces of wind and water erosion. The long and often steep slopes heighten the potential for water erosion. Frequent cultivation in spring and winter to control weed growth causes a fine dust mulch to be formed on the soil surface, so wind erosion can be severe. Water erosion in the winter of the crop period is generally greater than in the fallow. The soil profile has a higher water content during the second winter, so infiltration is reduced. Surface residues are at a minimum and crop growth has not yet covered the soil surface. The near surface of the soils in this region are frequently frozen during part of the winter, and the infiltration rate is greatly reduced.

Stubble mulching is one method of circumventing some of the problems with erosion. The crop residues are partially incorporated into the soil mulch with the use of disk or sweep implements, rather than being totally buried as with the moldboard plow. These residues increase surface roughness and reduce the erodibility of the land. No-tillage has been and is being investigated as a means of crop production in this region. Total moisture storage is generally comparable to that of the standard stubble and bare fallow methods, but less moisture is held near the surface. Consequently, seed zone water contents are often too low for rapid germination and emergence after planting. Other problems have also arisen with the practice of no tillage, including the lack of effective economic weed control methods and difficulties obtaining vigorous, uniform stands.

The maintenance of adequate seed zone moisture for stand establishment at the optimum time is one of the primary concerns in the drier fallow-crop rotation areas. Farmers report that, although the level of adequate moisture remains more or less constant throughout the summer at the base of the mulch, there appears to be a loss both in the amount and the level of moisture in late August and September. This loss may increase the depth to adequate moisture beyond the reach of deep furrow drills. The farmers then have to wait until fall rains rewet the desired seed zone before planting. These rains often do not occur until after the optimum planting dates. Delayed seeding results in poor stands, decreased protection from erosion, and reduced potential yield.

One of the objectives of this study was to measure water content changes in the upper soil profile during late summer and fall to attempt to quantify the observed moisture losses. Both the extent and timing of the losses were considered important. Initial exploration into the mechanisms causing these losses was made. The hypothesis was that increasing nighttime vapor pressure gradients from the moist soil of the seed zone to the soil surface may cause the accelerated drying of the seed zone.

Another purpose of this research was to investigate the effect of planting date on the rate of stand establishment and on yield of winter wheat and barley. It had been noted in another study in the same area that soil temperature at the seeding depth decreased rapidly in October (Pehlivantürk, 1976). The objectives of this part of the experiment were to: 1) relate the effect of seed zone temperature to rate of stand establishment; 2) present long-term soil temperature averages to show the trend of temperature in late summer and fall; and 3) attempt to discern the period of time beyond which planting should not extend because of delayed stand establishment.

The thesis is presented in four sections: a literature review of topics involved, a manuscript concerning the seed zone moisture loss, a manuscript concerning seed zone temperatures and stand establishment, and an appendix of information and data not reported in the manuscripts.

LITERATURE REVIEW

Theory of Soil Moisture and Temperature Flux

Soil moisture and temperature are interrelated properties. Soil moisture movement in both liquid and vapor phases is strongly affected by temperature gradients; soil temperature and heat flux are influenced to a great extent by the presence and movement of soil moisture. Under field conditions, the soil is in a dynamic state: temperature and moisture content variations occur with depth and time, each responding in part as independent processes, in part as dependent processes. Experiments which separate the effects of these two processes have been important in clarifying the mechanisms of each as well as the factors which affect them, but have often not been directly applicable to field situations.

In the absence of a temperature gradient, liquid moisture movement by mass flow in saturated soils can be described by the Darcy equation

$$q = -K_l \nabla H$$

in which q is the flux (the quantity of water transported through a unit cross-sectional area per unit of time), K_l is the saturated hydraulic conductivity of the soil, and ∇H is the hydraulic gradient. The conductivity of the soil is affected by the pore size distribution and continuity, which in turn are affected by the water content, bulk density, soil texture and structure, and inclusion of air bubbles. Hydraulic conductivity is generally considered a function of water content for a given soil with static physical properties. Liquid moisture flux, then, in unsaturated soils is described by

$$q = -K_l(\theta)\nabla H$$

where θ is the volumetric water content. Because of problems in determining the hydraulic gradient in the soil, the unsaturated flow equation can be written

$$q = -D_l(\theta)\nabla\theta$$

where D_l is the liquid diffusivity of the soil (the hydraulic conductivity divided by the slope of the moisture characteristic curve), and $\nabla\theta$ is the volumetric water content gradient. This equation is basically in the form of Fick's law of diffusion. The use of diffusivity in this context does not imply that liquid water movement in soil is a process of diffusion; it is merely a mathematical aid in calculating the flux. Hillel (1971) and Taylor and Ashcroft (1972) give more thorough derivations and explanations of the above formulae.

Water vapor movement is a process of diffusion and, occasionally, mass flow. However, diffusion is generally thought to be the primary mechanism of isothermal vapor flux, and can be described by

$$q = -D_v f a \nabla P$$

where D_v is the diffusivity of water vapor in air, f is the air-filled porosity, a is the tortuosity of the path the vapor has to follow, and ∇P is the vapor pressure gradient (Gardner, 1960). The movement of water vapor is affected by changes in the tortuosity (for example, by changes in soil texture or structure), air-filled porosity (which is affected by water content, soil texture, and soil structure), and the pressure gradient (which is influenced by the gradients of temperature, osmotic potential, and matric potential, and is inversely proportional to the path length, since $\nabla P = \Delta P/L$). The influence of temperature on water pressure gradients is large. Hillel (1971) states that the large matric potential change from 0 to 100 bars results in a vapor pressure change of only 1.6 mbars, whereas a small temperature change from 19 to 20 C results in a 1.5 mbar change in vapor pressure. As a consequence, vapor movement in soils is influenced to a considerable extent by temperature gradients. However, as described later in this section, vapor movement under the influence of temperature gradients is enhanced by processes other than diffusion alone. Consequently, the last equation does not accurately describe vapor flux under non-isothermal conditions. Osmotic potential gradients can also be important in vapor flux, but they are generally considered to be negligible in nonsaline soils.

The effect of temperature gradients on liquid moisture flow is discussed later in this section of the Literature Review, as are the effects of liquid and vapor flux and temperature on each other.

Soil temperature is often described in terms similar to soil moisture. For example, the heat flux of a given soil which is homogeneous and uniform except for the flow of heat is given by

$$S = -K_h \nabla T$$

where S is the heat flux, K_h is the thermal conductivity, and ∇T is the temperature gradient (van Wijk and de Vries, 1963). The equation can also take the form of a diffusion relation when the value of the thermal diffusivity is known. The thermal diffusivity is the ratio of the thermal conductivity to the volumetric heat capacity (the amount of heat required to raise the temperature of a unit volume of soil by one degree).

According to van Wijk and de Vries (1963), changing intensity of short wave radiation is the primary cause of fluctuation in soil surface temperatures. A layer only "a fraction of a millimeter in thickness" absorbs nearly all long and short wave radiation impinging upon it. This surface layer is therefore a heat source when it is absorbing sunlight, and a heat sink when it is absorbing heat from the profile. Consequently, the temperature variation of this surface layer is always greater than the variation at lower depths.

It can be seen by the heat flux equation that increasing the thermal conductivity will increase the heat flux. If the soil can easily conduct heat, then the change in temperature of the surface layer will decrease, although the depth to which significant changes occur will increase. Therefore, the higher the thermal conductivity, the more effective a soil will be as a heat reservoir (Chang, 1968).

Soil is not a homogeneous medium, but is composed of organic matter, water, air, and solid particles of various colors, sizes, shapes, and composition. The thermal properties of these materials vary considerably. One can see from Table 1 that as the air-filled porosity of the soil increases, the thermal conductivity will decrease rapidly, whereas the opposite will be true for increases in the water content.

In a laboratory study investigating the relationship between thermal conductivity and certain soil physical parameters, Smith and Byers (1938) drew the following conclusions: 1) in a dry soil, the thermal conductivity varies little for different soil types, other things (water content, bulk density, etc.) being equal; 2) the thermal conductivity is directly proportional to the bulk density, with a theoretical minimum at 0 $g\text{-}cm^{-3}$ of 5.68×10^{-5} $cm\text{-}sec^{-1}$ (about that of dry air), and a theoretical maximum at 2.7 $g\text{-}cm^{-3}$ (approximately equal to the particle density) of 8×10^{-4} $cm\text{-}sec^{-1}$;

Table 1. Approximate average values of thermal properties for soil constituents at 20 C and 1 atm.

Material	Density ($g\text{-}cm^{-3}$)	Specific Heat ($cal\text{-}g^{-1}\text{-}{}^{o}C^{-1}$)	Volumetric Heat Capacity ($cal\text{-}cm^{-3}\text{-}{}^{o}C^{-1}$)	Thermal Conductivity (10^{-3} $cal\text{-}cm^{-1}\text{-}sec^{-1}\text{-}{}^{o}C^{-1}$)
Quartz	2.65	0.175	0.46	20
Many soil minerals	2.65	0.175	0.46	7
Soil organic matter	1.3	0.46	0.60	0.6
Water	1.00	1.00	1.00	1.42
Air	0.0012	0.24	0.00029	0.062

Source: van Wijk and de Vries (1963).

and, 3) the thermal conductivity is inversely proportional to the porosity, with a theoretical minimum and maximum as in 2) at porosities of 1.00 and 0.0, respectively. They proposed that the thermal conductivity of a dry soil could be estimated by the equation:

$$K = K_2P + K_1(1-P)$$

where K_1 and K_2 are the theoretical maximum and minimum thermal conductivities, respectively, of the soil in question, and where P is the fractional porosity.

Nakshabandi and Kohnke (1965) studied the relationship between the thermal conductivity and diffusivity of soils and the soil moisture tension and other soil physical properties. They found that soil water content variations have a greater effect than changes in bulk density on these heat transmission characteristics. Differences in grain size had little effect on the thermal conductivity and diffusivity at a given bulk density. They showed that for three soil types (sand, silt loam, and clay), the effect of moisture tension on thermal conductivity was similar, even though the effect of moisture content *per se* was quite different between the soils. A generalized curve of this relationship is given in Figure 1.

Willis and Raney (1971) pointed out that heat distribution in the soil is influenced by tillage, soil structure, bulk density, soil texture, layering, water content, and incident radiation. A loose,

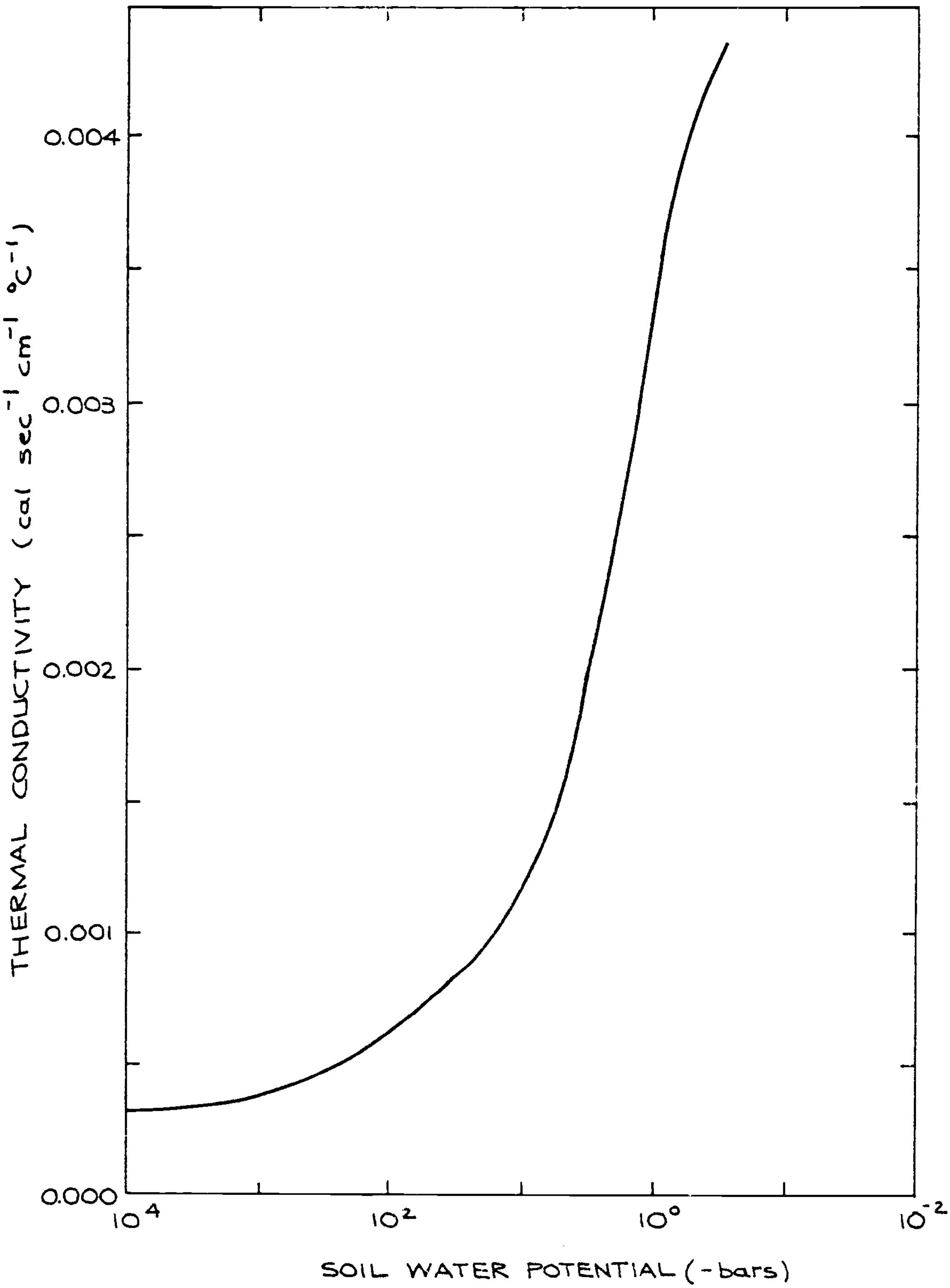

Figure 1. The generalized relationship between soil water potential and thermal conductivity. (Redrawn from Nakshabandi and Kohnke, 1965.)

dry soil mulch has a lower thermal diffusivity and specific heat capacity than untilled soil, so the temperature variations within the mulch will be greater than in untilled soil. The presence of a mulch will also decrease the temperature variations in the soil below it. They also noted that the upper layer of a cultivated soil may warm faster in the spring, but that the soil under the cultivated layer may remain cool longer than under an uncultivated soil. The reverse can occur in the fall. Consequently, a tilled surface layer cools more rapidly, and the untilled subsurface layers less rapidly, than an untilled profile.

Soil Moisture Movement Due to Temperature Gradients

Bouyoucos (1915) first described experimental results concerning water movement due to thermal gradients in soils. He considered vapor movement to be negligible, and felt that liquid water moved from warm to cold. He also described the "thermal critical moisture-content," i.e., the moisture content at which maximum moisture movement occurred. His methods were criticized by Smith (1943), who concluded that the mechanism appeared to be capillary movement induced by vapor condensation. He also found a moisture content at which movement was greatest, and stated that the rate of water transport was largely affected by the physical condition of the soil. For example, an aggregated or fragmented soil allowed much larger vapor flux than an undisturbed clay.

Lebedeff (1927, as reported in Baver, 1940), studying in the Soviet Union, attached considerable importance to the movement of water in the vapor phase. He reported that 7.2 cm of water condenses annually in the soil at Odessa, where the mean annual precipitation is 40 to 45 cm. He found fluctuations in the water content of the surface layer of soil caused in part by condensation from the atmosphere and in part by condensation from lower soil horizons. He suggested that a dry, cool period in the summer, followed by a hot period, could result in substantial losses of water from the soil. As the surface is cooled, the vapor pressure decreases, so vapor moves up from the warmer, deeper layers, and much of that can be lost by evaporation.

Gurr et al. (1952) showed in a laboratory experiment with salt solutions that liquid flow occurred from cold to hot. They concluded that vapor flow from the hot to the cold end of a closed soil column increased the water potential at the cold end, and liquid flow returned down a potential gradient toward the hot end. They proposed that a continuously circulating system would be established within the columns, as long as sufficient moisture was present in the soil to permit liquid flow. Although water movement was greatest for intermediate moisture contents and least for dry and wet soil columns, they reported that liquid movement occurred at potentials of -7.9 bars. Their results suggested that, even with a uniform soil moisture content, redistribution within a soil profile would occur due to temperature gradients.

In a laboratory experiment, Jones and Kohnke (1952) showed that it was the volume, rather than the size, of the unsaturated soil pores which governed the soil moisture content at which water vapor movement began. The moisture tension at which initial and maximum vapor movement occurred increased as particle size decreased. For a medium sand, the vapor movement began at -0.02 bars and reached its maximum at -0.07 bars; for a silt loam, the figures were -0.5 and -5.0 bars, respectively. The volume of the air-filled pores also affected the total vapor flux which occurred. They concluded that water vapor flux in a given soil under a given vapor pressure gradient is regulated by the balance between air-filled pore space, evaporating surfaces, and moisture reserve remaining in the soil.

Rollins et al. (1954) reviewed earlier work on soil moisture movement caused by thermal gradients and presented theoretical and experimental results of their own work. They wrote that the equilibrium state requires cyclic moisture flow, i.e., vapor flow from warm to cool, and liquid flow from cool to warm. The calculated rates of vapor movement from diffusion alone were one-sixth those actually measured in their laboratory study. This was attributed to incorrect values either for the diffusion coefficient in air or for the tortuosity factor, which represented the ratio of the diffusion coefficient in porous materials to the diffusion coefficient in air. They also found that the rate of vapor flow was a non-linear function of the temperature gradient for a given bulk density and soil moisture content. That is, vapor flux increased with increasing temperature, even though the temperature gradient remained the same. This could be expected because of the non-linear relationship between vapor pressure and temperature (see Appendix Figure 1).

Taylor and Cavazza (1954) conducted a laboratory experiment with continuous and broken soil columns. In the continuous columns, a steady state distribution was attained; the broken columns did not achieve a steady state. The broken columns eliminated return flow of liquid water, so Taylor and Cavazza concluded that vapor flow is the main effect of a temperature gradient, and liquid flow is only a response to the potential gradients caused by vapor flow. They found that the diffusion coefficient calculated from the experimental results was higher than expected, and attributed this to the coupling of heat and moisture diffusion in soils, or to the possibility of surface migration or "molecular hopping" of adsorbed water.

They also concluded that hysteresis plays a large part in liquid movement in soils.

Gardner (1955) demonstrated the effects of temperature on water potential in a laboratory experiment with tensiometers. A warm soil of lower water content could have the same water potential as a wetter, colder soil, if the temperature difference was sufficient. He concluded that two soils with equivalent water contents only have equivalent water potentials when their temperatures are equal. (To this might be added that the soils would also have to have attained their moisture contents by a similar wetting or drying process, due to the influence of hysteresis.) Gardner's data showed a "consistent tendency" for the water potential to decrease 0.008 bar for every 1 C rise.

In 1957, Philip and de Vries presented a theory of moisture movement in porous materials which included the interaction of vapor, liquid, and solid phases and the presence of microscopic temperature gradients across air-filled pores and soil particles. They suggested that condensation and evaporation from liquid "islands" between soil particles may influence the rate of moisture movement considerably. Because the menisci of these liquid islands have very small radii, rapid equilibration can be attained with the vapor in the soil atmosphere, thereby speeding apparent vapor "movement." The following year, de Vries (1958) published a theoretical examination of simultaneous heat and moisture transfer in porous materials. He pointed out that vapor movement through liquid islands, which he referred to as distillation, is very important because it increases the conductivity of the poorest conductor of the system, i.e., the gaseous part. In the temperature range from 0 to 40 C, vapor distillation can increase the conductivity of the air-filled pores from two to nine times. He also calculated that when the moisture flux is 10^{-7} g-cm^{-2}-sec^{-1} or less, moisture movement due to temperature gradients becomes important.

Hanks (1958) presented calculations and laboratory measurements of isothermal water transfer in dry soil. The measured-to-calculated ratio of these values was 1.04, 1.39, and 1.32 for fine sandy loam, silty clay loam, and silt loam, respectively. Since he found that simple diffusion consistently underestimated the measured flux, he suggested using the ratio of measured to calculated flux values as a correction factor. Diffusion was felt to be the primary mechanism involved, but he concluded that vapor movement probably involves more than pure diffusion. There was good agreement between his data and the theory presented by Philip and de Vries. They had concluded that measured values would be higher than the calculated values in direct relation to the moisture content, assuming simple diffusion. Hanks used air dry soil, so his values of enhanced movement would be expected to be smaller than those obtained by Gurr et al. (1952), 3.6X; Rollins et al. (1954), 6X; and Taylor and Cavazza (1954), 11X.

Mattes and Bowen (1963) subjected soil columns to temperature gradients under laboratory conditions. They showed that water moved from warm to cool within the columns. They also demonstrated that condensation could be induced by packing the soil on the low temperature side. The condensation was due to the decreased diffusion coefficient and increased thermal conductivity in the more dense soil.

Jackson (1964a, 1964b) began a series of papers dealing with water vapor diffusion in dry soil (relative vapor pressure less than 0.97) in light of the classical diffusion theory, modified to include the condensation-evaporation reaction between liquid and vapor. He found good agreement with experimental sorption values obtained from soil cores under isothermal laboratory conditions (1964a). Like previous investigators, he reported that water diffusivity values reached a maximum at a particular water content and decreased as the water content changed from that value. He found no simple relationship between the diffusivity-water content function and total porosity or texture. He suggested that pore size distribution, soil structure, type of clay mineral, and presence of ions in the clay complex may affect vapor diffusion. He also concluded that simple diffusion may apply only to the wet regions of soil moisture content, where moisture transfer is primarily by viscous flow, and dry regions, where vapor flow predominates. Intermediate regions are complicated by the operation of both processes, so he felt that simple diffusion theory is probably not applicable to them. He showed that the diffusion coefficient is directly related to the slope of the adsorption isotherm. (The adsorption isotherm is the relationship between water vapor density and the liquid water content.)

Jackson (1964b) also found that simple diffusion theory, when liquid-vapor condensation-evaporation reactions were included, fit desorption values for dry soil. The curve of diffusion coefficient versus water content showed a maximum value, as in the sorption experiment, but the maximum was of lesser magnitude and occurred at higher moisture contents than the sorption values. This result was expected because of hysteresis. Soil texture made a difference in the range of diffusivity values as well as on the rate of change of diffusivity with water content. He stressed that this effect would need to be considered when attempting to describe diurnally fluctuating systems, where the soil alternately gains and loses moisture.

Cary (1965) published the results of a laboratory experiment and a theoretical discussion of water flux in moist soil. He found vapor transport several times greater than that predicted by Fick's law and the diffusion of water vapor in air. Consequently, he proposed a hypothesis of liquid transfer in unsaturated soil. He suggested that water molecules are in various states of hydrogen bonding to others, and that the freer molecules could possibly serve as a lubricant for films of water. These films could move in response to any gradient (temperature, pressure, etc.) and this mechanism would not require water vapor to vaporize and recondense. This theory fit the energy relations he measured in the laboratory. He did not feel that the air-water surface tension gradient, as proposed by Philip and de Vries (1957), was a primary effect of temperature gradients, because thermal-osmosis occurs in saturated systems which do not have these interfaces. He also presented phenomenological flow equations for heat and moisture using both pressure and temperature gradients.

Jackson et al. (1965) substantiated the idea of Gurr et al. (1952) that a circulatory system is established under a temperature gradient in closed soil columns. They described a dynamic circulating system consisting of vapor movement from the hot toward the cold end of a soil column and liquid movement from the cold toward the hot end.

Jackson (1965) presented a theoretical and experimental evaluation of liquid and vapor diffusion coefficients in relatively dry soil. He described water transfer as occurring both by vapor diffusion through air-filled pores and by movement through thin water films, or as liquid movement along the surfaces of the soil particles. He speculated that clays would have higher liquid flux due to the increased surface area and that sands would have higher vapor flux due to increased pore size. He found that the maximum diffusion rate (i.e., at the optimum water content) was increased more by higher temperatures than the diffusion rates at greater or lesser water contents. The total diffusion coefficient, which included both liquid and vapor diffusion coefficients, changed eight- to ten-fold over a temperature interval of 36 C (6.0 to 42.5 C). According to his calculations, the maximum diffusion rates occurred near moisture contents corresponding to a theoretical monolayer of water on the soil particles.

Cary (1966) reviewed the theories and knowledge of thermally-induced moisture transport in soil. He developed equations describing moisture flow near the soil surface in response to diurnal temperature cycles. He showed that moisture flows from warmer to cooler regions of the soil in both the liquid and vapor phases, if other gradients are minimized. He suggested four possible reasons for the liquid flow: 1) surface tension gradients, since the surface tension increases with decreasing temperature; 2) soil moisture suction gradients, which also increase with decreasing temperature; 3) random kinetic energy changes associated with the hydrogen bond distribution which develops under a temperature gradient; and 4) thermally-induced osmotic gradients. Cary showed that, although significant flow can occur from warm to cool even at saturation, thermally-induced flow becomes relatively more important compared with the flux arising from hydraulic head gradients, as the hydraulic conductivity decreases. He presented equations predicting the flux of liquid and vapor due to temperature gradients, and calculated the direction and amount of vapor and liquid phase moisture movement in an example.

In a laboratory experiment comparing different heating and cooling regimes, the effect of mulches and different ambient pressures, Cary (1967) concluded that vapor transfer near the surface is due both to diffusion and to viscous air flow caused by wind-induced pressure gradients. Because of the exponential relation between temperature and vapor pressure, a thermal gradient will produce significant fluxes of water in a moist profile. He felt that the diurnal temperature wave would cause net daily downward flux of vapor unless cooling conditions were severe. Lowry (1967) suggested that in relatively dry soils, high daytime temperatures would force water vapor to move down in the soil, thus causing further drying of the soil surface. The cool soil surface at night may condense vapor which is moving up in response to the reversed temperature gradient.

Abramova (1968), in a field experiment using encased soil columns, with either closed or screened bases, concluded that water vapor moved downward and upward from the 20-cm depth in the soil during the night, because that was the warmest soil layer at that time. He found that 16 to 60% of the water evaporating from the upper layers of soil was moving as vapor into the deeper layers, where it condensed.

Rose (1968a) developed the theory necessary for the calculation of evaporation from moisture and temperature profiles and relevant soil physical properties. He conducted a field experiment in which temperature and moisture changes were measured for six days after irrigation. He then calculated evaporation, liquid and vapor moisture flux, and the change in moisture storage in the upper 15 cm of the soil. The vapor flux was directed downward during the day and was either nonexistent (early in the experiment) or directed upward during the night. Liquid flux was always upward, but decreased as the soil dried. He noticed a mid-morning drop in the calculated evaporation rate associated with a strong downward vapor flux. Evaporation at night was greater than commonly assumed, and averaged 0.6 that of the preceding day.

In a laboratory experiment designed to compare isothermal and non-isothermal evaporation in soil, Sutor and Novák (1968) exposed soil columns to relative humidities varying from 0.1 to 1.0 at the surface. At the volumetric moisture content corresponding to the highest diffusion coefficient, non-isothermal evaporation (i.e., with the surface of the soil column cooler than the main body of soil) approached 2.8 times the evaporation under isothermal conditions. At higher and lower moisture contents, the ratio of non-isothermal to isothermal evaporation was larger, and was near 4.0 at moisture contents approaching the hygroscopic coefficient (-27 bars). When the relative humidity above the soil surface was 96-97%, evaporation under the temperature gradient equaled the vapor flux. At relative humidities above this, water condensed in the upper layers; below 96-97%, the upper layers lost water more rapidly than it was replaced by vapor movement.

Hadas (1968) compared the models of moisture transfer due to thermal gradients proposed by Philip and Cary with values obtained in a laboratory study. He found that the models predicted values 0.8 to 8.0 times smaller than those actually obtained. He suggested that the failure of prediction was caused by the use of: 1) average thermal conductivities rather than a dynamic value which changes with moisture content; 2) average β values (which represent the influences of pore geometry, void cross-sectional area, and microscopic temperature discontinuities) rather than dynamic values influenced by heat flux, moisture content, and distance; and 3) the omission of changes in matric suction induced by hysteresis and temperature.

Rose (1968b) presented the theory and results of a field experiment concerning water movement due to diurnal fluctuations in temperature. He suggested that microscopic temperature gradients across air-filled pores and that evaporation and condensation of vapor from isolated regions of liquid may be sufficient to enhance vapor movement over that predicted by molecular diffusion. In another paper (1968c), he analyzed the results of the field experiment. He concluded that vapor phase transport can nearly equal liquid phase transport at water potentials as high as -0.2 to -0.3 bars, and is the dominant transport mechanism at potentials lower than -5 bars. He felt that vapor phase transport enhancement was probably due to a discontinuous liquid phase rather than to atmospheric pressure fluctuation or mass movement caused by the expansion and contraction of the soil atmosphere in response to temperature gradients or in response to wind-induced air turbulence. He noted, as had others, that liquid movement was predominantly upward, resulting from potential gradients, and that vapor movement fluctuated diurnally with the temperature gradients.

Warkentin (1971) pointed out that since relative vapor pressure does not vary significantly from 100% until very low water potentials are attained (see Appendix Figure 2), isothermal flux of water vapor would not be expected to be important until the soil becomes very dry.

Jackson et al. (1973) published the results of a field experiments which demonstrated the dynamic nature of water flux near the soil surface after irrigation. The flux at all depths (to 9 cm) changed direction one to four times per day in the 37 days following the initiation of drying. At night, temperature and water content gradients caused upward flow. After sunrise, the water in the upper layers evaporated, while water deeper than 1 to 2 cm flowed down in response to temperature-induced gradients. Drying was therefore bidirectional. They noted a large downward flux in the morning hours. However, several periods of downward flux at other times (during the late afternoon and night) could not be explained on the basis of temperature and moisture gradients. They calculated the plane of zero moisture flux to vary from 15 to 20 cm four days after irrigation to 20 to 30 cm after 16 days.

The same experimental data were used by Jackson et al. (1974) to test the theory of Philip and de Vries. They found that this theory could adequately predict fluxes at intermediate water contents, but not at high or low contents. They concluded that the diffusion coefficient must be accurately known and that hysteresis in the vapor diffusion coefficient should be accounted for, in order to predict reasonable flux values.

Westcot and Wierenga (1974) placed sealed soil columns in a field plot, and attempted to use a computer simulation model to predict soil temperatures and vapor flux. The results of moisture redistribution and temperature in the columns emphasized the need to include heat transfer by vapor movement to accurately predict upper profile temperatures. The initial water tension of the columns varied from 0.33 to 15 bars, yet there was very good agreement between the model and the measured values. Vapor flux accounted for 40-60% of the heat flux in the upper 0-2 cm and 20-25% at 25 cm.

Soil Drying and the Use of Mulches

Attempts to minimize soil moisture loss in areas where water is a primary factor limiting yields have produced considerable information about the process of soil drying and the effect surface mulches have on water loss. There is, however, disagreement concerning the effect of some factors on long-term losses and our ability to reduce cumulative evaporation through the use of mulching.

Penman (1941) found little difference in the total evaporation from mulched and unmulched cores of a sand and a clay loam soil. Some cores were exposed to long-wave radiation in the laboratory so that the soil surface was 10 C higher than the air temperature for eight hours each day. These cores dried at the surface more rapidly than those exposed to isothermal drying conditions. The initial loss stage lasted only one to two days; thereafter, the evaporative loss was much slower and nearly constant. Penman proposed the idea that there are two distinct periods of the year--an isothermal period, when the soil surface temperature is not appreciably different than that of the air, and a non-isothermal period, when radiation increases the soil surface temperature over that of the air. The former condition is typical of winter months, the latter of summer months. He suggested that mulching would have the greatest benefit during the isothermal period, because the soil surface is slow to form a dry mulch. Mulching would probably be of little benefit during the non-isothermal period, when rapid drying decreases initially high rates of water loss.

Kolasew (1941, as reported in Lemon, 1956) divided the evaporation process into three stages. The first stage is one of rapid, steady-state loss, dependent on the water transmission rates through the soil and aboveground conditions such as windspeed, temperature, relative humidity, and radiant energy. This stage stops when a dry barrier develops. The second stage is one of rapid decline in loss rate as the soil dries. This stage is dependent upon "intrinsic soil factors" governing the rate of moisture flow toward the surface. The third stage is one of very slow rates of loss, dominated by adsorptive forces over molecular distances at the solid-liquid interfaces in the soil. Kolasew had conducted wind tunnel experiments with stratified and unstratified soil columns. The former had less evaporation, which Kolasew attributed to two processes: when the upper layers were compacted, less vapor flow could occur; when the upper layers were loose, liquid flow was reduced.

Lemon (1956) concluded from his work that little could be gained from decreasing moisture loss in the third stage of evaporation. He suggested that there are three methods for reducing losses during the first two stages: 1) decrease the turbulent transfer of water vapor above the soil surface by increasing surface roughness; 2) reduce capillary conductivity of water to the surface through tillage or chemical additives; and 3) decrease the capillary conduction and moisture holding capacity of the surface layer by the addition of surfactants. He reported the results of an experiment where sorghum (Sorghum bicolor Moench) residues at rates of 36,000 kg/ha did not reduce evaporation when compared to a bare soil. He discovered that the mulched soil absorbed similar amounts of radiation during the day, but conserved more heat at night. The increased temperature of the mulched soil evidently caused the higher losses. Lemon suggested that the rodweeder and "various stubble mulching machinery" may act to stratify the soil to some extent, thereby reducing evaporation. He reported that diffusion of water vapor through a mulch is reduced to the greatest extent by the first 2 to 3 cm, after which increasing the thickness of the mulch results in decreased additional effectiveness.

Horning and Oveson (1962), in a report concerning stubble mulching in the Pacific Northwest, suggested that the best combination for this area was a shallow spring tillage (to a depth of 8-15 cm), which is sufficient to kill weeds, but does not cause drying to an appreciable depth, and summer rodweeding at a maximum depth of 8-10 cm, so that deeper drying of the soil surface would not occur. The advantages of a stubble mulch over no tillage in this area include weed control and increased moisture storage in the seed zone. Total stored soil moisture was not much affected by surface management.

Using numerical simulation techniques, Hanks and Gardner (1965) compared the water losses which occur in soils with different diffusivity-water content characteristics. They used the one-dimensional flow equation for isothermal movement of liquid and vapor. Their calculations implied that, in order to reduce evaporation during the falling rate stage, the diffisuvity of the soil to liquid and vapor must be reduced in the wet range of moisture contents. Decreasing the diffusivity at lower water contents did not materially affect the calculated cumulative evaporation. Reducing the diffusivity of a surface layer reduced cumulative evaporation, but the effect was rapidly attenuated as the depth of the layer increased, and was most pronounced during the constant rate stage. They suggested that, although mulches would be expected to have little effect on the total evaporation during the falling rate stage, they would be effective during the constant rate stage.

Gardner and Hanks (1966) measured the heat flux in soil columns in the laboratory. They were able to trace the movement of the evaporation zone down into the soil profile with the use of heat flux plates. They found that the latent heat of vaporization increased the flux of the plate directly above the zone of evaporation. The evaporation process utilized the incoming heat, so that the soil of this zone would be cooled. The evaporation zone moved downward at a continuously decreasing rate, and remained approximately 1 cm thick throughout the experiment. The heat flux near the surface began to increase rapidly as first stage drying finished. By the time the evaporation zone was deeper than 2 cm, the evaporation rates were only one-tenth the initial rates.

Cary (1967) suggested two ways of decreasing soil moisture loss: 1) decrease the transfer coefficient of water vapor between the moist soil and the atmosphere; and 2) insulate the soil from the energy supply of the atmosphere. If the vapor pressure of the atmosphere is relatively high, evaporation could probably be reduced by insulating the soil so that it does not warm to a point where its vapor pressure is higher than that of the atmosphere. If the atmosphere is very dry, a reduction in the transfer coefficient may be required to decrease evaporation. He recommended consideration of the pore size distribution in the dry layer as well as the overall porosity, because the transfer coefficient of water vapor is in part due to viscous flow. Kohnke (1968) pointed out that the rate of water vapor diffusion is proportional to the square of the effective porosity. As a consequence, as pore size increases, the rate of vapor movement increases exponentially.

Working under isothermal laboratory conditions with mulched and unmulched soil columns, Bond and Willis (1969) also found that cumulative evaporation of the columns was approximately equal for all treatments (0-6, 720 kg/ha rye straw). With increasing rates of mulch, the first stage evaporation rate was decreased, but evaporation remained in the first stage longer. Mulch rates above 2, 240 kg/ha (approximately complete cover) had decreasing effects on the rate of first stage drying.

Massey and Siddoway (1970), working in southeastern Idaho, found that evaporative losses from summer-fallowed land were greater, the higher the soil water content of the profile. When profile storage was lower than normal, losses from evaporation were also low. They found that the water content of the seeding zone (7.5-15 cm) at planting was positively correlated with the water content of this zone at the initiation of spring tillage. They concluded that only rarely will summer precipitation affect seed zone moisture content, because few storms (less than 8%) produce more than the 3 cm of precipitation necessary to penetrate the mulch. However, they felt that summer precipitation can delay evaporative losses. Massey and Siddoway also concluded that wheat yield differences due to time of initial spring tillage in the fallow were caused by fall seedbed water conditions. Percent stand of winter wheat was highly correlated with eventual grain yield and with seedbed water content.

Nagpal (1971) stated that large pores resist water vapor movement less than small pores because of the decreased tortuosity of the diffusion path. He found that heat transfer was independent of the pore size distribution, and that the vapor component of heat transfer was insignificant.

Willis and Bond (1971) reported that simulated tillage of soil columns reduced evaporative losses. They "tilled" a fine sandy loam at 2.5 or 7.5 cm on 1, 4, 7, or 18 days after evaporation had begun. Tillage at any time caused an immediate decrease in the evaporation rate over no tillage, but the earlier tillage showed greater overall reduction in water loss. When tillage was performed on day 1, evaporation was reduced by more than 50% for more than three weeks. After 67 days, the 7.5-cm depth averaged about 5% greater evaporation reduction than the 2.5-cm depth. The decrease in evaporation in the tilled columns was reflected in higher moisture contents throughout those columns.

In another isothermal laboratory study, Hillel and Hadas (1972) found that the least evaporation occurred from columns in which an aggregated mulch overlaid a compacted column. The optimum size of the aggregates in order to minimize evaporation was 0.25-1.0 mm.

Kühn et al. (1972) conducted a laboratory experiment using tritium-labelled water. They placed 0.1-cm thick soil layers containing labelled water at 0, 1, 2, and 3 cm below the surface of uniformly moistened soil, and exposed the columns to a 10 C temperature gradient between the surface (coldest) and the 10-cm depth, to simulate nightly temperature conditions. They measured the activity of the atmosphere above the columns as a means of detecting evaporation from the different layers. As the depth of the labelled layer increased, the time required for evaporation from this layer increased. Except for the surface layer, time required for evaporation was higher when the initial moisture content of the soil was higher. Because of the time lag with increasing depth, they concluded that there could be no significant evaporation during the night from depths exceeding 3 cm. However, it seems that more rapid movement of the labelled water would have occurred if the soil above these labelled layers had been dry. This would have also more closely simulated the conditions which are prevalent during the summer in arid and semi-arid areas.

Hillel and Rawitz (1972) suggested in their review article concerning soil water conservation that surface treatments such as a shallow, aggregated layer or other mulch can only be expected to have a large effect on the initial phase of evaporation. Surface treatments have only a small effect on the second stage, where reduction in the evaporation rate is dependent upon decreasing the diffusivity and conductivity of the soil with depth. They felt that deep tillage would decrease the diffusivity at lower water contents, but concluded that this treatment would probably be too expensive. Surface tillage can generally not be carried out until after the surface has dried, and by that time the initial stage would be finished. The usefulness of tillage is then limited to controlling weeds and to reduce evaporation in soils subject to high shrink-swell variations. If initial evaporation can be reduced, penetration of soil water is enhanced, and water storage is increased.

Kimball (1973) attempted to differentiate between water vapor loss due to diffusion and that due to mass flow processes in a field experiment using mulches of glass beads and soil. The mulch materials were of various diameters, and the soil aggregates were treated with a water repellent to decrease absorptive effects. The average effective diffusion coefficient was calculated to be 1.26 times greater than the molecular diffusion coefficient. There was no significant difference between the ratio of effective to molecular diffusion coefficients for different mulches, except that the intermediate size glass beads had a significantly lower ratio. The reason for this was not accounted for, as the investigator had expected lower ratios as the particle size decreased. The ratio also decreased with depth of mulch for all but the glass aggregates.

Willis and Amemiya (1973) presented a generalized diagram of the effect of a mulch on soil temperatures. The range of soil temperature was expected to be smaller under a mulched surface than under a bare surface. Fenster (1973) presented data from a study in Nebraska which substantiated their diagram. Wheat residue at rates of 1680 kg/ha decreased average daily temperature variations at the 5 cm-depth. The average daily maximum temperatures under a bare fallow were 5.4 C higher, and average daily minimum temperatures were 3.4 C lower, than under a residue.

Yeşilsoy (1973) conducted a laboratory experiment to measure evaporation, soil temperature, and moisture movement in columns of soil under simulated tillage conditions. He used three soils from the Pacific Northwest: Naff silty clay loam, Ritzville silt loam, and Wapato clay. The tillage treatments included: simulated moldboard plow; moldboard plow plus a fine surface mulch (5 cm thick); moldboard plow and a fine surface mulch with a compacted layer at the bottom of the mulch (to simulate the effect of rodweeding); no tillage plus a straw mulch equivalent to 4500 kg-ha^{-1} straw; and no tillage, as the control. The columns were initially brought to field capacity and then were exposed to diurnal temperature variations. Moisture and temperature determinations were made during the experiment. Yeşilsoy found that the total moisture losses were higher in the control than in the other treatments with the silty clay loam and the clay. However, there were no significant differences in moisture losses between treatments of the silt loam. He attributed this result to the self-mulching characteristic and weak structure of the Ritzville soil. Moisture loss from the silt loam was restricted to the upper 30 cm, whereas in the other soils, losses occurred throughout the columns. Calculated water movement in the vapor phase was ten times greater than that in the liquid phase when surface temperatures were greatest. Although there were no significant differences between surface treatments of the silt loam, both non-tilled treatments of the other soils had lower moisture transfer due to thermal gradients than the tilled treatments in those soils.

Papendick et al. (1973) used different combinations of sweep tillage depths with rodweeding depths, with and without applied mulch, to study the effects these fallow treatments would have on seedbed temperature and water content in eastern Washington. The minimum temperatures at the base of 6-and 11-cm mulches were similar, but the maximum was higher under the shallower mulch. Daily mean temperatures were higher (as much as 4 C) under the shallow mulch than under the deep mulch. These temperature differences were most pronounced during hot weather. A straw mulch applied to the soil surface decreased temperatures an average of 1 C. Mean daily soil temperatures indicated a net downward flux of heat even in early September. Soil water was more evenly distributed under the shallow mulch, but the deep mulch retained more water in the seed zone. A coarse mulch was less effective in retaining water in the seed zone than a fine mulch, but there had been no tillage of the coarse mulch after the initial spring sweep operation. They found a distinct loose layer (bulk density approximately 1.0 $g\text{-}cm^{-2}$) over the rod depth, especially with the deeper rodweeding. They calculated that the major effect of the mulch is realized where the mulch is 11 cm thick or less.

Papendick et al. also concluded that, because of the temperature dependence of liquid and vapor flow, water will move both up and down from the zone of vapor pressure maximum which occurs in the moist soil under a dry mulch. These processes, over a long period, can contribute to drying this layer, even though matric gradients will tend to move water back up. They felt that the stratification produced by deep rodweeding (where loose soil above the rod depth was covered by more compact soil) served to decrease water loss in two ways. First, the loose layer insulates the compact moist soil and limits the upward transmission of water. Second, the more dense, aggregated layer near the surface increases the resistance to vapor flow. The compact rod pan produced by any depth of rodweeding increases the unsaturated hydraulic conductivity so that replacement of lost water is enhanced.

Stone et al. (1973) studied the magnitude and direction of water movement in fallow field in South Dakota. They used tensiometer readings to a depth of 150 cm and calculated flux at that depth using the Darcy equation. Evaporative losses remained small during the summer, except when rain had rewet the surface layers. Losses from drainage below the 150-cm depth were small but continuous throughout the summer. Of the 9.8 cm of water lost during the summer from the 0-150-cm profile, 6.9 cm were lost by evaporation and 2.9 cm were lost by flux at the 150-cm depth.

Jackson (1973) found significant diurnal fluctuations of soil water content in a field study of evaporation. These fluctuations decreased with time and depth. His data did not indicate that rapid drying of the surface soil reduces cumulative evaporation below that for a surface which remains wet longer, but he suggested that mulching either with residues or by tillage may decrease total evaporation. He was unable to differentiate between the three stages of drying, because soil water changes were so dynamic. He suggested that the concept of three evaporative stages may have little meaning under natural field conditions. In a later study, Idso et al. (1974) were able to differentiate the three stages of drying under natural field conditions. They utilized albedo (reflectance) measurements to distinguish between the stages. The occurrence of surface rewetting at night reinstated stage two for several days when the evaporative demand was low. They were unable to discern the transition from stage two to three when the plane of zero water flux was located below a critical level in the profile. They concluded that stage three was apparently initiated at a surface water content corresponding to two molecular layers of water.

Lindstrom et al. (1974) found no difference in over-summer water storage between different spring fallow tillage treatments in eastern Washington. The loss of water during the summer of the fallow was small in comparison to the annual precipitation or to the total water stored in the profile. They concluded that the time of major losses must be in the late winter and early spring; consequently, the timing of spring tillage was felt to be very important. They found that seed zone moisture contents were lower under chemical fallow than under treatments which had been tilled in the spring.

Leggett et al. (1974), in a review paper of summer fallow practices in the Pacific Northwest, reported that a high percentage (50-75%) of precipitation during the first winter after harvest is stored in the soil profile. They attributed this to the initially dry condition of the profile, the low evaporative demand during the winter, and the occurrence of precipitation in effective amounts. Losses during the summer are small and primarily due to evaporation, although percolation and runoff may also be of occasional importance. Another source of soil water loss during the summer period is due to weed and volunteer growth. The authors reported that very little difference **in** water conservation has been observed between stubble-mulched and bare fallow. Early spring tillage reduces water loss by controlling weed growth and by reducing the capillary conductivity to the soil surface, thereby decreasing evaporation.

Soil Moisture-Temperature Effects on Germination and Emergence

The importance of water content and temperature on seed germination has been extensively studied, although the methods used by some investigators have been questioned. Some work has been done on the effect of moisture and temperature on emergence and stand establishment.

Sachs (1860, as reported by Koller, 1972) first formulated the concept of maximum, minimum, and optimum temperatures for germination. Jones et al. (1926, as reported in Schlehuber and Tucker, 1967) conducted a laboratory experiment with Marquis and Turkey wheat. They found that the seedlings emerged most rapidly and shoots developed earliest at soil temperatures of 24-28 C. The largest root systems developed at 12-16 C. Although the roots developed much more rapidly than the shoots at 8-12 C, the plumules emerged before the roots had developed at 28-32 C.

Edwards (1932, as reported by Koller, 1972) cited several examples where the incubation period strongly influenced the optimum temperature and width of the maximum-minimum temperature range. As the incubation period was increased, the optimum temperature for germination was lowered, became less sharply defined, and the range over which the seeds germinated was widened.

In a study of wheat seed germination in relation to osmotic water potential, Owen (1952) found that some seeds would germinate at potentials of -32 bars. Water was supplied to seeds in the vapor phase by separating the seeds from the osmotic solutions. He found that, as the potential decreased, the time for germination increased and the total germination was reduced.

Gingrich and Russell (1956) studied the effect of soil moisture tension on the growth of corn (Zea mays L.) seedling roots. They reported that radicle elongation increased, but fresh and dry seedling weight decreased as the tension increased from 1 to 12 bars. The degree of hydration of the seedlings was negatively correlated with water tension. The effects were most pronounced as the tension increased from 1 to 3 bars.

Powell and Pfeifer (1956) found that they could divide a population of Cheyenne wheat into two groups, according to how well the seeds could germinate and grow under different moisture tensions in the laboratory. They used osmotic solutions equivalent to 7 and 14 bars tension, and germinated the seeds at 17.5 C in these solutions. The germinated seeds were divided into two groups after nine days, and planted in the field. The seeds produced by the parents which germinated and grew well in the laboratory under a given osmotic stress responded similarly when placed in osmotic solutions.

Hanks and Thorp (1956) placed wheat seeds 1.3 cm deep in soil of different moisture potentials and found that the rate of emergence was decreased as the water content of the soil decreased. The total emergence was also reduced in two of the soils used (a silt loam and a fine sandy loam) as the water content decreased.

Peters (1957) used soils of different texture to study the effect of moisture content and water potential on water uptake by corn seedling roots. In soils having the same water potential but different moisture contents, root elongation was greater in the soils of higher water contents. This effect was more important at 3 and 8 bars than at one-third and 1 bar tension. As the water potential decreased, both water uptake and elongation of the roots decreased.

McGinnies (1960) studied the effect of moisture stress and temperature on the germination of six range grasses. He used six osmotic potentials, from -0.33 to -15 bars, and three temperatures, 10, 20, and 30 C. As the water potential decreased, germination was delayed, the rate of germination was reduced, and the total number of germinated seedlings declined. The optimum temperature was 20 C for all six species. Seed size was positively correlated with germination at 15 bars tension. At 10 C, the initial germination rate was much reduced, but it was still increasing after 28 days. McGinnies concluded that the total germination may have approached that reached by the seeds at 20 C, if sufficient time had been allowed for germination.

In a laboratory study of sorghum (Sorghum bicolor Moench) seed germination, Evans and Stickler (1961) also found that a decrease in water potential reduced the germination rate. They found a significant interaction between water potential and variety, and reported a significant difference between seed source at lower water potentials. At lower temperatures, the rate of germination and the lengths of the plumules and radicles were reduced. They stated that the addition of gibberellic acid overcame the effects of lower water potential and temperature to some extent.

Collis-George and Sands (1962) conducted a laboratory experiment with alfalfa (Medicago sativa L.), oats (Avena sativa L.), and perennial ryegrass (Lolium perenne L.). They found that matric potential inhibited germination rate more than osmotic potential. This was an important realization, because work with osmotic solutions was done on the assumption that the effects they would have on seed germination were not different from the effects of similar soil matric potentials. Collis-George and Sands suggested that biological systems may not act as if a semipermeable membrane separates them from the surrounding osmotic solutions. Consequently, the actual potential of the water in experiments using osmotic solutions is probably higher than calculated.

Read and Beaton (1963) investigated the effect of fertilizer, moisture and temperature on wheat seed germination. In the control treatment (no fertilizer), the time for germination was increased as the water potential decreased. The rate of germination was also higher at 27 C than at 16 C, and both were higher than the rate at 6 C. The reduction in temperature from 16 to 6 C had a much greater effect on reducing the germination rate than the change from 27 to 16 C. Some of the fertilizers used decreased both the total germination and the rate, others affected only the rate of germination, and others had either no effect, or retarded germination only at low temperatures.

Mayer and Poljakoff-Mayber (1963) published a general review of the germination process. They described imbibition as a physical process, dependent primarily on the properties of the colloids within the seed, the permeability of the seed coat, and the availability of liquid or gaseous water. They stated, as had Edwards, that the optimum temperature for germination depends on the time allowed for germination to occur. The more time allowed, the lower the optimum temperature. Since time allowed for germination varies, the reports of optimum temperature also vary. They cited published values for wheat as ranging from 15 to 31 C, depending on the source of information. Minimum (3-5 C) and maximum (30-43 C) germination temperatures also varied due to source of information.

Sunderman (1964) studied seedling emergence of winter wheats in the Pacific Northwest. He found significant differences between varieties with respect to their ability to emerge in the field when seeded at different depths. There was a significant correlation between coleoptile length measured in the laboratory and percent emergence in the field. As temperature decreased, total emergence decreased. When planted at 7.6 cm, average total emergence dropped from 94.0% to 73.8% as the average seed zone temperature fell from 27.2 and 16.6 C to 12.8 C. When planted at 10.2 cm, total emergence decreased from 80.4% to 47.4% with the same drop in temperature.

The interactive effects of temperature and osmotic potential were investigated by Tadmor et al. (1969). They used osmotic potentials from 0 to - 15 bars, temperatures from 4 to 25 C, and six range species, including wheat and barley. The onset of germination, which they defined as the day 10% germination was reached, was delayed in the cereals at 4 C and by potentials less than 4 bars. The osmotic potential x temperature interaction was significant, especially at extreme temperatures. As the temperature diverged from the optimum, final germination became more dependent upon the osmotic potential. The total reduction in final germination percent was small, the maximum being 50% for barley at 15 bars, 25 C. The range species were much more sensitive to both water potential and temperature. The effect of osmotic potential on germination rate was greatest at favorable temperatures; the relative effect of water potential was greatest when the germination rate was highest. At all temperatures above 4 C (10-25 C), the onset of germination in barley occurred in one or two days and three to five days, respectively, for osmotic potentials of 0 and -15 bars. At 4 C, the onset was delayed eight to nine days and 17 to 19 days, respectively.

Hadas (1969) compared experimental data from other investigators with calculations of imbibition time as affected by contact area and water potential. He concluded that imbibition is little affected by total contact area and total water stress, but that these factors and the specific part of the seed in contact with water may be important during the "triggering" stage which follows imbibition. The "triggering" stage was described by Overbeek (1966) as the stage at which the full metabolic processes of the seed begin, once sufficient water has been imbibed.

Kaufmann and Ross (1970) germinated wheat seeds in soil of different water potentials and temperatures. They covered the seeds with 1 to 2 mm of soil and counted the emerged seedlings. They found no emergence at -14.9 bars potential, although some roots had developed as long as 3 to 5 cm. They compared the germination of seeds in sucrose solutions with that in soil, and found that total germination was unaffected by osmotic potential, although the time required to reach the final number was increased. They reported that temperature had little influence on wheat germination in their study.

Wanjura et al. (1970) presented a model to predict cotton seedling emergence which had good agreement with field results. They used hourly temperatures at the seed depth as the only variable, and evaluated the elongation of the hypocotyl in response to temperature. They also included the possibility of "negative elongation" for temperatures less than 14.44 C, as a means of accounting for prolonged growth inhibition caused by low temperatures. They concluded that "seed level temperature is the chief determinant of emergence time when planting is properly accomplished and no adverse environmental factors, except temperature, occur following planting."

Water movement toward germinating seeds was the subject of an investigation by Dasberg (1971). He measured water uptake from the soil by Oryzopsis holciformis seeds using gamma ray attenuation. He found that the initial water content did not affect the distance from which water was absorbed by seeds. The initial growth of the roots was less affected by the water potential than was the growth of the shoots. Although percent germination was not much changed by different water contents, water uptake as a percentage of the initial weight of the seed increased with higher water contents. These relationships are shown in Figure 2.

Trouse (1971) noted that some seedlings gained as much as ten times their original seed weight prior to emerging from the soil, even though the dry weight of the seedling and seed are reduced as much as 50%. This reduction is presumably the effect of respiration. Trouse emphasized that the enlargement of the embryo before emergence is primarily due to moisture absorption. Sufficient water must be available for the formation of new tissue and for the enlargement of new and old cells in the embryo.

Wheat seed was germinated on the surface of two soils and a semipermeable membrane by Pawloski and Shaykewich (1972). They used water potentials of -0.8, -5.3, -7.8, and -15.3 bars, and held temperature constant at 20 C. There was no difference in germination rate between the membrane and the soils at -0.8 bars, but the rate was reduced on the soils compared to the membrane at -15.3 bars. There was only slight difference between the germination rates on the membrane at different water potentials, whereas the rate was considerably reduced between -7.8 and -15.3 bars on the soils. They felt that the hydraulic conductivity of the media caused these differences. However, the hydraulic conductivity of

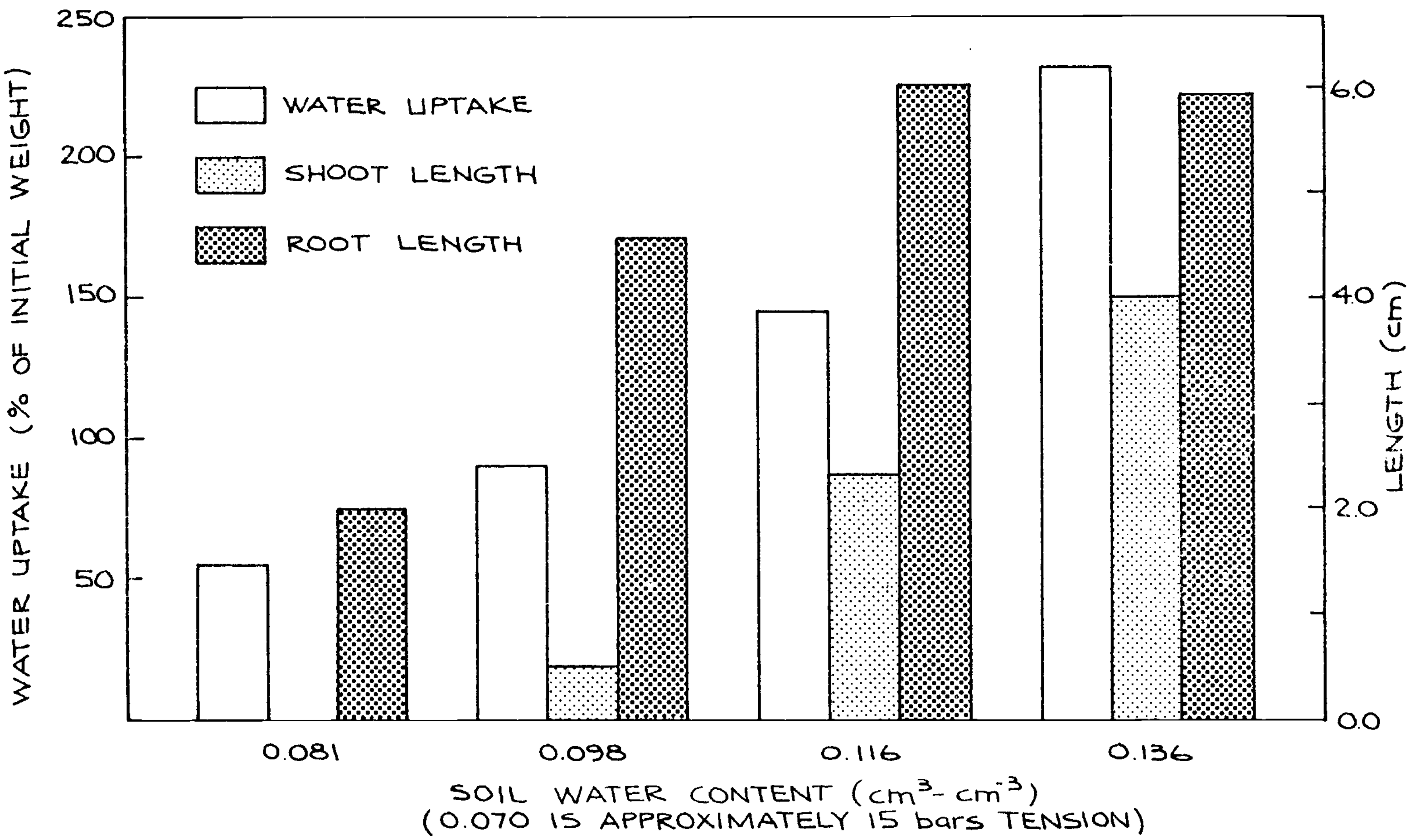

Figure 2. Relative water uptake and length of shoots and roots of Oryzopsis holciformis when germinated in soils of different water content. (Data from Dasburg, 1971.)

one soil was an order of magnitude greater than that of the other at a given water potential, and they found no differences in germination rate between the soils.

Hillel (1972) reviewed soil moisture effects on seed germination. He stated that mean values for water potential in dry seeds often exceed -500 bars, so seeds can absorb water from even very dry soil. However, the volume of soil necessary to supply adequate water for germination is normally much greater than the volume of the seeds themselves, so transport processes in the soil become important. He quoted the figures of Philips for the diffusivity of seeds to water as being about 10^{-4} cm^{2}-hr^{-1}. Since soils have water diffusivities several orders of magnitude greater than this when they are reasonably moist, he concluded that soil water diffusivity probably does not limit imbibition unless the soil is very dry. He suggested that the reduction in contact area with decreasing water potentials has a more important influence on imbibition.

Koller (1972), in another review article, stressed that field conditions are dynamic; the temperature has both a diurnal fluctuation and a general upward or downward trend corresponding to the annual cycle, whereas the water potential of the seed zone also fluctuates and generally decreases with time after planting. The rate of water potential decline will affect the influence of temperature on final germination. The faster the potential decreases, the greater will be the effect of low temperature, so that the optimum temperature for low potentials will be higher than under more optimal conditions. The primary effect of temperature under low moisture potentials is on the lag phase, but with higher water contents, the effect on the rate after the lag phase becomes more important. Koller linked matric potential effects to the moisture diffusivity. He pointed out that the greatest gradient in potential exists at the interface between the seed and the soil, which is also where the largest difference in pore size distribution exists. Much of the seed surface is associated with large pores which drain quickly at low tensions, thereby decreasing the contact area with water. This is the reason fine, lightly compacted seedbeds are best under many conditions. He also mentioned that diurnal cycles of water condensation from deeper layers may occur in the subsurface layers due to nightly temperature inversions.

Ward and Shaykewich (1972) determined the water retention curve of wheat seeds (cultivar Neepawa) as well as the relationship of hydraulic conductivity and diffusivity with water content. Their tabulated data are presented in graphical form in Figures 3 and 4. The sharp increase in diffusivity and conductivity at about -30 bars brings these characteristics into the range of soil water diffusivity and conductivity. They concluded that the early stages of imbibition are limited more by water transport in the seed than by transport

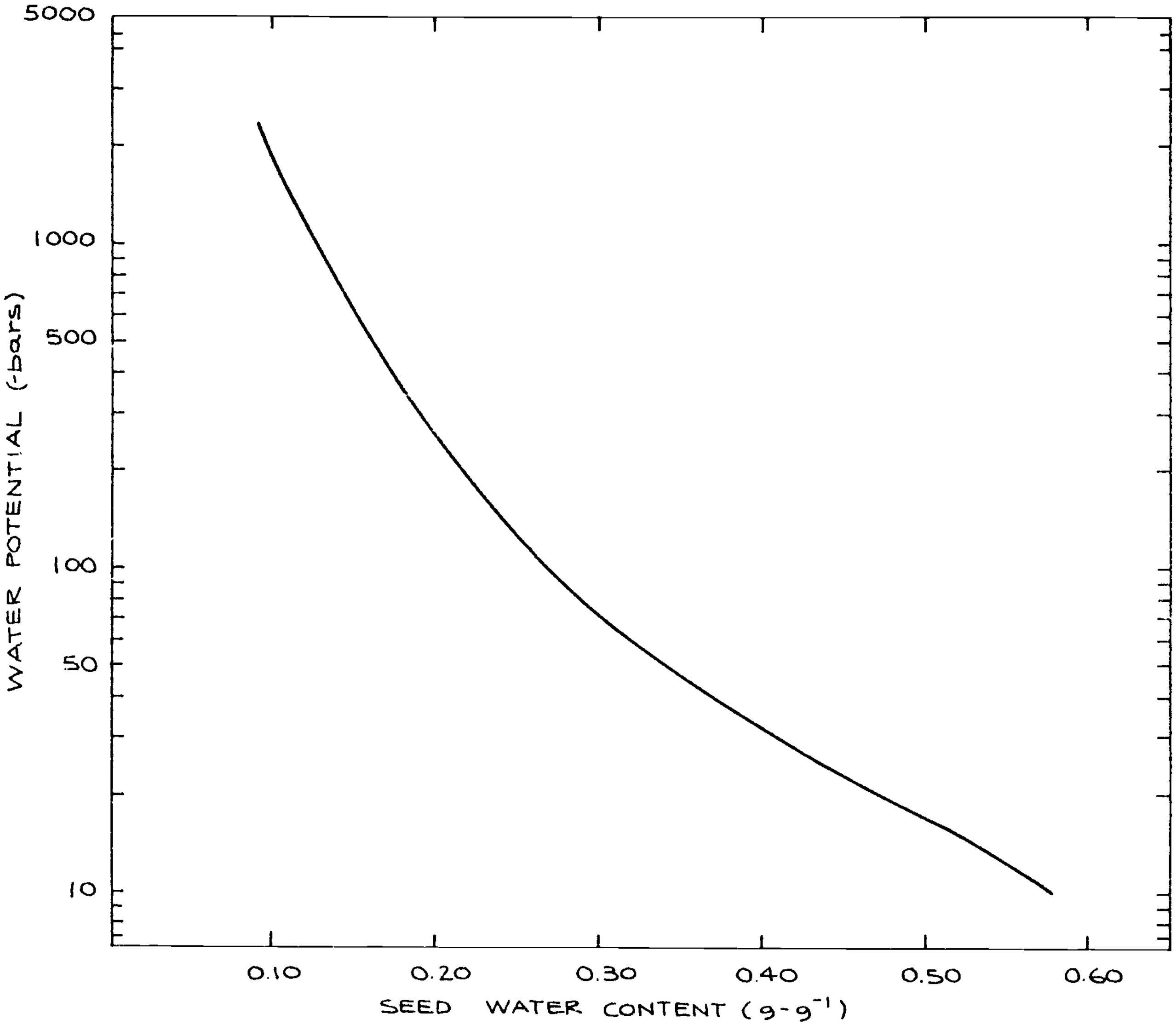

Figure 3. The water characteristic curve of Neepawa wheat. (Drawn from data of Ward and Shaykewich, 1972.)

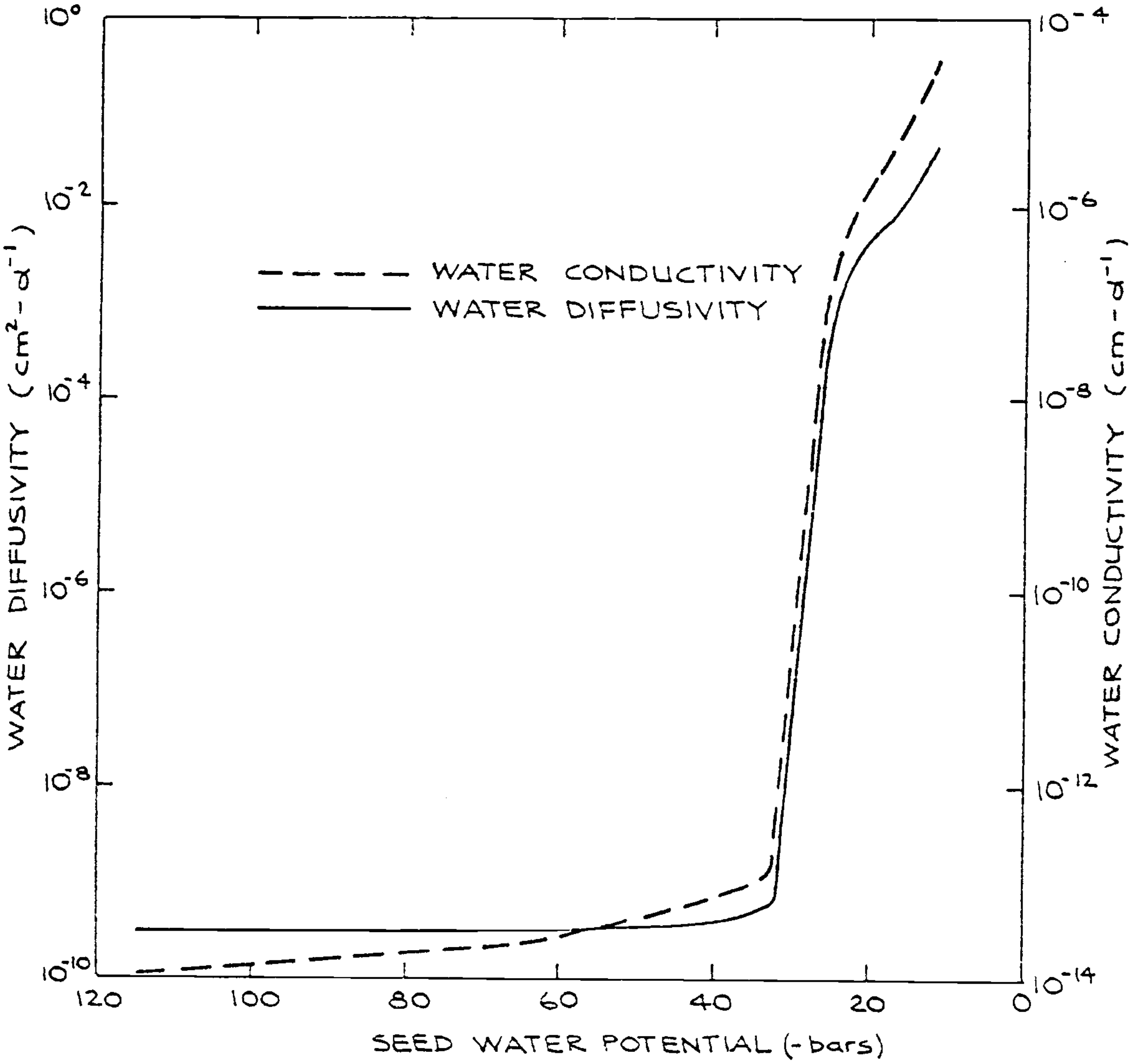

Figure 4. The relationship of hydraulic conductivity and diffusivity with seed water potential of Neepawa wheat. (Drawn from the data of Ward and Shaykewich, 1972.)

through the soil. This change in diffusivity and conductivity may be the result of the attaining a critical moisture content, after which the "triggering" stage can occur.

Singh and Gill (1972), studying dwarf wheat, found that a soil temperature of 20 C and a depth of 4 cm was optimum for seedling development. They found that at 20 C, germination percent, coleoptile length, shoot length, fresh and dry seedling weight, and seedling protein content were maximized. At 15 C, emergence was decreased by 24%, coleoptile length was reduced 1.6 cm, shoot length was decreased 4.5 cm, fresh seedling weight dropped to nearly half that at 20 C, dry seedling weight was reduced 20 mg (almost 20% that at 20 C), protein content declined more than 25% that at 20 C, and chlorophyll content was only slightly more than half that at 20 C.

A review of germination as affected by temperature, aeration, and moisture was presented by Currie (1973). He stated that some seeds may germinate faster when subjected to harmonically fluctuating temperatures than at constant temperatures, and offered a speculative explanation for this phenomenon. He characterized the reaction of germination to temperature to be similar to enzymatic reactions; that is, that the rate changes by some exponential function of the temperature change. The typical formula for such relationships is:

$$R_2 = R_1 \times Q_{10}^{(T_1 - T_2/10)}$$

where R_1 and R_2 correspond to the reaction rates at temperature (T) one and two, respectively, and the Q_{10} is a more or less constant value for each reaction. He presents an example where the Q_{10} for germination is assumed equal to three for a seed exposed to temperature variations of 10 C. For an average temperature, the initial rate is set equal to 1.0, and by reflection, it can be seen that the rate for the temperature fluctuation with the same average is 1.325 (see Figure 5). The same initial rate could be attained by using a constant temperature 2.5 C higher than the original mean.

Hegarty (1973) stated that the rate of germination is closely related to temperature in laboratory experiments, as is the rate of emergence in field experiments. He reported Kotowski's (1926) results with vegetable seeds, that Q_{10} values are higher at low than at high temperatures. The reason for this is that germination is a complicated process, so that each change in temperature will affect different facets of the process differently. He suggested that if a single rate-limiting reaction was occurring, the logarithm of the reaction rate should be directly proportional to the reciprocal of the absolute temperature (the Arrhenius relationship). This is not the case with germination. Hegarty presented graphs of the average seed zone temperature versus the reciprocal of the days to 50% emergence for carrots and other vegetables. The resulting straight line crosses the temperature axis at the theoretical minimum

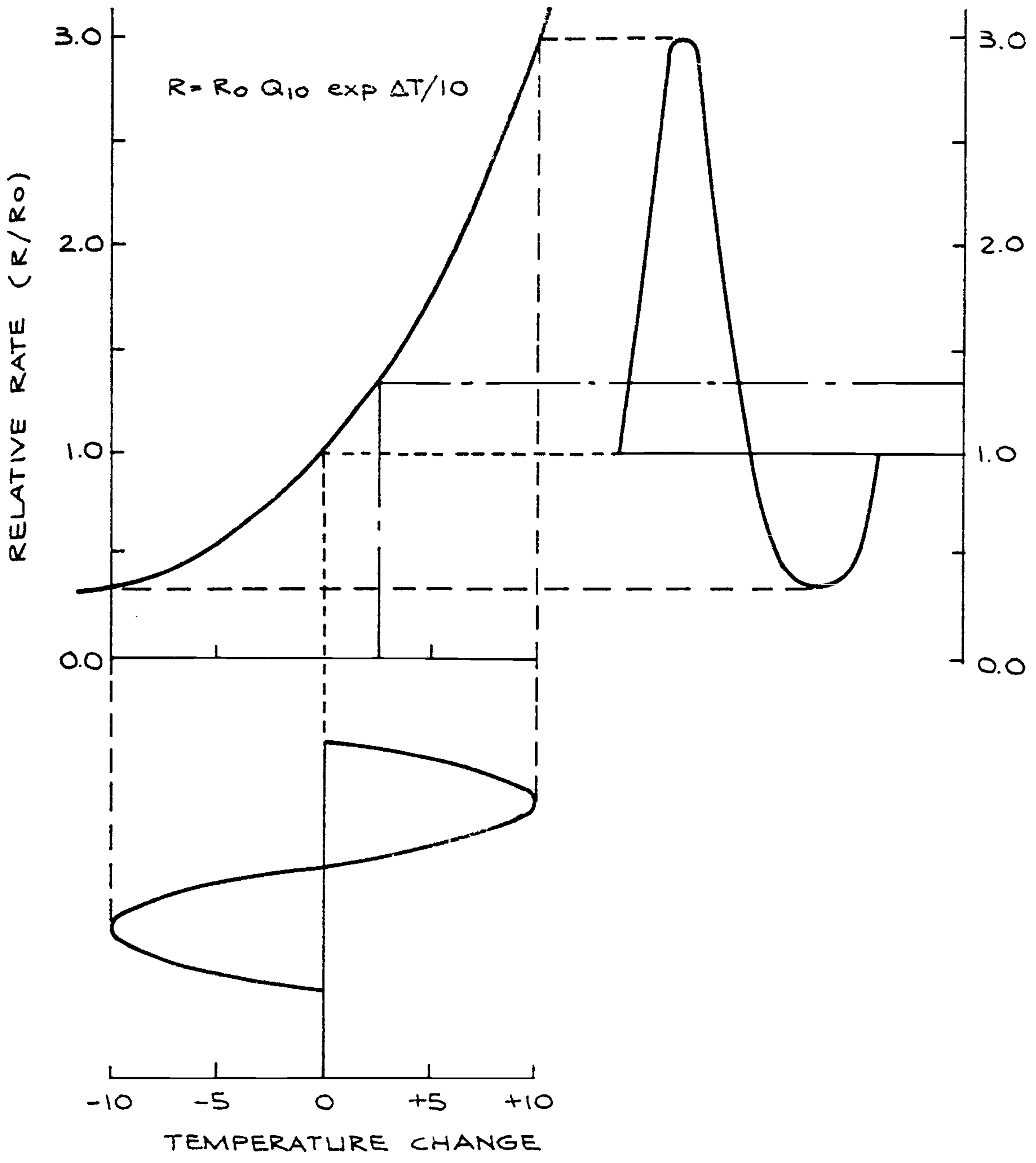

Figure 5. A theoretical representation of the effect of alternating temperatures (lower scale) on the relative rate of germination (graph on right side). The alternating temperature wave is reflected on the graph of reaction (germination) rate versus temperature. The resulting curve has a higher average value than would occur with a constant temperature equal to the average of the temperature wave. By reflection again, this higher relative rate would require an average constant temperature about 2.5 C higher than the average of the alternating wave.

temperature for emergence. He suggested that, since the rates of germination and emergence vary directly with temperature from about 5-25 C for several crops, physical processes may be as important as chemical processes in germination and emergence.

Gulliver and Heydecker (1973) stated that imbibition rate is dependent upon temperature, and is therefore dependent both on biological processes, such as the conversion of reserves, and on the physical moisture gradient. They indicated that low temperatures decrease the uniformity of germination, that is, the variance as well as the mean germination time is increased as temperatures are lowered. This poor uniformity may cause greater competition between plants so that later emerging individuals are crowded out.

Valovich and Grif (1974) published data concerning a laboratory experiment conducted on 33 species and varieties of plants. They attempted to establish the minimum germination temperatures for these species. They found varieties of barley and wheat which germinated (to a total of at least 10% that of the control) at 0 C in 30 to 50 days. In one variety of wheat, the mean daily increment of primary root growth was decreased from 1.55 cm at 20-23 C to 0.07 cm at 0.5 C, and in one variety of barley, from 1.27 to 0.06 cm. They concluded that, in general, growth deceleration is approximately exponential with temperature decreases from 10 to 0 C.

Hadas and Russo (1974a) pointed out that matric potential influences the seed-soil water contact, the potential at the seed-soil interface, and the hydraulic conductivity of the soil. Since the seed will germinate once it has reached a critical value of hydration, and since the rate of water uptake governs to time required for this hydration to take place, these three factors are more important than the matric potential per se. They concluded that in the favorable range of matric potential, seed-soil water contact and the hydraulic conductivity are the principal factors affecting water uptake by seeds. Hadas and Russo (1974b) calculated the aggregate size needed for optimum seed-soil water contact to be 0.1 to 0.2 the diameter of the seed.

Halitligil (1975) showed that the germination rate is lowered as either the temperature or water potential decrease, but that the effect was greater when both decrease. In a laboratory experiment, where wheat seed was planted 2 cm deep, 50% emergence was delayed from 4.1 to 22.0 days by lowering the temperature from 20 to 5 C when the water potential of the silt loam soil was -2 bars. At -17 bars, the same temperature drop caused an increase in the days to 50% emergence from 9.7 to 32.5. In a field experiment, a potential drop from -2 to -7 bars resulted in an increase in days to 80% emergence from 8.6 to 17.8, whereas a decrease in average seed zone temperature from 15.3 to 11.6 C caused an increase from

8.6 to 14.8 days. He noted that water potential had a greater effect in the field than in the laboratory. This was attributed to greater planting depths in the field.

Bhatt and Qualset (1976) conducted a laboratory study of the effect of temperature and variety on coleoptile length. They found that those genotypes with Norin 10 ancestry had mean coleoptile lengths of 43, 46, and 38 mm at 10, 21, and 32 C, while those varieties without the semi-dwarf genes had lengths of 56, 61, and 48 mm at the same temperatures. The semi-dwarf background seemed to impart some stability in coleoptile length over the temperatures used, but the absolute lengths were shorter than is desired for deep planting. They concluded that seedbed preparation is more important with the semi-dwarf wheats because of their reduced emergence potential.

Gul and Allan (1976) studied 93 lines of wheat under moisture potentials ranging from -2.2 to -14.4 bars. In the laboratory, the seeds were planted 3.5 cm deep and the temperature was held constant at 23 C. Seedling emergence was progressively delayed as the potential decreased. The average time for 5% emergence was 66, 92, 162, and 310 hours for potentials of -2.2, -6.0, -10.2, and -14.4 bars, respectively. This represents nearly a doubling of emergence time for each water potential decrease of four bars. Lower potentials also caused increased time for complete emergence, decreased total stand, and reduced early seedling growth. There was a significant line x potential interaction; that is, the best lines at -14.4 bars were poor performers at -2.2 bars, etc. Some lines were apparently well adapted to low water potential. In a field experiment, the line x potential interaction was insignificant. The investigators suggested that the lines studied were more sensitive to water potential differences than to temperature changes.

Lindstrom et al. (1976) presented a model predicting winter wheat emergence as affected by soil water potential, temperature, and depth of planting. In the laboratory, they found that germination rate decreased as the water potential decreased, but that total germination was not affected by potentials as low as -20 bars. They did not get 80% emergence in the laboratory within 20 days with water potentials lower than -10 bars, and suggested this level could not be reached in the field at -6 to -7 bars due to other factors. They felt that the rate of coleoptile elongation is the most important factor influencing emergence rate, because germination *per se* is rarely a limiting factor. They found that the critical water potential increased as the soil temperature increased, and conversely, that wheat would emerge from drier soil at low temperatures than at high. They presented equations for predicting emergence due to temperature or water potential effects alone and in combination, and offered a means of incorporating the depth of planting for depths greater than 3 cm.

Sharma (1976) studied the interaction of water potential and temperature on three range species. At all temperatures (5-50 C) the germination declined with decreasing water potential. The level of water potential at which complete germination did not occur varied with temperature and species. All species were best able to withstand the effects of low potential at their optimum temperatures (20-25 C). The time beyond which no sizable germination occurred increased with decreasing temperature, but was not affected by water potential. Early germination rates were generally faster at higher temperatures and were drastically reduced at very low temperatures, but final germination was not affected to the same degree.

Evans and Bhatt (1977) reported that they found a highly significant correlation between seedling vigor (as indicated by seedling weight 20 days after planting) and seed size.

Conway (1978) found that decreasing the soil moisture reduced the percent stand more at 15 and 22 C than at 8 C, increased the days to 25% emergence, decreased coleoptile length, and reduced ATP levels in the seedling at 22 C (small reductions in ATP content also occurred at 15 and 8 C). Lowering the temperature had more effect on the days to 25% emergence than did lowering the water potential. Days to 25% emergence were significantly correlated with the ATP content of the seedlings (r = -0.88). Coleoptile length was greatest at 8 C, least at 22 C.

Soil Temperature Prediction

If the seed can be placed in moist soil at nearly the optimum time, rapid germination and emergence will occur. However, if planting of winter annual crops is delayed for some reason, decreasing soil temperatures can prolong the time required for stand establishment. In order to establish the average latest date of planting for which adequate stands will be obtained before winter, the average drop in soil temperature must be known. If the soil temperature at the planting depth can be predicted accurately from known parameters, then the latest date to plant can be projected each year for the specific set of climatic conditions occurring that year. Several investigators have attempted to predict soil temperatures; the results of a few are reviewed here.

Wierenga and de Wit (1970) attempted to model soil temperature variations by depth using measured soil surface temperatures as the upper boundary and measured and calculated values of soil physical parameters. The major areas of poor fit with measured temperatures were for soil of intermediate moisture content. They felt that heat transfer processes other than those used in the model, especially the thermal effects of vapor movement due to temperature gradients, caused the discrepancy. The net result of the unaccounted for effects was a decrease in apparent thermal conductivity with temperature.

Bonham and Fye (1970) used simple linear regression to estimate average soil temperatures at 0, 7.6, 15.2, 22.9, and 30.5 cm from daily mean air temperatures or daily mean soil surface temperatures during the winter. They were able to predict the soil temperatures at these depths to within 2.8 C using air temperatures and within 1.7 C using soil surface temperatures. The use of linear regression avoided the necessity of using calculated values of thermal conductivity, which change with water content.

Neild (1971) presented regression equations for estimating soil temperature at 2.5, 5.1, 10.2, and 20.3 cm under bare soil and grass sod using air temperature and the week number of the year beginning in March (as a means of including the lag in temperature response). During the spring, summer, and fall, the standard error of the estimate averaged 1.6, 1.5, and 1.8 C, respectively for the 10.2 cm depth under the bare soil. At the same depth under the bare soil, he noted an average weekly temperature drop in the fall of 1.1 C. He used five years of data collected at a standard U.S. Weather Bureau shelter in the regression model. The coefficients of determination during the spring and fall were no lower than 0.85, whereas in the summer, lower coefficients were obtained.

Date of Planting

Date of planting experiments are often some of the first trials initiated when production research is conducted in a new area or with a new crop species or variety. Generally, it can be said that there is an optimum date of planting in a given environment for a given crop variety, but this optimum date is affected by many factors. Incidence of disease vectors, growth rate of the crop, availability of seed zone moisture, and need for weed control prior to planting are some of the factors which influence the optimum date. The importance of these and other variables changes with location and specific climatic conditions, so recommendations for a particular area are often made so as to include the most optimum range of planting dates for "normal" conditions.

Stephens and Hyslop (1922) reported that, at Moro, Oregon, if sufficient soil moisture was present to insure rapid germination, the highest yields from winter wheat were obtained when planted from mid-September to mid-October. In six years of trials, Turkey winter wheat produced the highest yields when planted on 17 September and 2 October. They suggested that for this area, if a farmer must sow wheat into a "dry" seedbed, higher seeding rates should be used and seeding should occur at least 30 days before freezing weather was expected. If the wheat was planted after mid-October, it frequently did not emerge until spring.

Martin (1926), in a review of experiments conducted throughout the western United States, stated that, although the optimum date for planting winter wheat varied by location, the middle dates (late September to early October) generally produced the highest yields.

In Minnesota, Janssen (1929) reported that late seeding of winter wheat caused delayed root development. Consequently, late-seeded plants were less winter-hardy and were not as able to generate new roots in the spring.

In a Masters thesis, Mallory (1960) presented data concerning the effects of variety, date of seeding, and rate of nitrogen application on the yields of winter wheat at three locations in eastern Washington. He found significant differences in yield from date of planting. The semidwarf varieties responded best to early (5 September) seeding, while tall varieties had highest yields with 3 October seeding. There was less soil moisture under the early seedings than the late (30 October). Earliest dates of planting had highest water use efficiencies. Moisture use was increased by fertilizing the plots. Mallory suggested that, because of the relatively poor emergence of semidwarf varieties when planted deep, there is a need for improved management in order to keep residual soil moisture high in the profile.

Beutler and Foote (1963), working in Pendleton, Oregon, (40 cm annual precipitation) found that standard varieties had higher straw yields when planted early, but that there was no significant change in grain yield. With semidwarf wheats, the grain yield was increased by early seeding but straw yield was decreased.

Cook (1968) reported that infections of Fusarium foot and root rots were highest in early seedings of winter cereals in the drier areas of the Pacific Northwest.

On dryland plots (25-36 cm annual precipitation) in Utah, Dewey and Nielson (1969) obtained maximum yields of winter wheat with early to mid-September planting dates. Less soil moisture was used in the 90-150-cm depth by September and October plantings than by wheat planted earlier.

Pehlivantürk (1976) conducted a field plot experiment at Moro, Oregon. He used two surface treatments: bare fallow, and bare fallow with 2400 kg/ha straw mixed into the surface with a rod-weeder. He planted winter wheat and barley on several dates from 14 August to 1 November, and recorded the soil temperature in the seed zone beginning at planting. He found no significant differences in grain yield between bare and straw mulched plots. There was a significant reduction in stand (plants per m^2) and a slight delay in emergence in the mulched plots. There were highly significant differences in yield between planting date; the highest yields were obtained from the 11 October date. No differences in yield were found for the dates between 30 August and 11 October. He also reported a rapid temperature drop which occurred in late September and October. Average monthly temperatures at the seed zone were 22, 17.2, 10.5, and 5.2 C for August, September, October, and November, respectively.

Papendick and Miller (1977) reported that, although early plantings in the dryland regions of the Pacific Northwest can effectively protect the soil against wind and water erosion, several problems can occur. First, root and foot rot diseases tend to attack early planted populations. Second, there can be insufficient moisture for sustained growth through the crop season. Third, excessive fall vegetative growth can make the plants more susceptible to winter and spring freezing damage.

Cook and Waldher (1977) investigated the effects of stubble mulching on the incidence of Cercosporella foot rot in winter wheat. They found that as plant size and vigor in the fall increased, so did the severity of this disease. They noted that stubble mulched plots had poorer stands and apparently lower vigor than the bare fallow plots, and the stubble mulched plots also had a higher incidence of weeds.

MANUSCRIPT I

Losses of Soil Water During Fallow in the Pacific Northwest

ABSTRACT

Farmers in the fallow-crop rotation area of the Pacific Northwest depend on residual seed zone moisture for early, vigorous stand establishment in the fall. Although losses of stored water during the summer of the fallow period are small and seed zone moisture content remains relatively high, there appears to be a rapid drop in the level of soil moisture in early fall. This study was conducted to quantify soil water content changes in the fallow during late summer and fall, and to determine the cause of any observed accelerated losses. The hypothesis was that increasing nighttime vapor pressure gradients from the moist soil of the seed zone to the soil surface cause larger losses than replacement from deeper layers can accommodate. These gradients could be caused by the combination of warm days and cool, clear nights characteristic of August and September. Four tillage treatments (moldboard plow and sweep plow, each in combination with shallow or deep rodweeding) were established on a Walla Walla silt loam (a mixed, mesic Typic Haploxeroll) during the fallow-crop periods of 1975-1977 and 1976-1978. Soil samples of the 0-150-cm profile were taken at monthly intervals from May through October in 1976; samples of the 0-30-cm profile were taken at more frequent intervals from August through November in 1976 and 1977. Soil temperatures at 6-cm intervals to 30 cm (1976) and at 1-3-cm intervals to

45 cm (1977) were automatically recorded at two-hour intervals from August through November. July and August of both 1976 and 1977 were wetter than normal, as was September 1977, and skies were frequently cloudy. Periods of significant moisture loss occurred in 1976; at 6 cm, the loss period was 4-16 September, and at 9-18 cm, significant losses occurred from 16 September to 2 October. Frequent precipitation in 1977 caused increases in water content throughout the 30-cm profile. Vapor pressure gradients were calculated for selected days in 1976, but no correlation with the periods of significant loss was found. Frequent rewetting of the surface mulch by rain and increased minimum air temperatures during July and August may have reduced the variation in the vapor pressure gradient. Average temperature profiles of the soil indicate that loss of water was not enhanced by temperature gradients. Losses of stored soil moisture from late May to early October were only 6 and 7%, respectively, for the bare fallow (moldboard plow) and stubble fallow (sweep plow) plots. However, there was a significant redistribution of water in the profile. A computer program which simulated one-dimensional isothermal liquid flow was used to determine the relative contributions of evaporation and redistribution to the water content changes observed below the seed zone in July and August 1977. From 13 July to 4 August, redistribution accounted for only 60% of the

observed 0.25 cm water loss in the 17-30-cm profile. None of the 0.11 cm loss from 4 August to 1 September was accounted for by redistribution. Consequently, 0.21 cm of water moved from the 17-30-cm profile into the seed zone during the total period, presumably to replace water lost through evaporation. Despite the abnormally wet and warm seasons during which this study was conducted, significant losses of soil profile water were observed in 1976. The calculations indicate that redistribution of water below the seed zone may be a significant factor in the observed losses. Redistribution occurring throughout the summer may not be manifested as visually noticeable drying of the seed zone until some critical water content is reached, or until evaporative losses exceed the replacement rate. Manipulation of the mulch to decrease evaporative losses during late summer may help maintain adequate moisture for rapid germination and stand establishment.

Additional index words: Evaporation, fallow efficiency, fallow tillage, seed zone moisture, simulation, soil temperature, unsaturated flow, vapor gradients, water redistribution.

INTRODUCTION

The time of stand establishment of winter cereals in the fallow-crop rotation area of the Pacific Northwest affects both grain yield and erosion control (Stephens and Hyslop, 1922; Beutler and

Foote, 1963; Cochran et al., 1970). The rate of emergence and stand establishment of crops in this winter rainfall region depends on the presence of sufficient residual moisture in the seed zone and on the temperature conditions in the upper soil profile after planting. Soil moisture stored during the winter months of the fallow period is maintained near the soil surface through the warm, dry summer by the use of a dust or stubble mulch (Papendick et al., 1973). Losses of the stored moisture during the summer months are relatively low (Leggett et al., 1974; Papendick and Miller, 1977).

In the lower rainfall areas, the general consensus is that the loss rate is accelerated in late summer. Some farmers, extension agents, and scientists have observed that the level of adequate soil water for rapid germination and emergence drops from a depth of 8-12 cm to 15-20 cm over a period of one to two weeks in late August and early September. This necessitates either deeper planting to reach sufficient soil moisture for germination, or delayed seeding until fall precipitation has rewet the seed zone (Leggett et al., 1974). Both practices can result in late, less vigorous stands which have lower yield potential and provide less protection against soil erosion (Cochran et al., 1970; Leggett et al., 1974). Seeding before the accelerated loss occurs results in well-established stands if soil temperatures are not too high, but if planted too early, crops often produce lower yields due to excessive water use (Stephens and Hyslop, 1922). Diseases such as Cercosporella foot rot and barley yellow dwarf can also limit yields of early planted crops (Bruehl, 1961; Cook and Waldher, 1977).

Many studies have been conducted to determine the effects of mulching on seedbed water loss (McCall, 1925; Lemon, 1956; Papendick et al., 1973); others report that little evaporative loss of stored soil moisture occurs over summer in the Pacific Northwest (Leggett et al., 1974; Lindstrom et al., 1974; Papendick and Miller, 1977). No information reporting the occurrence of an accelerated water loss period was found in the literature.

The objectives of this study were to determine if an accelerated loss of water from the seed zone occurred, and determine the possible causes of the loss. My theory was that slow, rather constant evaporative losses from the seed zone occur during summer; these small losses are replaced by upward liquid flow from the soil beneath the seed zone. In late summer, the combination of warm days and cool, clear nights characteristic of the region causes increased nighttime vapor pressure gradients from the moist seed zone to the soil surface. Replacement through liquid flow cannot compensate for the increased losses, and consequently, the seed zone dries out.

MATERIALS AND METHODS

Field plots were established at the Sherman Unit of the Columbia Basin Agricultural Research Center on a Walla Walla silt loam soil (a mixed, mesic Typic Haploxeroll) during the fallow-crop periods of 1975-1977 and 1976-1978. The field plot design was split-plot (Petersen, 1976); the main plots were standard bare fallow (moldboard plow used for initial tillage in April) and standard stubble fallow (sweep plow or disk used for initial tillage in April). The main plots were split and two depths of soil mulch were created in each using a rodweeder at shallow (7-10 cm) or deep (10-15 cm) settings. Four surface conditions were established with these tillage treatments:

1) Bare fallow, shallow mulch -- moldboard plow (15-20 cm deep) followed by secondary tillage with a disk or sweep, and shallow rodweeding (7-10 cm).
2) Bare fallow, deep mulch -- moldboard plow (15-20 cm deep) followed by secondary tillage and deep rodweeding (10-15 cm).
3) Stubble fallow, shallow mulch -- sweep plow or disk (10-15 cm deep) followed by secondary tillage and shallow rodweeding (7-10 cm).
4) Stubble fallow, deep mulch -- sweep plow or disk (10-15 cm deep) followed by secondary tillage and deep rodweeding (10-15 cm).

The mulch depths were maintained at their respective levels during three summer rodweeding operations.

Soil samples of the 0-150-cm profile were taken in 15-cm increments at monthly intervals from late May through October in 1976. Samples from the 0-30-cm profile were taken in small increments (1-6 cm) at intervals from ten days to one month from mid-summer to late fall in both years. Soil water content of the samples was determined gravimetrically.

Thermocouples were inserted at depths of 2, 6, 12, 18, 24, and 30 cm under all tillage treatments in early August, 1976. Soil and air (1 m above the soil surface) temperatures were recorded by a PPM datalogger at two-hour intervals until mid-November. In 1977, thermocouples were placed at much closer intervals (1-3 cm) to a depth of 45 cm in the upper soil profile of the bare and stubble fallow, shallow mulch plots, and temperatures were monitored continuously on a Honeywell strip-chart recorder from mid-August through November. Measurements for each depth represented the average of four thermocouples wired in parallel spaced about 30 cm apart horizontally. Other climatic data (daily precipitation, air and 10-cm soil temperature, relative humidity, and cloud cover conditions) were acquired from the records of a standard U.S. Weather Bureau shelter about 1 km from the plots.

The fall and winter of 1976-1977 were extremely dry. In order to have near normal subsoil moisture conditions during the following summer, the plots were sprinkler irrigated during March and April, 1977. Three applications of water (4, 4, and 3 cm) about two weeks apart were made over periods of five to six hours to simulate rainfall. Uniformity of application was hampered by windy conditions.

A soil water characteristic curve for the upper soil profile was determined by pressure plate, pressure membrane, and vapor equilibrium techniques. Bulk density measurements of the profile were made using standard gravimetric techniques. Approximate vapor pressures at the soil surface and the 12-cm depth were calculated using air and soil temperature and moisture measurements.

Statistical analyses of the soil water data were made according to Petersen (1976), and his conservative approximate significant difference (ASD) and the "protected" LSD were used to detect differences between means.

RESULTS AND DISCUSSION

Temperature and precipitation for monthly periods during the study are shown in Table 1. The number of cloudy and partly cloudy days in the months of July through November, 1976, were 19, 22, 13, 21, and 25, respectively. Fewer such days are normally expected, especially in July and August. Precipitation in

Table 1. Air temperatures, 10-cm soil temperatures, and precipitation for designated months of 1976 and 1977 compared to long-term averages.

	Month				
	July	Aug	Sept.	Oct.	Nov.
Air Temperature (C)					
Maximum					
Average (1963-77)	27.8	27.2	23.1	16.4	8.7
1976	26.1	24.3	24.4	23.4	9.4
1977	26.1	29.9	20.0	16.3	7.1
Minimum					
Average (1963-77)	12.2	10.8	7.9	2.6	0.0
1976	15.5	14.2	12.1	4.2	0.9
1977	11.7	13.2	6.4	2.3	-3.2
10-cm Soil Temperature (C)					
Maximum					
Average (1963-77)	-	29.4	24.2	15.8	6.9
1976	-	26.1	24.1	16.5	8.1
1977	-	30.0	21.4	15.4	6.3
Minimum					
Average (1963-77)	-	19.1	14.5	8.2	3.3
1976	-	17.4	16.7	9.9	4.7
1977	-	22.4	14.1	8.7	3.2
Precipitation (cm)					
Average (1912-76)	0.5	0.6	1.6	2.4	4.3
1976	2.0	3.0	0.1	0.2	1.1
1977	0.9	2.3	2.2	0.6	5.1

August and September, 1977, was sufficient to rewet the soil mulch to the seed zone and below, and caused soil water content changes throughout the 30-cm profile (Figure 1).

There were significant losses of soil water to a depth of 22 cm over time in 1976 (Figure 2). These losses occurred from 4-16 September at 6 cm, and from 16 September to 2 October at deeper levels. There were significant differences in soil water content to a depth of 22 cm due to methods of tillage. At some levels, the differences were due to mulch depth; at other levels, differences were due to mulch type. Values averaged over tillage treatments are presented in Figure 2. A significant date of sampling x tillage treatment interaction occurred at 22 cm, so the values from this depth are omitted in the graph. Due to a change in sampling technique, it is possible that the water content change at 6 cm is not actually a loss, but is the result of including less moist soil from the next increment.

Using the soil water desorption characteristic curve, the change in water content at 9 cm from 16 September to 2 October was equivalent to a change from -3.7 to -7.8 bars; the change at 12 cm from -1.1 to -1.7 bars. Farmers in this area use deep furrow drills to place seed at 12-15 cm in residual moisture, and the change in water potential observed at 12 cm would probably not affect germination, emergence, and stand establishment (Lindstrom

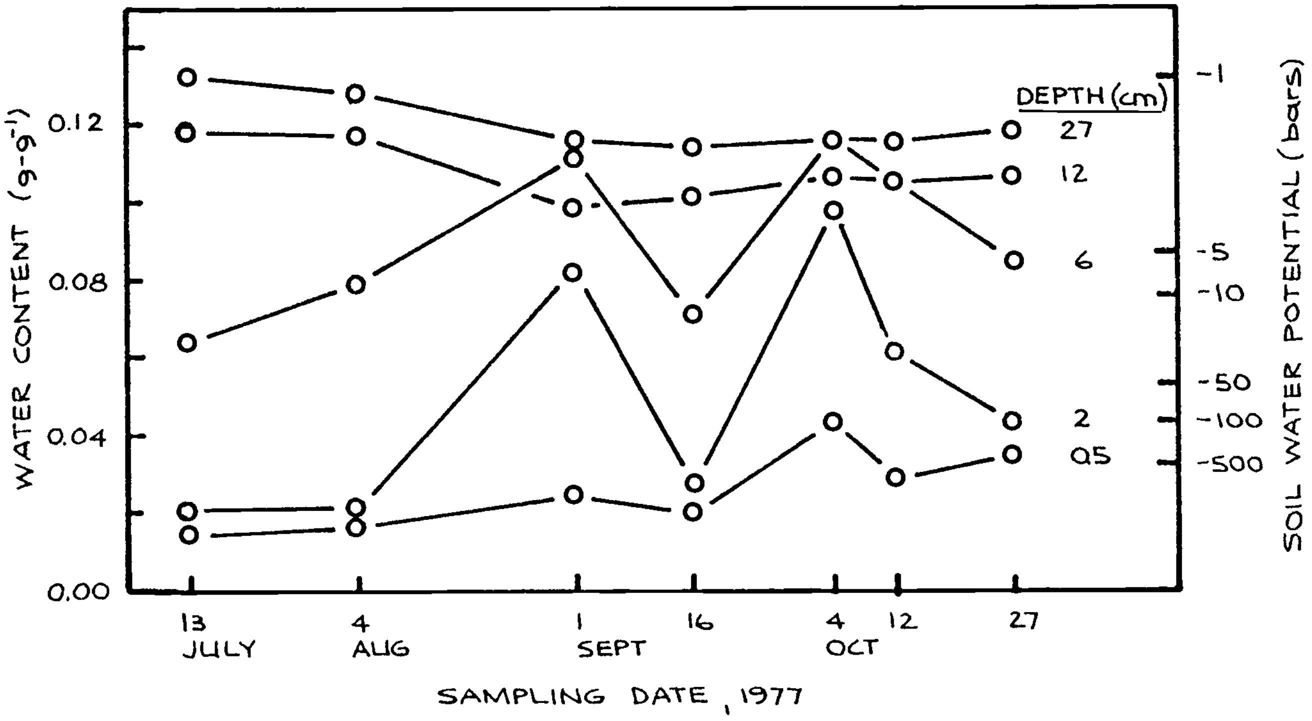

Figure 1. Gravimetric soil water content and potential as a function of time for selected depths under the stubble fallow, deep mulch treatment (1977).

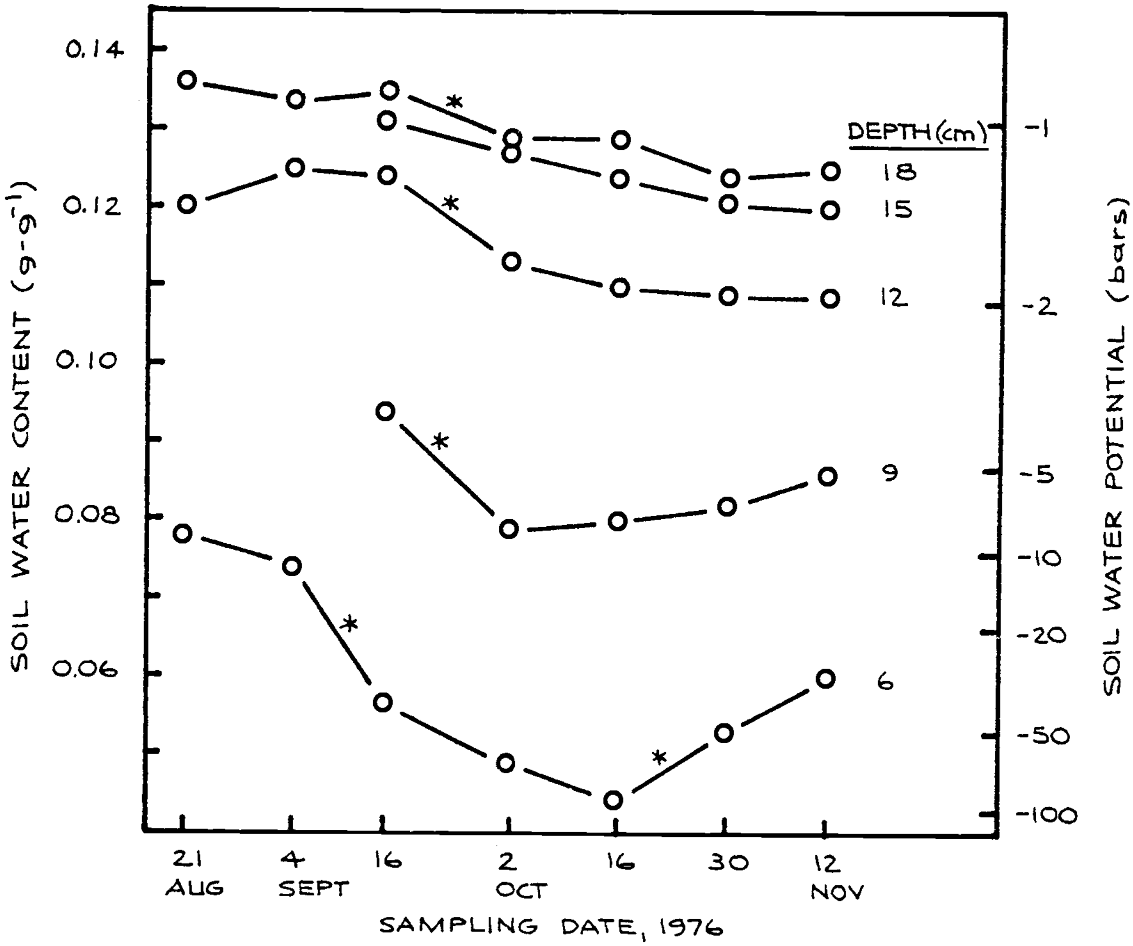

Figure 2. Gravimetric soil water content and potential as a function of time and depth averaged over all tillage treatments. Significant ($p = 0.05$) water content changes are indicated by an asterisk.

et al., 1976). If vapor movement from the seed zone to the atmosphere is an important mechanism by which water loss occurs, the cloudy, wet conditions in 1976 would have reduced the losses. Higher than normal minimum air temperatures and precipitation in July and August would reduce the vapor pressure gradient and therefore decrease vapor movement toward the surface. Cloud cover had the effect of increasing nightly soil surface temperatures, which would also reduce the vapor pressure gradients at this time.

Loss of Water by Vapor Transfer

An attempt was made to elucidate the importance of vapor movement by calculating the vapor pressure gradient for several days (Table 2). The relative humidity and temperature of the air and soil were used to calculate the absolute vapor pressure at four-hour intervals on several dates in 1976. The gradient was considered to extend from a zone with 100% relative humidity at 12 cm to the soil surface, regardless of the actual moisture conditions in the profile. It was assumed that complete mixing of the atmosphere occurred, so the calculated vapor pressure at 1 m would represent that at the soil surface. It was also assumed that the soil atmosphere was saturated at the 12-cm depth, since the measured water potential was not lower than -3 bars under any tillage treatment. The 12-cm temperature was used to calculate the

Table 2. Calculated vapor pressure gradients (mm Hg-cm^{-1}) under tillage treatments on selected dates in 1976. Treatment codes: PS = moldboard plow, shallow mulch; PD = moldboard plow, deep mulch; SS = sweep plow, shallow mulch; SD = sweep plow, deep mulch. Missing values are indicated by a dash.

Date	Tillage Treatment	Hour					
		2400	0400	0800	1200	1600	2000
17/8	PS	0.5	-	0.3	0.2	0.5	0.5
	PD	0.4	-	0.3	0.3	0.6	0.4
	SS	0.5	-	0.4	0.3	0.6	0.5
	SD	0.4	-	0.3	0.2	0.6	0.5
22/8	PS	0.6	0.6	0.5	0.5	1.0	0.7
	PD	0.7	0.8	0.6	0.6	-	0.7
	SS	0.6	0.6	0.5	0.4	1.1	0.8
	SD	0.7	0.6	0.5	0.3	0.9	0.8
26/8	PS	0.4	0.5	0.3	0.3	0.6	1.0
	PD	0.4	0.5	0.3	0.3	0.9	1.1
	SS	0.4	0.6	0.4	0.4	0.6	0.9
	SD	0.4	0.6	0.3	0.4	0.6	0.9
1/9	PS	0.7	0.4	0.4	0.2	0.4	0.8
	PD	0.6	0.2	0.3	0.4	0.4	1.0
	SS	0.6	0.3	0.3	0.2	0.4	0.8
	SD	0.6	0.3	0.4	0.2	0.4	0.8
5/9	PS	0.3	0.2	0.4	0.4	0.6	0.6
	PD	0.3	0.3	0.4	0.4	0.7	0.6
	SS	0.3	0.3	0.4	0.5	0.6	0.7
	SD	0.3	0.2	0.3	0.3	0.6	0.7
10/9	PS	0.7	0.7	0.4	0.2	0.4	0.8
	PD	0.7	0.5	0.5	0.5	0.8	0.9
	SS	0.7	0.6	0.4	0.2	0.5	0.7
	SD	0.7	0.6	0.4	0.3	0.4	0.8
16/9	PS	0.4	0.2	0.2	0.2	0.3	0.2
	PD	-	-	0.1	0.2	0.4	0.2
	SS	0.3	0.2	0.1	0.1	0.2	0.2
	SD	0.4	0.2	0.1	0.1	0.2	0.2

(Continued on next page)

Table 2. (Continued)

Date	Tillage Treatment	Hour					
		2400	0400	0800	1200	1600	2000
21/9	PS	0.5	0.4	0.2	0.1	0.2	0.3
	PD	0.6	0.5	0.2	0.3	0.2	0.4
	SS	0.5	0.4	0.3	0.1	0.2	0.3
	SD	0.6	0.5	0.3	0.1	0.2	0.3
26/9	PS	0.4	0.5	0.5	0.2	0.3	0.6
	PD	0.4	0.5	0.4	0.1	0.3	0.5
	SS	0.5	0.4	0.5	0.1	0.4	0.5
	SD	0.5	0.4	0.5	0.1	0.4	0.6
1/10	PS	0.5	0.5	0.3	0.1	0.4	0.4
	PD	0.4	0.5	0.4	0.2	0.4	0.4
	SS	0.4	0.5	0.3	0.1	0.3	0.4
	SD	0.4	0.4	0.4	0.1	0.4	0.5
7/10	PS	0.4	0.5	0.2	0.2	0.4	0.5
	PD	0.3	-	0.2	0.2	0.5	0.6
	SS	0.4	0.5	0.2	0.3	0.4	0.5
	SD	0.4	0.5	0.2	0.2	0.4	0.5
16/10	PS	0.6	0.4	0.3	0.1	0.3	0.5
	PD	0.6	0.4	0.4	0.2	0.3	0.6
	SS	0.6	0.5	0.4	0.1	0.4	0.5
	SD	0.6	0.5	0.4	0.1	0.3	0.5

saturated vapor pressure at that level. The smallest gradients generally occurred during the day; the largest gradients occurred at night.

This calculated gradient gave an estimate of the magnitude of the driving force for vapor movement on the selected dates. A measure of the actual gradient as the evaporation zone changed over time would have been more accurate, but the depth of this zone was not known precisely, nor were temperature measurements made at sufficiently small depth increments to estimate this dynamic quantity. One would generally expect larger vapor pressure gradients to occur on days during periods of significant water loss. However, this correlation was not found. There was also no correlation between increased water loss from the profile and the occurrence of low minimum temperatures near the soil surface at night.

When soil temperature is averaged over time and plotted for different depths, the resulting graph indicates the direction of net heat flow in the profile (Papendick et al., 1973). Because both liquid and vapor phase transfer of water is influenced by temperature (Cary, 1966), the graph should also indicate the direction of thermally-induced water movement. Temperature at different depths was averaged over two-week periods corresponding to the intervals between moisture sampling (Figure 3). During the first three periods between sampling, the average temperature at 2 cm

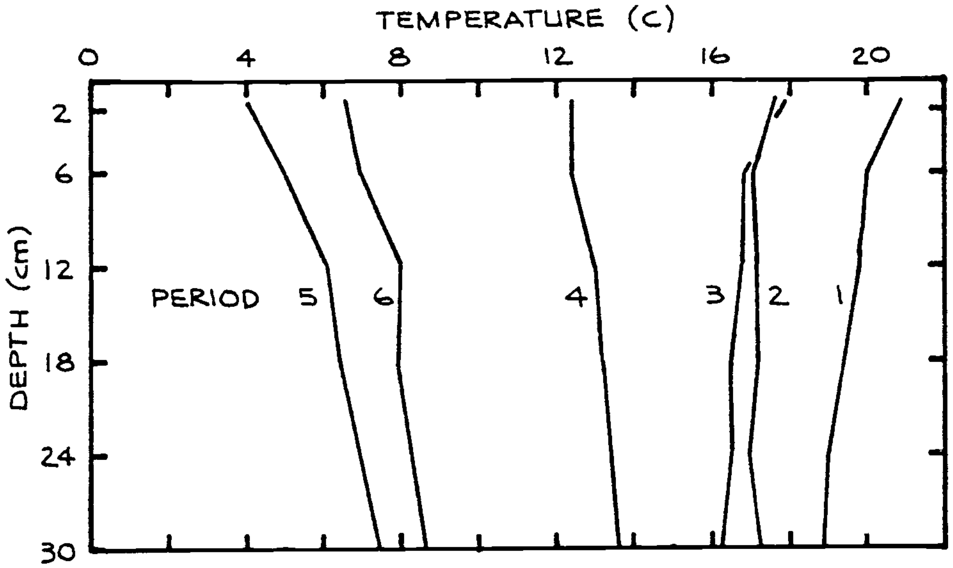

Figure 3. Average soil temperatures for two-week periods beginning 15 August 1976.

was greater than at deeper levels; there was little difference between the temperature at 6 and 12 cm. One could expect a net transfer of water from 12 to 6 cm since there was a matric potential gradient in that direction, but the flux would apparently not be enhanced by temperature gradients. During the last three periods, the average temperature gradient would have favored liquid and vapor transfer from 12 cm toward the surface, but significant losses were not observed during this time. During late October and early November (periods 5 and 6 in Figure 3), the soil water content at 6 and 9 cm increased. Precipitation was received on 25 October (0.25 cm) and 1 November (0.28 cm). Since little precipitation occurred, water must have moved up through the 12-cm layer from 18 cm or deeper. This movement would have been favored by matric potential gradients and the average temperature gradient. Farmers often wait for the moisture to "rise" if the seedbed was too dry for planting in the optimum range of dates from mid-September to early October. This phenomenon may be explained by the occurrence of thermally-enhanced water flow along matric potential gradients.

Redistribution

Bare fallow and stubble fallow plots lost 1.8 and 1.4 cm of water, respectively, in the 0-150-cm profile from late May to early October. These losses represent only 6 and 7% of the stored moisture in late May. Fallow efficiency for the summer months is defined as the sum of the stored soil moisture at the beginning of the summer and the precipitation occurring during summer, divided by the stored moisture at planting in the fall, multiplied by 100. For the 26 May to 2 October period, both tillage treatments had fallow efficiencies of 77%. This substantiates the findings of others who reported only low moisture losses during the summer in the Pacific Northwest (Leggett et al., 1974; Papendick and Miller, 1977). However, marked changes in the distribution of soil moisture occurred.

Changes in the soil water content of the 0-150-cm profile show a pattern typical of water redistribution in response to matric potential gradients (Figure 4). The losses observed in the deeper levels of the 0-30-cm profile (Figures 1 and 2) may be due to water redistribution deeper in the profile. As the soil below the seed zone loses water because of downward and upward movement due to potential gradients, replenishment of water lost from the seed zone becomes slower. Losses by evaporation from the seed zone will therefore become more apparent as replacement becomes limited by decreasing hydraulic conductivity and lowered reserves in the soil immediately beneath the seed zone.

In an attempt to make an initial estimation of the influence of redistribution in the profile, a computer program involving a numerical solution to the flow equation was used.[1] In this program, top

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[1] The computer program, developed by Michael Ungs, Suntaree Yingjajaval, and Larry Boersma, Soil Science Department, Oregon

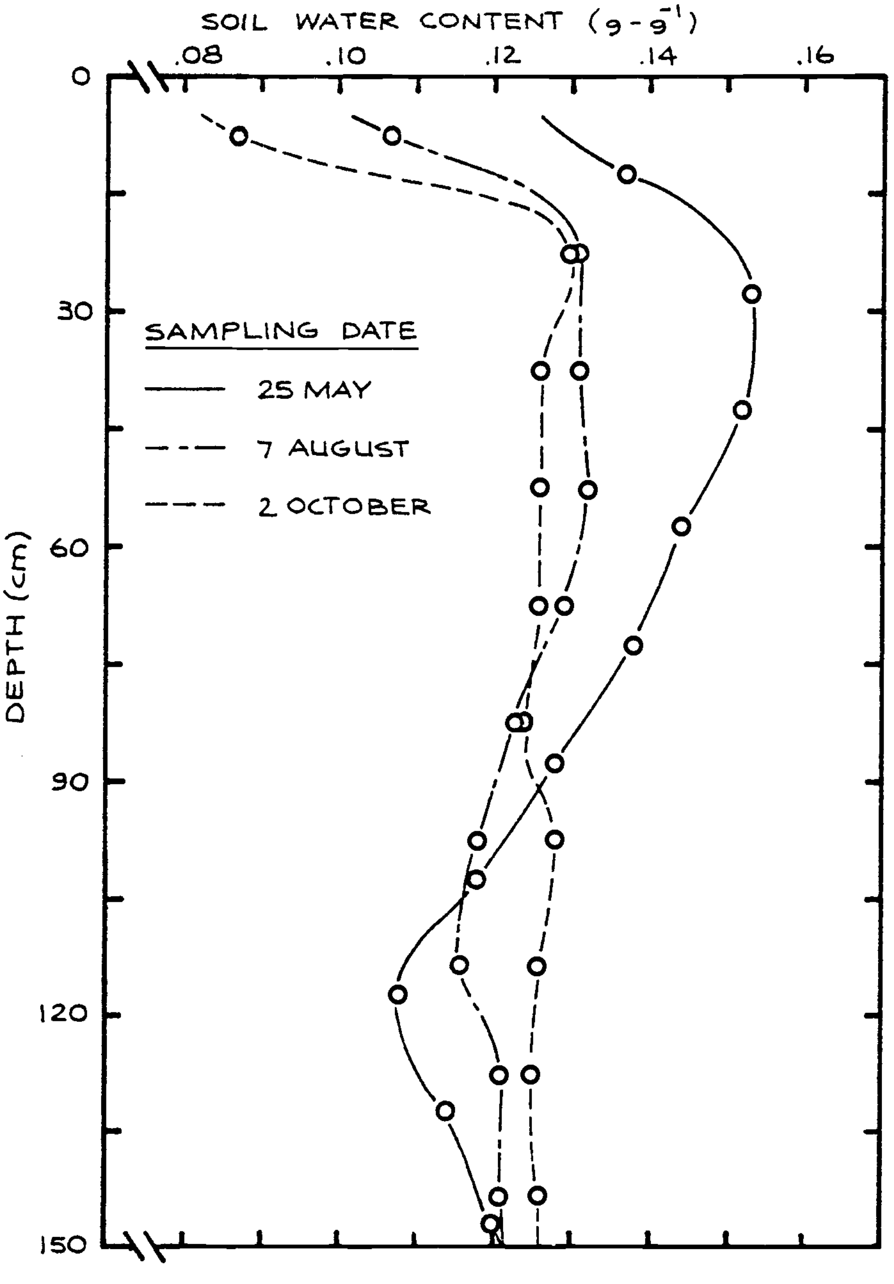

Figure 4. Gravimetric soil water content by depth on three dates during fallow, 1976. Data points are averages of bare and stubble fallow tillage treatments.

and bottom boundary conditions can be specified to simulate conditions such as steady-state infiltration, evaporation, or the presence of a water table. Because the bulk density changed considerably with small changes in depth from the surface to 17 cm (Figure 5), the top boundary was placed at 17 cm. In order to discern the effect of redistribution alone, no evaporation or infiltration was allowed to occur at the top boundary.

Measured values of gravimetric water content in one treatment on three dates during 1977 were multiplied by the bulk density to obtain the volumetric water content. The curves were extended beyond the 30-cm depth with volumetric water content values from similar dates in 1976, because deep samples were not taken in 1977. The functions of hydraulic conductivity (K) and diffusivity (D) versus water content (θ) were calculated from curves of a similar soil, since the actual functions for the Walla Walla soil were not available. For the range of water contents representing -0.3 to -6.5 bars potential, the assumed functions were:

$$K(\theta) = 1.59396\ \theta^{6.78196}\ \text{cm-hr}^{-1}$$

$$D(\theta) = 11513.875\ \theta^{5.15523}\ \text{cm}^{2}\text{-hr}^{-1}$$

State University, is based on the equation for one-dimensional isothermal liquid flow in a homogeneous profile.

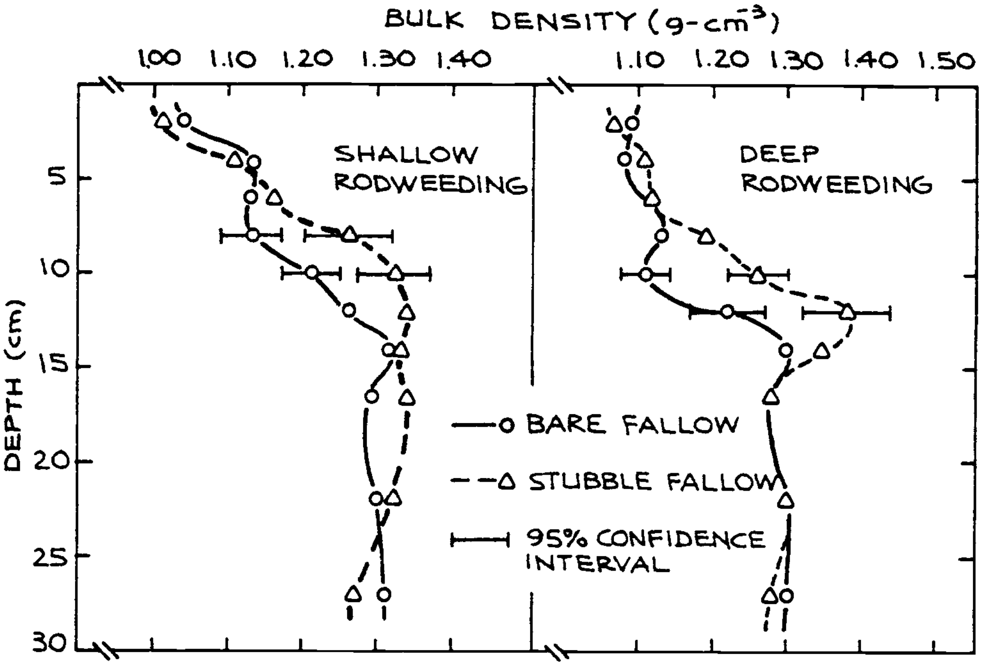

Figure 5. Bulk density profiles for four tillage treatments in 1977.

There were several potential sources of error in this calculation, including the lack of isothermal conditions, the lack of true homogeneity in the actual profile, and the assumed K(θ) and D(θ) functions. However, as a first approximation, the results are indicative of the relative contributions of upward and downward liquid flow in the soil below the seed zone.

From 13 July to 4 August, a total of about 0.25 cm (0.012 cm-d^{-1}) of water was lost from the 17-30-cm profile of the bare fallow, shallow mulch treatment. The loss represents 10.6% of the total water stored in this 13-cm segment on 13 July. Of this loss, about 0.10 cm was unaccounted for by redistribution induced by water potential differences alone. Therefore, about 40% of the water loss in this part of the profile was probably due to upward flow, presumably to replenish evaporative losses from the seed zone. From 4 August to 1 September, however, redistribution alone accounted for none of the observed losses in this section of the profile, although the simulation did predict a change in the water content profile. The total loss for this period was only 0.11 cm (0.004 cm-d^{-1}). This represents 5.2% of the stored soil water in the 17-30-cm portion of the profile on 4 August. The average daily loss rate during the second period was only one-third that during the first.

There are at least two reasons for the lower losses in August. First, precipitation was plentiful during August (Table 1) and the amounts and pattern of rainfall occurrences kept the mulch wet or moist during the last half of the month. This condition would have decreased the evaporative demand and the vapor pressure gradient from the seed zone to the soil surface. Smaller losses from the seed zone would reduce the demand for water from deeper layers. Second, hydraulic conductivity and diffusivity decrease as water content decreases. On 13 July, calculated values of $K(\theta)$ and $D(\theta)$ at 30 cm were 1.7×10^{-5} cm-hr^{-1} and 1.9 cm^{2}-hr^{-1}, respectively; on 4 August, these values were 8.2×10^{-6} cm-hr^{-1} and 1.1 cm^{2}-hr^{-1}. The decrease in these values also explains some of the reduction in losses from the 17-30-cm zone in August. Because rainfall began increasing the water content of the soil beneath the seed zone after early September, further simulation tests were not conducted.

CONCLUSION

It is apparent that the two seasons during which this study was conducted were not typical. Nevertheless, significant losses of seed zone soil moisture were observed in 1976. The original hypothesis that these accelerated losses result from increasing vapor pressure gradients due to lower nighttime soil surface temperatures is not supported by the calculations presented here. The process of redistribution of soil water in the profile may be a significant factor in the observed losses. This redistribution may not be manifested in visually noticeable drying of the seed zone until the seed zone and the layers immediately below reach critical water contents, or until evaporative losses exceed the replacement rate.

In this study, the mulch did not become as "stratified" in any of the treatments as did the deep mulch reported by Papendick et al. (1973). This may have been due to differences in soil texture or in specific depths of tillage operations. Rolling or skew-tredding the mulch to compact the surface may reduce evaporative losses in late summer. This could decrease the loss of soil water reserves under the seed zone. Consequently, replacement of evaporated water could maintain seed zone water content so that rapid, timely germination and stand establishment of fall planted crops can occur. The validity of this hypothesis has not yet been tested.

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MANUSCRIPT II

Effect of Soil Temperature on Emergence of Winter Wheat and Winter Barley in the Field

ABSTRACT

In the Pacific Northwest, potential yield and erosion control are significantly affected by time of stand establishment of winter cereals. The objectives of this study were to investigate the effect of soil temperature on the rate of first emergence and 70% stand of winter wheat and winter barley in the field, and to develop a means of predicting the average last date of planting at one location in eastern Oregon after which stand establishment is excessively delayed. Two depths of soil mulch on stubble- and bare-fallowed plots were used to investigate the effect they would have on seed zone temperature, rate of first emergence, rate of 70% stand, and grain yield. McDermid wheat and Hudson barley were planted on seven dates about two weeks apart from 20 August to 12 November 1976. In 1977, McDermid wheat was planted on five dates at approximately biweekly intervals from 1 September to 27 October. Seeds were placed into moisture with a deep furrow drill, and were covered with about 5 cm of soil. Soil temperatures were monitored at seeding depth in adjacent fallow plots, and 10-cm soil temperatures at a nearby U.S. Weather Bureau shelter were recorded. Average soil temperatures were 0.5-2.0 C higher under the bare fallow than under the stubble fallow treatments, but there were no significant differences in emergence rate due to tillage treatments. Regression equations of emergence rate and average

10-cm soil temperature at the shelter were highly significant. Barley had a different temperature response than wheat. The equations indicated that wheat required 149 and 210 degree days above a minimum of 0.7 and 0.4 C for emergence and 70% stand, and barley required 92 and 159 degree days above a minimum of 6.1 and 3.5 C for emergence and stand, respectively. A graph of 15-year average daily 10-cm soil temperatures from 1 August through 30 November at Moro, Oregon, was used with the equations to predict the average last date for planting to obtain 70% stand within a specified time period. The graph and equations were also used to predict the average length of time needed for 70% stand when wheat or barley is planted on a given date. Planting date had a significant effect on grain yield. Barley was more sensitive to planting date than wheat. There were no significant differences in yield due to tillage treatment. By spring, early plantings of wheat had used about 3 cm more soil water than late plantings. Water is the primary limiting production factor in this area. Although other factors enter the critical decision of when to plant, seed zone temperature is an important one in this region. The average last date to plant and still obtain 70% stand within 14 days is 25 September.

Additional index words: Degree days, growth stages, planting date, stand establishment, water use.

INTRODUCTION

The establishment of an adequate stand at the optimum time is an important factor affecting potential grain yield of winter wheat (Triticum aestivum L.) and winter barley (Hordeum vulgare L.)[1] (Beutler and Foote, 1963; Stickler and Pauli, 1964). In the fallow-crop rotation area of the Pacific Northwest, adequate, well-developed stands also reduce water erosion during the winter of the crop period (Cochran et al., 1970; Papendick and Miller, 1977). It has long been recommended in the lower precipitation areas that seeding be done from mid-September to early October (Stephens and Hyslop, 1922). Cereals planted earlier often utilize excessive amounts of the limited moisture, are more susceptible to winter-killing, and are frequently subject to diseases (Bruehl, 1961; Cook, 1968; Cook and Waldher, 1977; Papendick and Miller, 1977). Later seeding often results in delayed emergence and stand establishment due to rapidly dropping soil temperatures.[1] Cereals planted after mid-October frequently do not emerge until the following spring (Stephens and Hyslop, 1922).

Kanemasu et al. (1975), working on emergence of field-planted sorghum (Sorghum bicolor Moench) varieties, found that, when the

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[1] Pehlivantürk, A. 1976. Effect of soil temperature, seeding date, and straw mulch on plant development and grain yield of two winter wheat and two winter barley cultivars. M. S. Thesis. Oregon State University.

average soil temperature was plotted against the reciprocal of days to emergence, the resulting straight line could be represented by

$$ST = S/t + ST_{min}$$

where ST is the average surface-to-seed zone temperature, S (the slope) is the degree days needed for emergence, t is the time from planting to emergence in days, and ST_{min} (the intercept) is the minimum temperature at which emergence occurs.

Lindstrom et al. (1976) pointed out that, although germination of winter wheat can occur in even very dry soils, emergence of the seedlings is strongly influenced by moisture availability. They presented equations for predicting the emergence of winter wheat using soil temperature, soil water potential, and depth of seeding as independent variables. Other predictive equations based on soil moisture potential and temperature effects on winter wheat emergence have been given by Halitligil[2] and Conway.[3] Valovich and Grif (1974) have shown that some germination of barley and wheat will occur at temperatures very

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[2] Halitligil, M. B. 1975. Effect of soil moisture, temperature, bulk density and texture on emergence of three wheat varieties (Triticum aestivum L.). M. S. Thesis, Oregon State University.

[3] Conway, M. P. 1978. Temperature and moisture effects on stand establishment of seven winter wheat cultivars and selected progeny (Triticum aestivum L. em Thell). M. S. Thesis. Oregon State University.

near 0 C, when sufficient time is allowed for germination.

The objectives of this study were: 1) to investigate the effect of average soil temperature on the rate of first emergence and 70% potential emergence (70% stand) of winter wheat and winter barley in the field; and, 2) to develop a means of predicting the average date after which the soil temperature at one location in eastern Oregon is sufficiently low to delay emergence and stand establishment of these crops. It was assumed in this study that the seeds could be placed into adequate soil moisture with the use of a deep furrow drill, so that availability of water to the seed was not a limiting factor. Four tillage treatments were used to investigate the effect they would have on seed zone temperatures, rate of first emergence, rate of stand establishment, and grain yield.

MATERIALS AND METHODS

Field plots were established on a Walla Walla silt loam soil (a mixed, mesic Typic Haploxeroll) at the Sherman Unit of the Columbia Basin Agricultural Research Center during the fallow-crop periods of 1975-1977 and 1976-1978. A strip-plot design (Petersen, 1976) was used; the main plots were standard bare fallow (initially tilled with a moldboard plow) and standard stubble fallow (initially tilled with a sweep plow or disk). The main plots were split and rodweeded at shallow (7-10 cm) or deep (10-15 cm) depths in order to create two depths of soil mulch. The plots were rodweeded at their respective depths during the summer when necessary to control weed and volunteer growth. At the time of planting, the four tillage systems had produced these surface conditions:

1) bare fallow, shallow mulch -- moldboard plow (15-20 cm deep) in April, followed by secondary tillage with a disk or sweep to smooth the soil surface, and shallow rodweeding (7-10 cm);
2) bare fallow, deep mulch -- moldboard plow and secondary tillage as in 1), and deep rodweeding (10-15 cm);
3) stubble fallow, shallow mulch -- sweep plow or disk (10-15 cm deep) in April, followed by secondary tillage and shallow rodweeding as in 1); and,
4) stubble fallow, deep mulch -- sweep plow or disk and secondary tillage as in 3), and deep rodweeding (10-15 cm).

In 1976, McDermid winter wheat and Hudson winter barley were planted on seven dates (20 August, 4 and 16 September, 2, 17, and 30 October, and 12 November) in strips across all tillage treatments. In 1977, McDermid wheat was planted on five dates (1, 16, and 30 September, and 12 and 27 October) in the same manner. Barley was not planted in 1977 because of space restrictions. The plots were fertilized by broadcasting ammonium nitrate at a rate of 40 $kg\text{-}ha^{-1}$ just prior to seeding. In both years, the depth to adequate soil moisture for rapid germination and emergence was determined for all plots, and the deep furrow drill was set to reach the depth of moisture in the driest plots. Consequently, seed was planted into moist soil and at roughly equivalent depths in all tillage treatments.

Foundation McDermid wheat harvested the previous year was used in both trials, but in 1977, only seed which had not passed through a 0.28 cm (7/64 in) slotted screen was used. Seed size has been shown to have a significant effect on seedling vigor[3] (Evans and Bhatt, 1977). The planting rate in 1976 was 65 kg-ha^{-1} in 30-cm wide rows; when the sized seed was planted at the same within-row rate (about one viable seed per 1.25 cm of row) in 35-cm wide rows, the areal seeding rate was 97 kg-ha^{-1}. Certified Hudson barley harvested in 1968 was planted in the 1976 trial. All seed lots had high germinability when tested under standard germination conditions in the laboratory.

Soil water content measurements were made within a day of seeding by sampling the 0-30-cm soil profile in small increments (1-6 cm) and determining the water content gravimetrically. Estimations of water potential were made using the water characteristic curve for the soil. Seed zone temperatures were estimated from soil temperatures recorded in adjacent fallow plots. Daily precipitation, air temperature, and 10-cm soil temperature for August through November, 1963-1977, were acquired from the records of a nearby (1 km) U.S. Weather Bureau shelter.

Dates of first emergence from the soil and of 70% potential emergence were recorded. Soil water content to 150 cm was measured on 3 March and 9 April 1977 under each planting date of one replicate of wheat. Growth stages according to Zadoks' scale (Zadoks et al., 1974) were determined for wheat on 28 February 1978. Relative stand ratings (in percent of the best plot) were made for each species prior to harvest in 1977. The plots were harvested with a Hege combine in 1977, and grain yield per square meter was calculated.

Statistical analyses were conducted according to Petersen (1976); his conservative approximate significant difference (ASD) and the "protected" LSD were used to detect differences between means.

RESULTS AND DISCUSSION

The planting depth in relation to the soil surface of the fallow varied from date to date, depending on the moisture conditions of the profile, but an attempt was made to maintain a constant depth of soil over the seed. Depth of planting varied from 10-14 cm, but the seeds were covered by approximately 5 cm of soil on all dates. The soil water potential at the depth of seeding was not less than -3 bars at seeding. Soil water contents were not monitored after seeding, but Lindstrom et al. (1976) reported little change in seed zone water contents from planting to emergence.

Soil temperatures as measured in adjacent fallow plots showed diurnal variations of up to 11.3 C at 10 cm. There was no consistent difference in temperature cycles or averages due to mulch depth. The average daily temperature under the bare fallow was 0.5-1.0 C higher than under the stubble fallow in 1976 and was 1.0-2.0 C higher in 1977. Lower soil temperatures under a mulch have been reported by others (Papendick et al., 1973; Willis and Amemiya, 1973). However, there were no significant differences in days to first emergence and 70% stand due to tillage treatment. Observation of the plots occurred only once per day, and this may have been one reason for the failure to detect differences in emergence rate between tillage treatments.

Soil Temperature Effects on First Emergence and 70% Stand

The usefulness of prediction equations based upon actual seed zone temperatures is limited by the lack of long-term records. Although these equations are useful in our basic understanding of plant response to temperature, we have no way of knowing if the temperatures recorded during a particular study period are characteristic of the region. If the emergence of crops is well described by equations using available Weather Bureau data, the equations can be more useful. Long-term records can be used to predict optimum or latest average planting dates. Predictive equations for soil temperature can be constructed which are relatively precise for use every year (Neild, 1971). Since the temperatures at 10 cm in the field were closely correlated with the 10-cm temperatures recorded at the shelter, ($r = 0.987$), the latter have been used in regression equations with emergence rate.

The average 10-cm soil temperature from planting to emergence is plotted against the reciprocal of days to first emergence and 70% stand of wheat and barley in Figures 1 and 2. The regression equations were converted to the form used by Kanemasu et al. (1975) to obtain

$$\bar{T} = 149/t_{EW} + 0.7$$

$$\bar{T} = 210/t_{SW} + 0.4$$

$$\bar{T} = 92/t_{EB} + 6.1$$

$$\bar{T} = 159/t_{SB} + 3.5$$

where $\bar{T}$ is the average 10-cm soil temperature at the Weather Bureau shelter, t is the time in days from planting to emergence or stand, and the subscripts E, S, W, and B represent first emergence, 70% stand, wheat, and barley, respectively.

Two aspects of these equations are of interest. First, the theoretical minimum temperature required by wheat for emergence and stand is near 0 C, while for barley, the minimum temperature is higher. Barley apparently requires higher temperatures to sustain the minimum metabolic rate needed for emergence. Second, however,

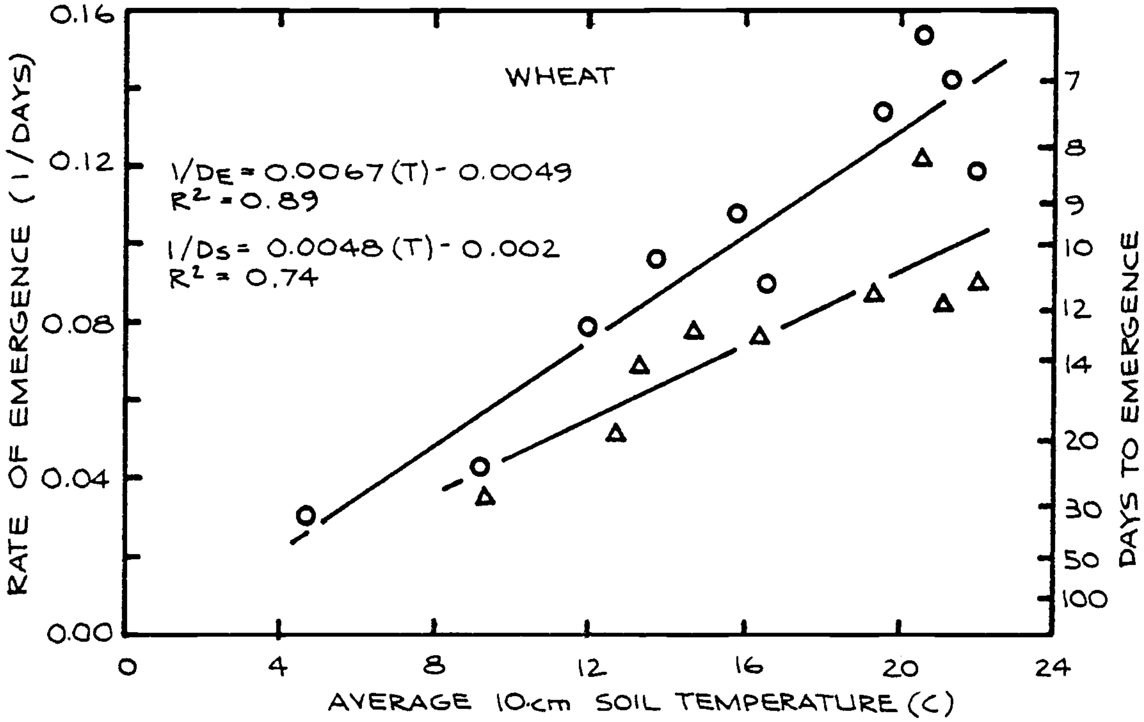


Figure 1. The relationship between the reciprocal of days to first emergence (O) and 70% stand (Δ) of wheat to the average 10-cm soil temperature from planting to emergence.

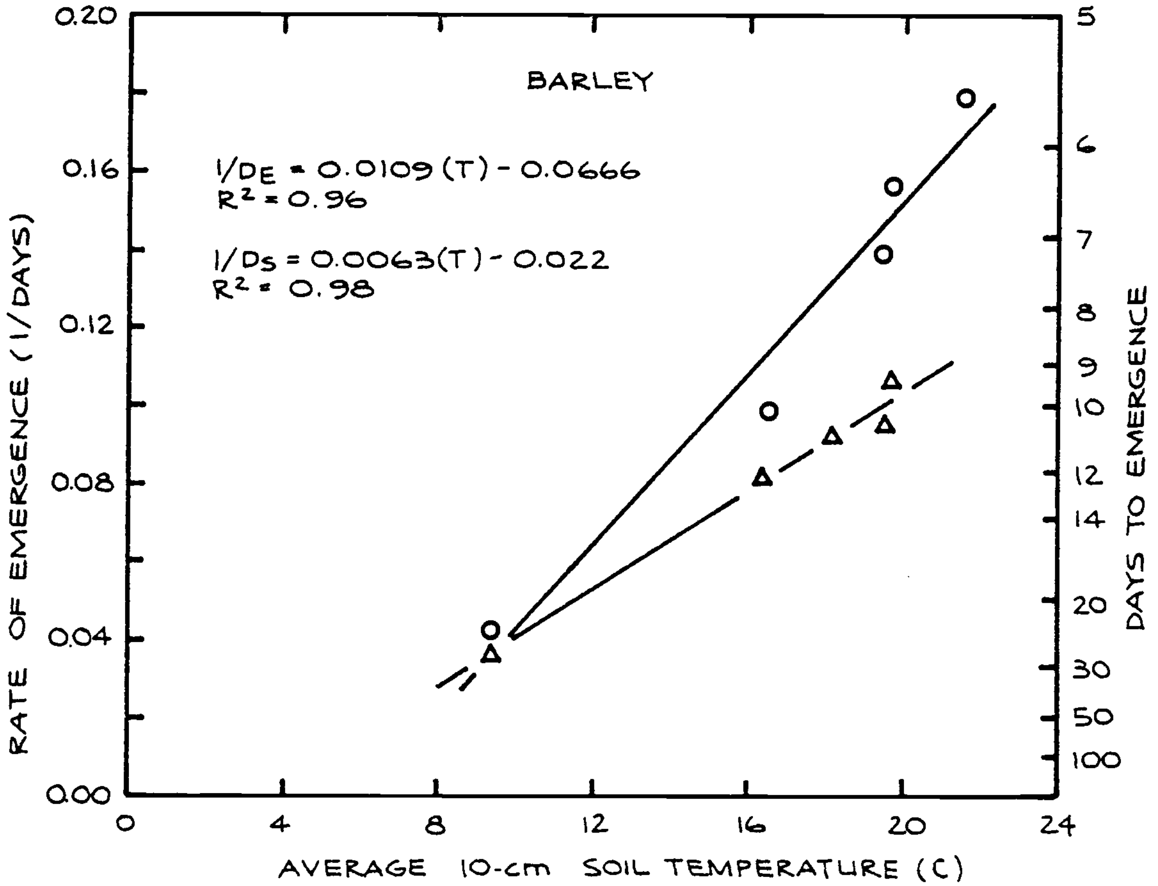


Figure 2. The relationship between the reciprocal of days to first emergence (O) and 70% stand (Δ) of barley to the average 10-cm soil temperature from planting to emergence.

barley requires fewer degree days for emergence and 70% stand than wheat. The metabolic and physical activity during germination and coleoptile elongation of barley evidently respond more quickly to rising temperatures than in wheat. These two characteristics help explain the observation that barley often emerges sooner than wheat when planted near the optimum dates, but, as air temperatures decrease in the fall, barley development and tillering proceed at slower rates than wheat (F. E. Bolton, personal communication).

Long-term Average Daily Soil Temperatures

The 15-year (1963-1977) daily averages of 10-cm soil temperature are plotted against date in Figure 3. For each point, the 95% confidence interval is also plotted. The 95% confidence interval is calculated by the following equation

$$95\%\ \text{C.I.} = \bar{X} \pm t_{(0.05)}\ s/n^{\frac{1}{2}}$$

where $\bar{X}$ is the calculated mean value, $t_{(0.05)}$ is the tabulated t value at the 5% level with n-1 degrees of freedom, s is the standard deviation of $\bar{X}$, and n is the number of observations used to obtain $\bar{X}$. Since both n and the t value are constant for the average daily temperatures, and the value $t_{(0.05)}/n^{\frac{1}{2}}$ equals 0.555, the confidence intervals could be extended to about twice their length in order to encompass 68% of the expected values for each day. The great amount of variability

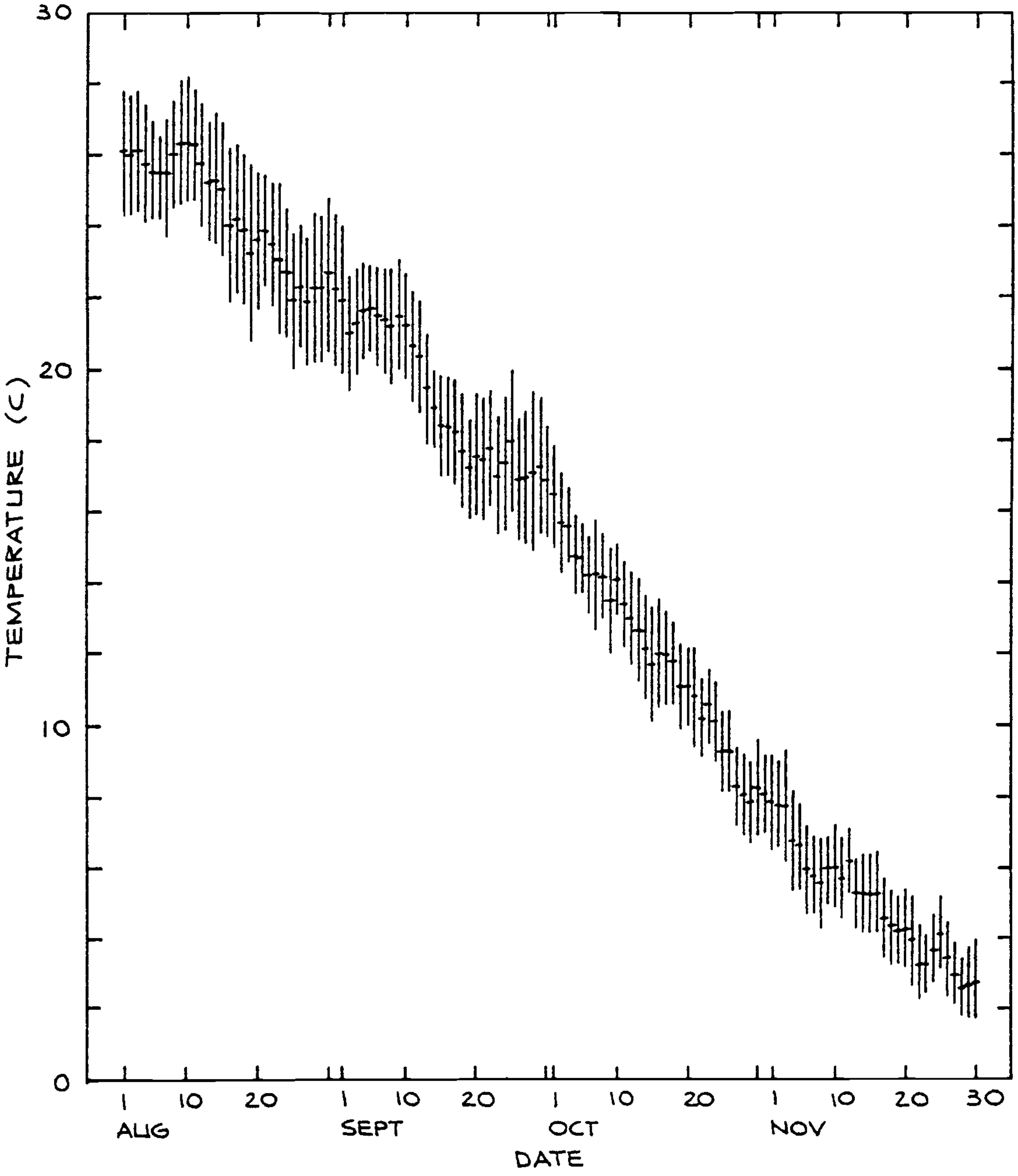


Figure 3. Average daily 10-cm soil temperature (horizontal bar) and the 95% confidence interval (vertical bar) for August through November, 1963-1977, at Moro, Oregon.

in soil temperature is evident.

The average date of planting to get 70% stand within a given period of time can be estimated by using Figures 1 and 3 or 2 and 3. If wheat was to be planted, and 70% stand within 14 days was desired, the average 10-cm soil temperature would need to be 15.3 C. This temperature corresponds to about 2 October (Figure 3). For an average temperature of 15.3 C over a 14-day period, the planting date must occur seven days earlier, on 25 September. If seeding were delayed until 15 October, the average 10-cm soil temperature will be between 9 and 10 C, and it would take 22-24 days to reach 70% stand. At these temperatures, barley would not reach 70% stand for 24-29 days after seeding.

Average planting depth in these trials was 5 cm, but this varied somewhat due to planter speed, depth to moisture, and condition of the mulch at planting. Lindstrom et al. (1976) suggested that depth of planting can be accounted for by the inclusion of a calculated function of coleoptile elongation rate versus degree days. Since differences in planting depth were not specifically tested in this study, no estimation of the effect of planting depth in this soil can be made.

It is known that varieties differ in their ability to emerge from deep plantings (Sunderman, 1964; Gul and Allan, 1976) and that the soil texture and bulk density can significantly influence the rate of emergence.[2] The probability of precipitation increases with time in the fall, and there is a tendency for many of the soils in the Pacific Northwest to form surface crusts after even light rainfall (Papendick and Miller, 1977). These surface crusts can impede emergence. Consequently, early seeding has the advantage of reducing the hazard of crusting.

Planting Date Effects on Stand and Yield

There were no significant differences in yield between tillage treatments, but planting date had a significant effect (Figure 4). Comparable yields were obtained with wheat and barley until the 17 October planting; after this date, the barley yielded significantly less than the wheat. Early and late dates of planting yielded significantly less than the middle dates. The yield response of the two species to planting date is similar to that reported elsewhere (Beutler and Foote, 1963; Stickler and Pauli, 1964).

The differences between planting dates may have been exaggerated because of the extremely dry fall and winter of 1976-1977. The normal crop period (10 months) precipitation total is 26.8 cm, but only 14.1 cm were received during the 1976-1977 crop period, and much of this occurred later in the spring. Early plantings of wheat used more soil moisture by early spring than did the later dates (Figure 5). The wettest part of the profile under the last planting date corresponds to only about -0.7 bar water potential. One would normally expect much wetter profiles on these dates.

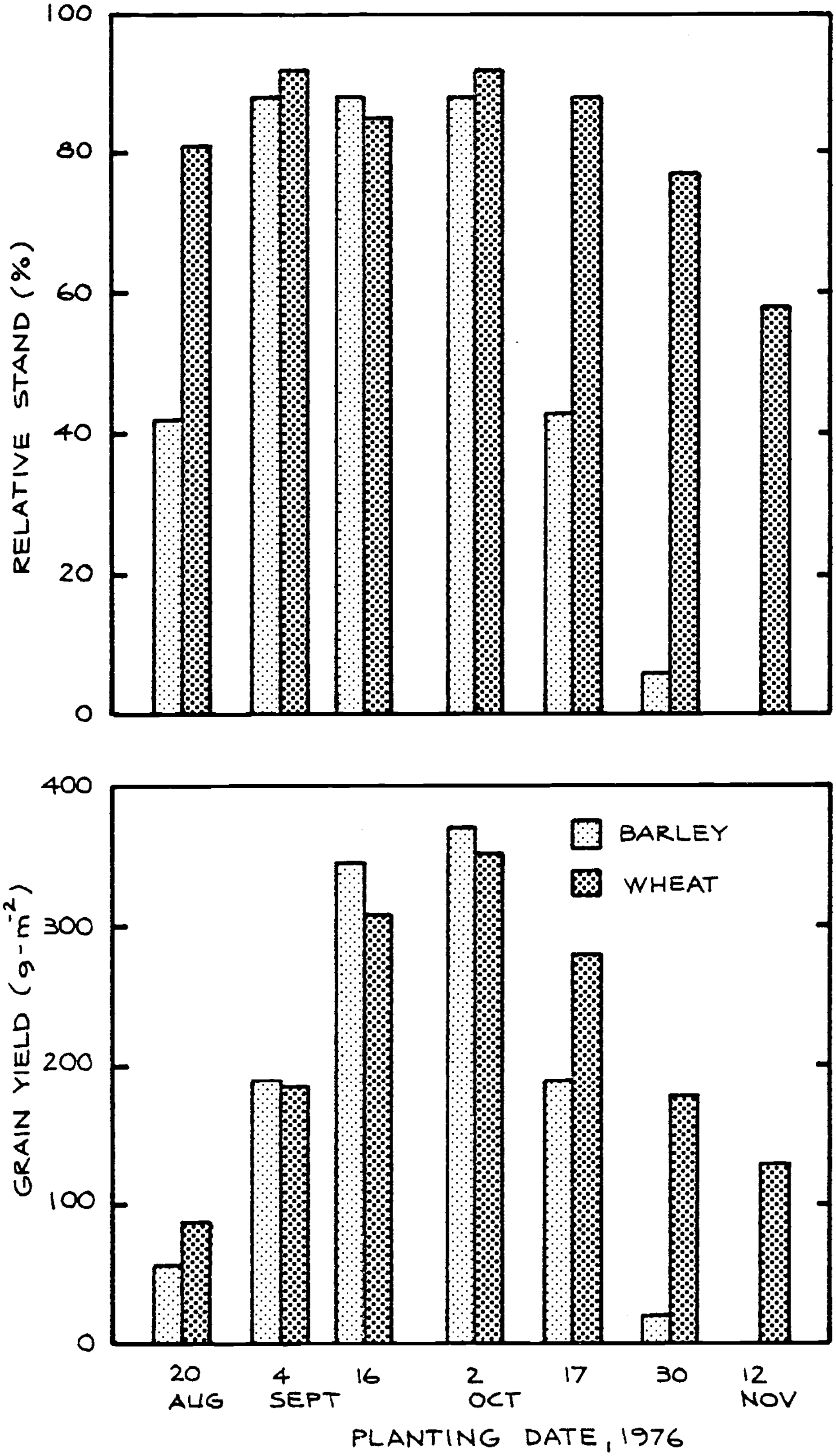
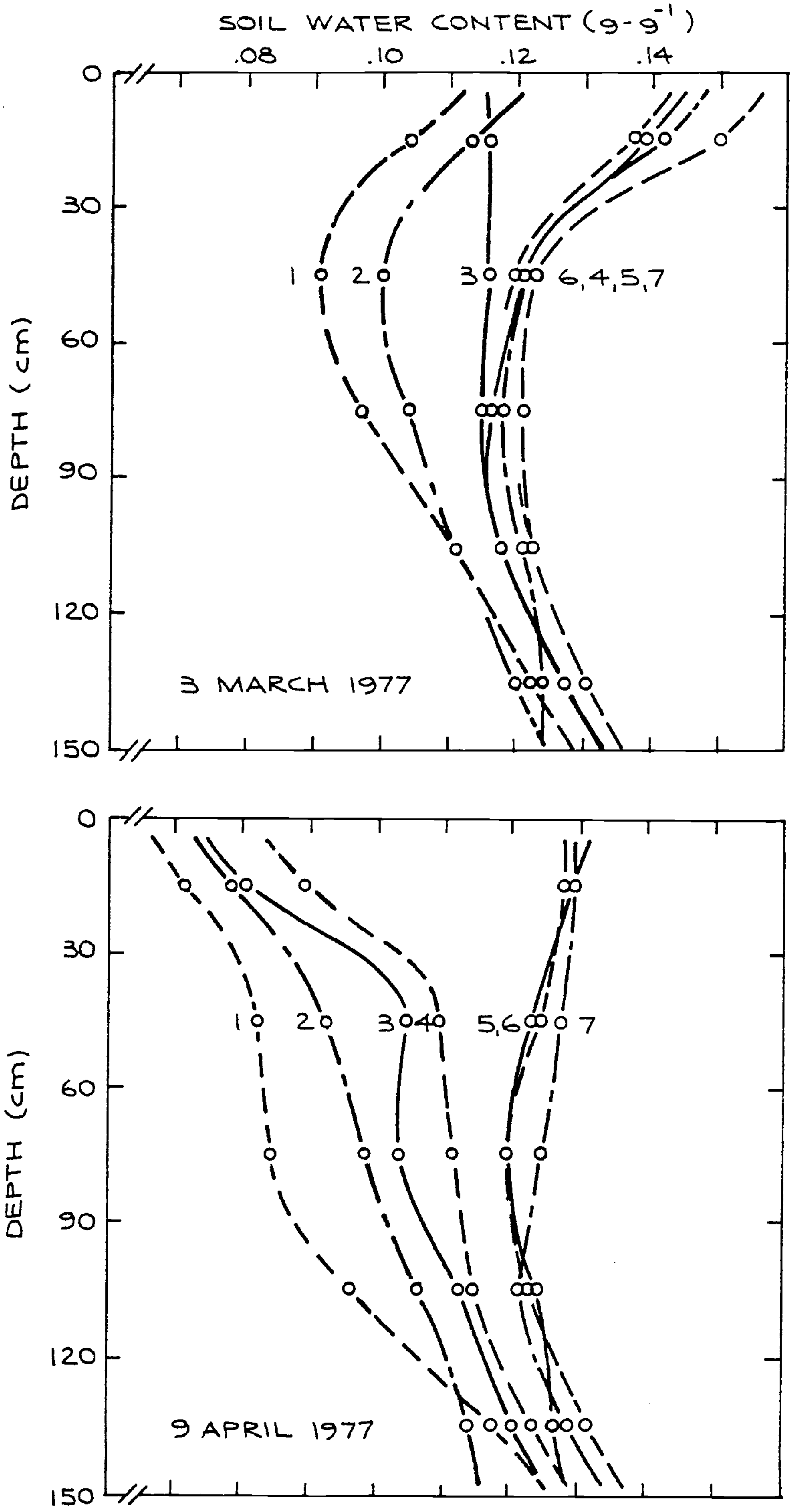


Figure 4. The effect of planting date on relative stand (in percent of the best plots) and yield of winter wheat and winter barley.

Figure 5. The soil water content profiles under wheat seeded on seven dates (20 August, 4 and 16 September, 2, 17, and 30 October, and 12 November, 1976) at two times in the spring of 1977. Data points represent measurements made under one replication of the bare fallow, shallow mulch treatment.


SOIL WATER CONTENT (g-g⁻¹)
.08
.10
.12
.14
DEPTH (cm)
0
30
60
90
120
150
1
2
3
6,4,5,7
3 MARCH 1977
DEPTH (cm)
0
30
60
90
120
150
1
2
3
4
5,6
7
9 APRIL 1977

Wheat in this region often extracts soil moisture to -30 bars ($0.06\ g\text{-}g^{-1}$ water content). This amount was used to calculate the total available water under each planting date. Total available water in the 0-150-cm profile on 3 March was 8.4, 9.2, 10.8, 11.9, 12.1, 12.1, and 12.8 cm for planting dates 1-7, respectively. On 9 April, total available water was 5.6, 7.0, 8.2, 9.1, 11.9, 12.0, and 12.2 cm, respectively. The wheat planted on 20 August had used about 3 cm more water than the middle dates by the time of sampling. Plants seeded on 20 August and 4 September were heavily tillered by November.

Two factors other than pattern of water use limited yields of plots planted on early and late dates. Early plantings of both wheat and barley in 1976 were infected with barley yellow dwarf, which is known to limit yields (Bruehl, 1961). Weed populations were largest in early- and late-seeded plots, and were larger in the stubble fallow plots than in the bare fallow. Weeds can significantly lower the water use efficiency of crops grown in semi-arid areas (Viets, 1971).

Both crops emerged and developed more slowly when planted at the later dates. The growth stages on 28 February 1978 of the wheat planted on five dates in 1977 (Table 1) give an indication of the relative stages of development at that time. Small plants are less able to compete with weeds and less able to grow during the relatively mild winters, because of their reduced leaf area. Due possibly to excessive

Table 1. Zadoks' growth stage and description of wheat planted on five dates in 1977. Determinations were made in each of three replications on a minimum of five plants per replicate on 28 February 1978.

Planting Date	Zadoks' Growth Stage	Description
1 September	18+, 29, 30	Eight and more leaves unfolded on main shoot; 9 or more tillers; pseudo stem erection.
16 September	16+, 28+, 30	Six and more leaves unfolded on main shoot; 8 or more tillers; pseudo stem erection.
30 September	14, 23 or 24	Four leaves unfolded on main shoot; 3 or 4 tillers.
12 October	13, 22 or 23	Three leaves unfolded on main shoot; 2 or 3 tillers.
27 October	12, 20	Two leaves unfolded on main shoot; no tillers.

water use and increased competition from weeds, several barley plots planted on the first and sixth date in 1976 had stands too thin to harvest. None of the barley plots planted in November had sufficient stands (less than 5% of the best plots) to harvest. All wheat plots had relatively high stand densities (Figure 4).

The sensitivity of barley to planting date might be attributed to the age of the seed, since at the time of planting, it was eight years old. However, any lack of vigor due to age apparently did not slow emergence of the seedlings from the soil. The analysis of variance of first emergence and 70% stand showed significant main treatment effects of crop species and date of planting. Barley emerged about one day before the wheat until the last planting date, when it emerged at the same time. Barley reached 70% stand about one day before the wheat on the average, but there was little consistency from date to date. Barley yields were slightly higher than wheat on the optimum planting dates.

In terms of relative stand, it appears that barley was more sensitive to planting date than wheat (Figure 4). This may result from lower vigor in vegetative growth and development, whether caused by inherent differences between the species or by the age of the barley seed, or from a difference in the temperature response curve of barley compared to wheat. Barley apparently has higher minimum temperature requirements for emergence than wheat, and it may also respond differently to higher temperatures.

CONCLUSION

The decision of when to plant is a critical one in the management of a farming operation. Many factors can modify a farmer's decision to plant at a particular time. If late summer and fall precipitation is sufficient to germinate weed seeds in the mulch, he may delay planting until the weeds are large enough to be controlled by tillage. If the fall is warm and dry, the presence of aphids carrying barley yellow dwarf virus would be a different reason to delay seeding operations. Adequate soil moisture in the seed zone is necessary for rapid emergence. If the seedbed is not too dry, seeding should probably be done before low temperatures become the limiting factor in emergence. Rainfall after this time is likely to be sufficient for germination and emergence. The efficiency and speed with which the seeding operation can be carried out over the large acreages can also dictate when planting operations must begin.

A method for predicting first emergence and 70% stand of winter wheat and winter barley has been presented in this paper. The equations assume that adequate soil moisture for germination and emergence is available and that the seeds are covered with about 5 cm of soil. The equations and figures indicate that, if 70% stand within 14 days of planting wheat is desired, the average last date to plant in this area is 25 September.

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APPENDIX

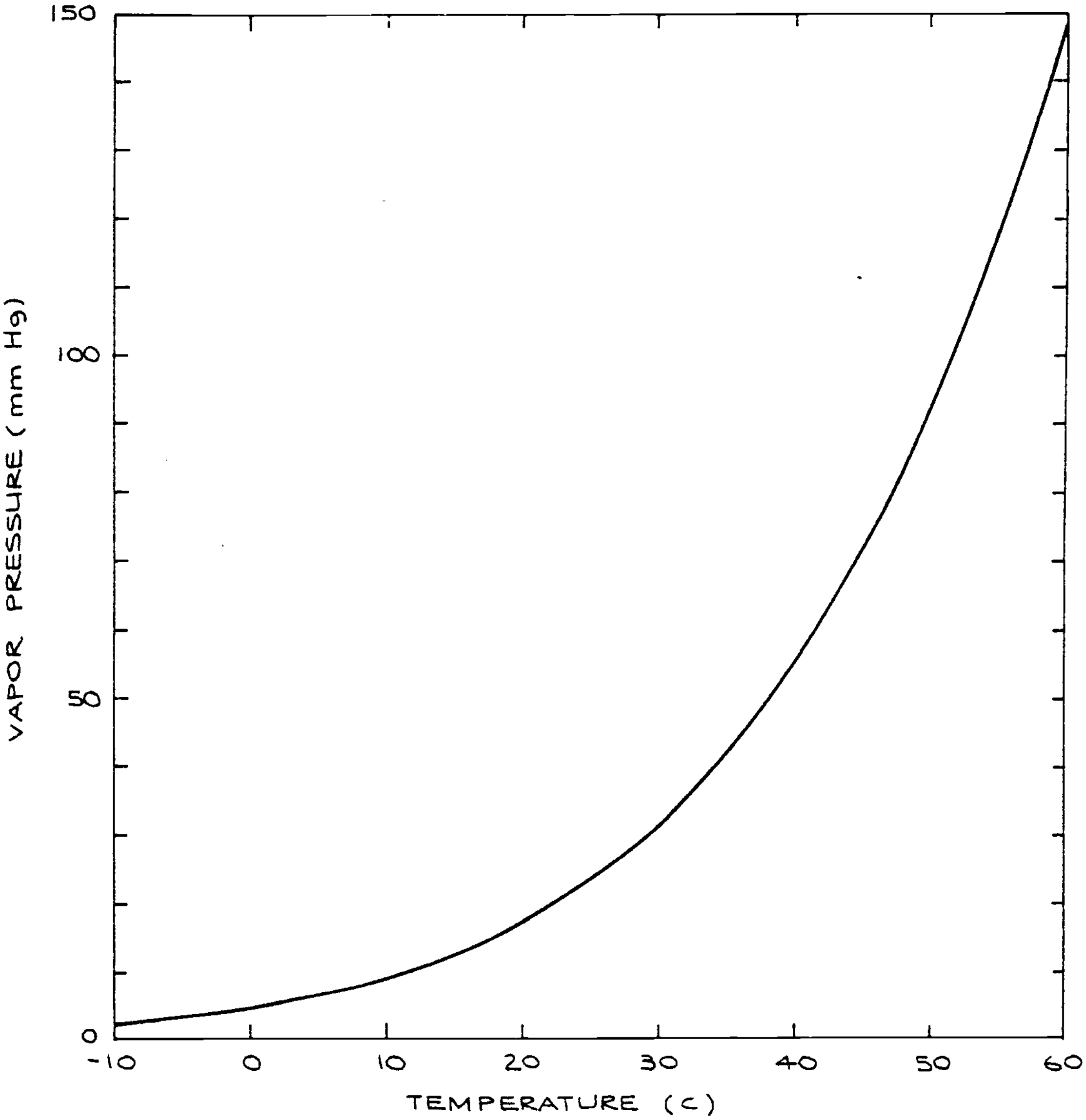


Figure 1. The relationship between water vapor pressure and temperature.

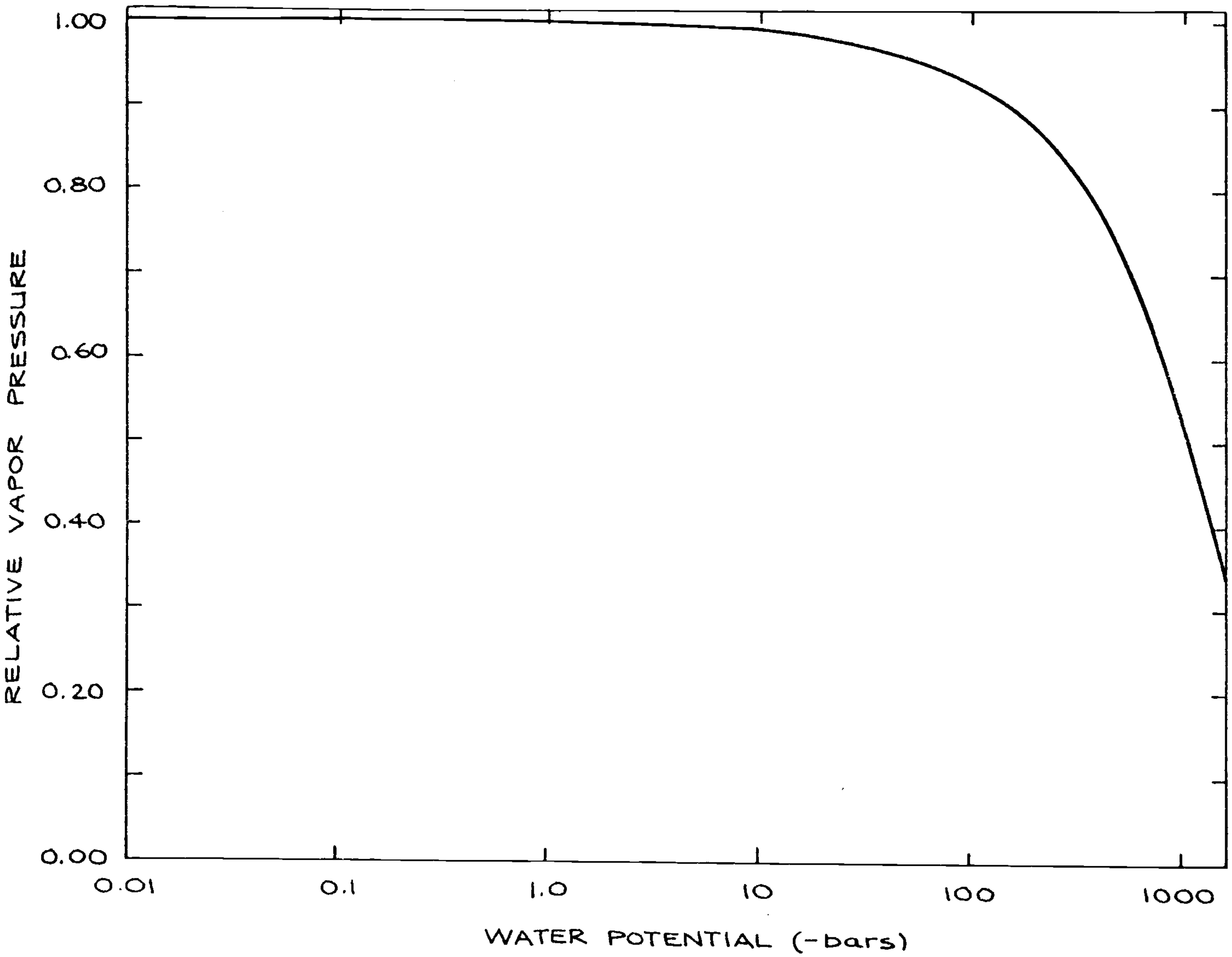


Figure 2. The relationship between relative vapor pressure and water potential.

Table 1 . Typical soil test values for the Walla Walla silt loam soil near the plot site. Values taken from various sources.

Soil Property	Soil Depth (cm)				
	0-30	30-60	60-90	90-120	120-150
Organic matter (%)	1.2	1.0	0.8	0.6	0.5
Total nitrogen (%)	0.06	0.05	0.04	0.03	0.03
Sulfate sulfur (ppm)	1.0	1.0	1.3	1.4	1.9
Phosphorus (ppm)	24	14	16	12	9
Extractable cations					
Potassium (ppm)	412	364	330	330	310
Calcium (meq/100 g)	6.8	6.9	6.6	6.6	10.4
Magnesium (meq/100 g)	2.8	3.2	3.7	4.1	4.9
Salts (mmhos/cm)	0.4	0.2	0.3	0.5	0.6
pH	6.6	7.2	7.7	8.2	8.7
Particle size					
Sand - .05-2 mm (%)	23.3	22.1	20.4	23.0	32.0
Silt - .002-.05 mm (%)	62.7	63.9	66.5	65.9	59.7
Clay - <.002 mm (%)	14.0	14.0	13.1	11.1	8.3

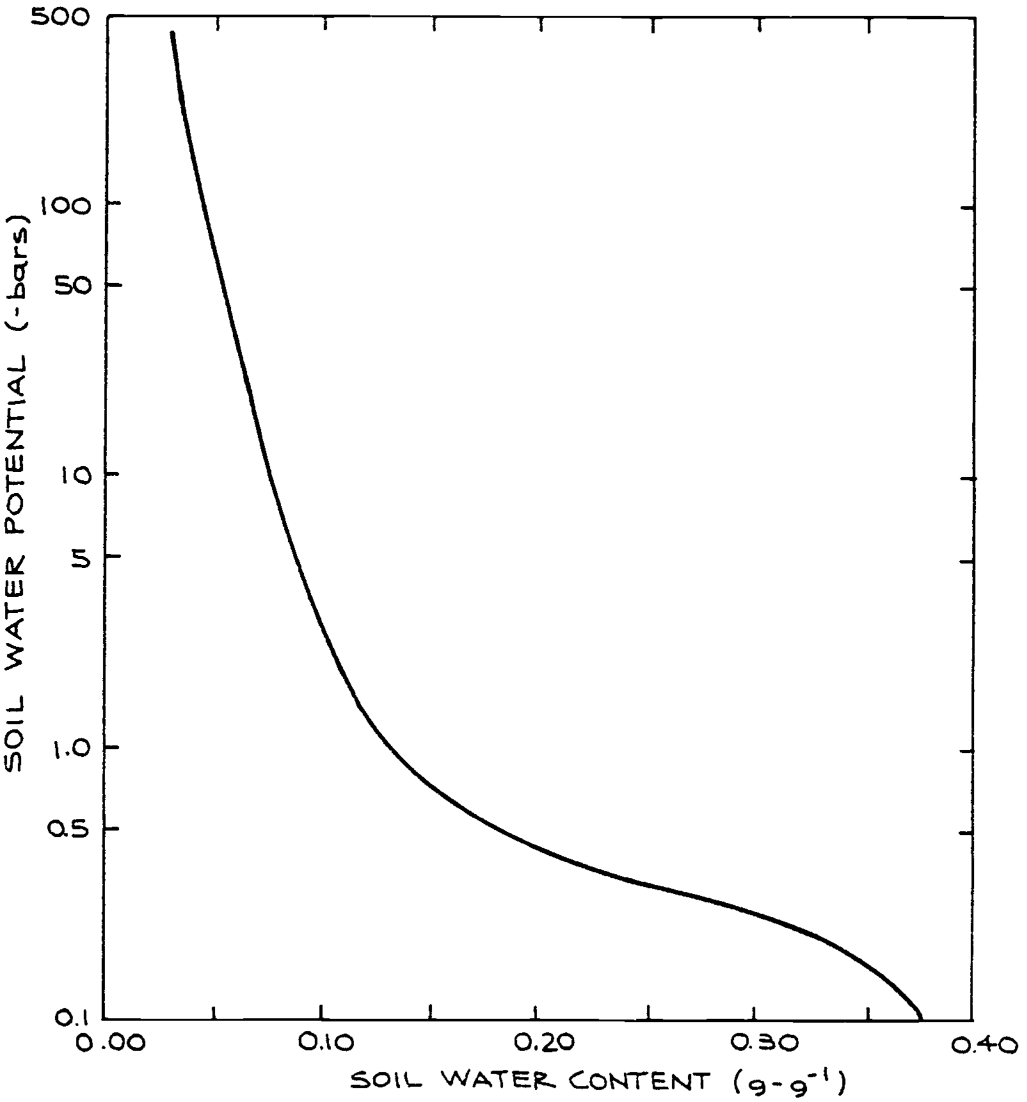


Figure 3. Soil water desorption characteristic curve for the 0-15-cm depths of a Walla Walla silt loam soil. The curve was constructed using values from pressure plate, pressure membrane, and vapor equilibrium techniques.

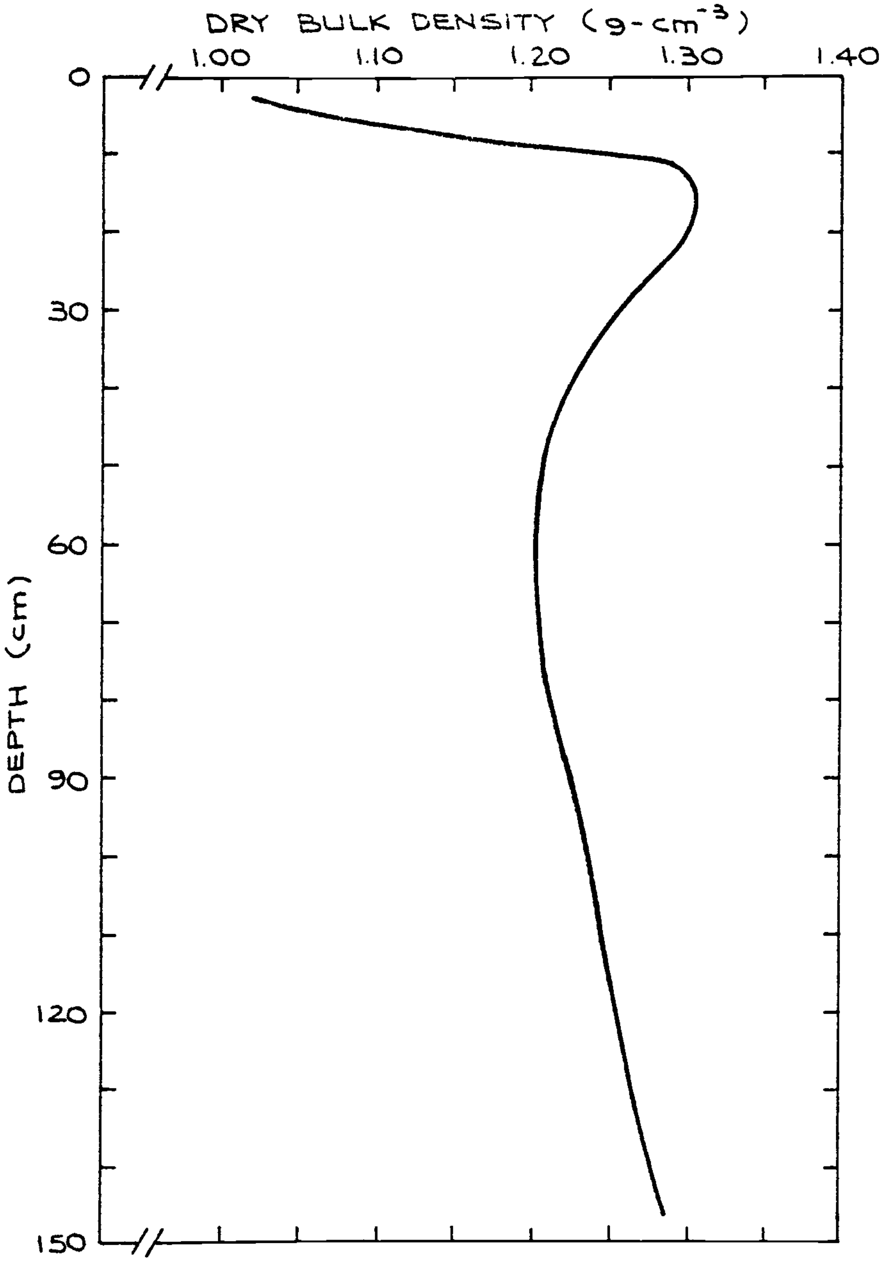


Figure 4. Bulk density by depth relationship of the 0-150-cm profile, averaged over all tillage treatments.

Table 2. Average dry bulk density (ρ), number of determinations (n), and standard deviation (sd) for different depths under four fallow tillage treatments, 1977. (Density and standard deviation given in g-cm^{-3}).

Depth (cm)	Bare Fallow						Stubble Fallow					
	Shallow mulch			Deep mulch			Shallow mulch			Deep mulch		
	ρ	n	sd	ρ	n	sd	ρ	n	sd	ρ	n	sd
1-3	1.04	18	0.10	1.09	17	0.09	1.01	17	0.09	1.07	16	0.09
3-5	1.13	18	0.08	1.08	17	0.08	1.11	17	0.06	1.11	18	0.07
5-7	1.13	18	0.10	1.12	17	0.07	1.16	17	0.11	1.12	18	0.09
7-9	1.13	17	0.09	1.13	18	0.07	1.26	17	0.13	1.19	17	0.14
9-11	1.21	17	0.09	1.11	17	0.08	1.32	18	0.11	1.26	18	0.10
11-13	1.26	16	0.13	1.22	18	0.13	1.34	18	0.11	1.38	18	0.14
13-15	1.32	18	0.12	1.30	18	0.16	1.33	17	0.11	1.35	18	0.10
15-18	1.29	18	0.10	1.28	17	0.09	1.34	17	0.06	1.28	18	0.08
18-24	1.30	36	0.06	1.30	32	0.06	1.32	36	0.06	1.30	34	0.08
24-30	1.31	34	0.08	1.30	32	0.05	1.27	29	0.07	1.28	31	0.07

Table 3. Mean monthly climatic data for Moro, Oregon.

Month	Precipitation (cm)	Air Temperature (C)	Evaporation (cm)
Jan	4.3	-1.3	
Feb	3.0	0.3	
Mar	2.4	5.2	
Apr	1.9	9.0	12.3
May	2.0	13.1	17.8
Jun	1.8	16.3	21.7
Jul	0.5	20.5	28.8
Aug	0.6	19.7	25.0
Sep	1.5	16.2	15.7
Oct	2.4	10.3	7.2
Nov	4.3	3.8	
Dec	4.3	0.9	
Total	29.0	Average 9.5	Total 128.5

Table 4. Monthly precipitation totals (cm) for the indicated fallow-crop cycles at Moro, Oregon.

Month	65-Year Average	1975-1977	1976-1978
August	0.6	3.2	3.0
September	1.5	0.0	0.1
October	2.4	3.0	0.3
November	4.3	3.4	1.2
December	4.3	3.2	0.5
January	4.3	3.2	0.5
February	3.0	2.4	1.6
March	2.4	2.4	1.3
April	1.9	2.7	0.2
May	2.0	0.4	6.9
June	1.8	0.2	0.7
July	0.5	2.0	0.9
August	0.6	3.0	2.3
September	1.5	0.1	2.2
Fallow total	31.1	29.2	21.7
October	2.4	0.3	0.6
November	4.3	1.2	5.1
December	4.3	0.5	8.2
January	4.3	0.5	7.1
February	3.0	1.6	3.3
March	2.4	1.3	1.9
April	1.9	0.2	
May	2.0	6.9	
June	1.8	0.7	
July	0.5	0.9	
Crop total	26.8	14.1	
24-Month total	58.0	43.3	

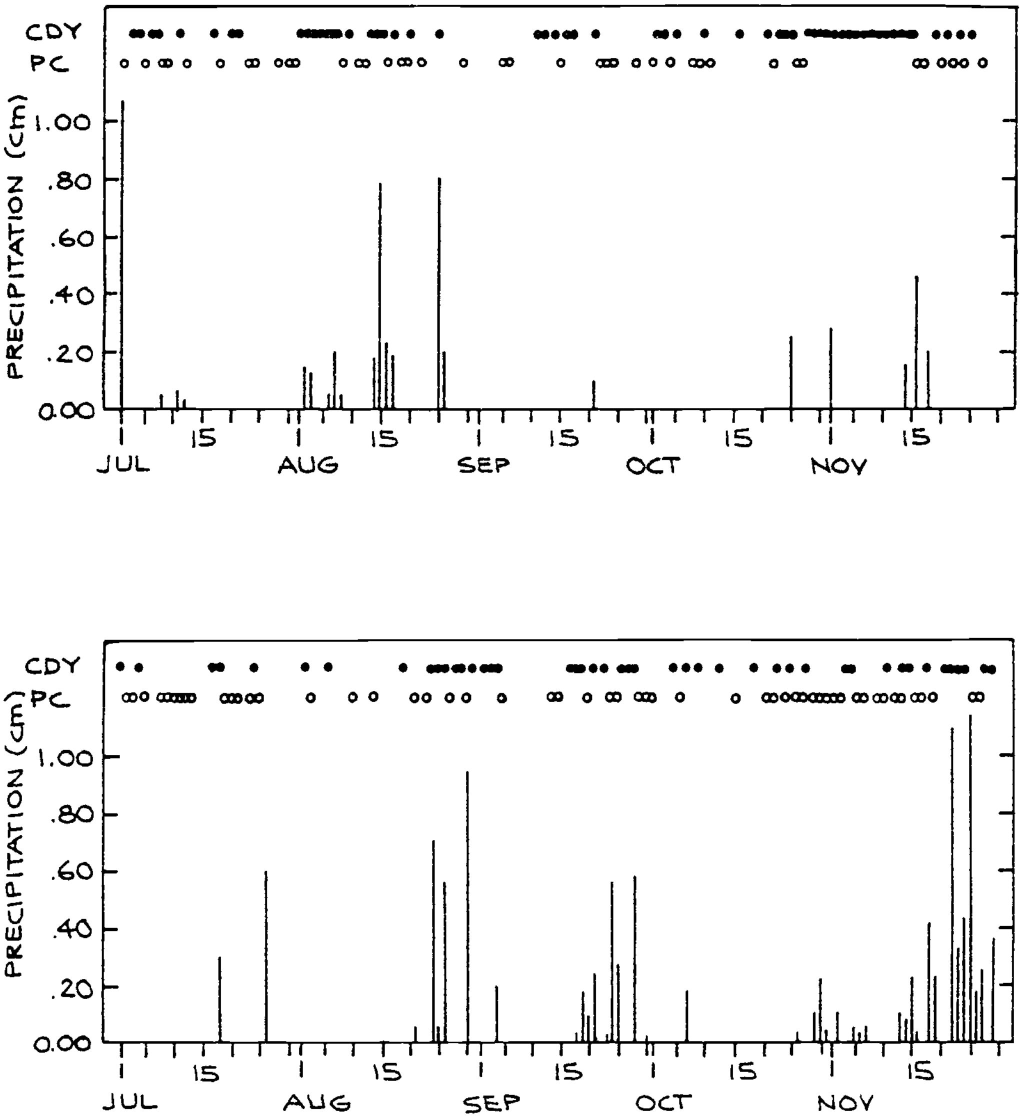
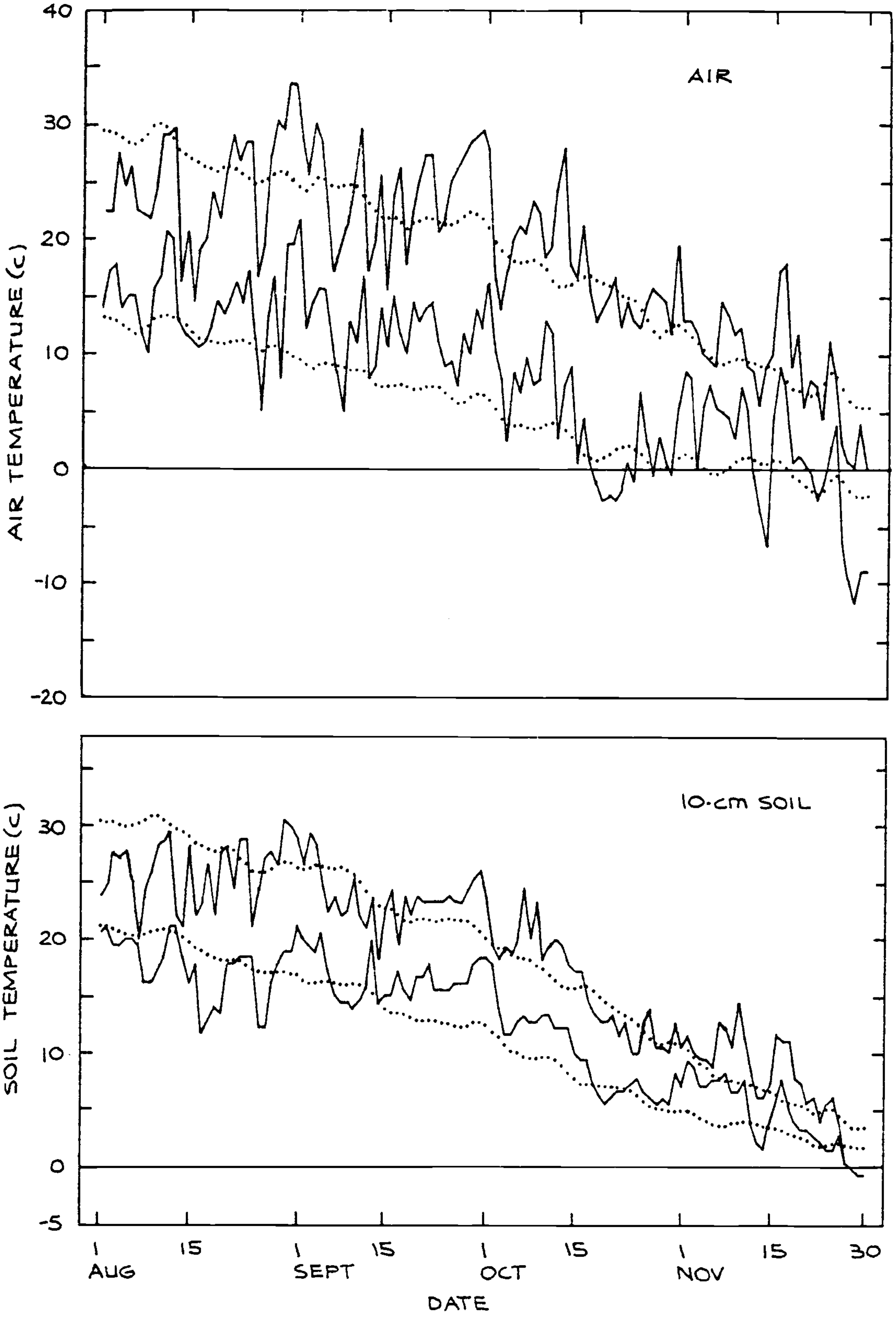


Figure 5. Daily precipitation amounts and cloud cover at Moro, Oregon, for July through November, 1976 and 1977. Cloudy (CDY) and partly cloudy (PC) conditions were recorded for daylight periods only. Precipitation recordings were made at 0800 hours, and may include precipitation from the preceding day.

Figure 6. Daily maximum and minimum air and 10-cm soil temperatures as a function of time in 1976 (solid lines), compared to the 15-year (1963-1977) running average of these daily temperatures (dotted lines). The running average was computed using a weighted average; the running average for day X is given by

$$\frac{T_{x-2} + 3T_{x-1} + 5T_{x} + 3T_{x+1} + T_{x+2}}{13}$$

where T is the temperature measured at the U.S. Weather Bureau shelter on the day indicated by the subscript.


AIR
AIR TEMPERATURE (c)
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10-cm SOIL
SOIL TEMPERATURE (c)
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-5
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AUG
15
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SEPT
15
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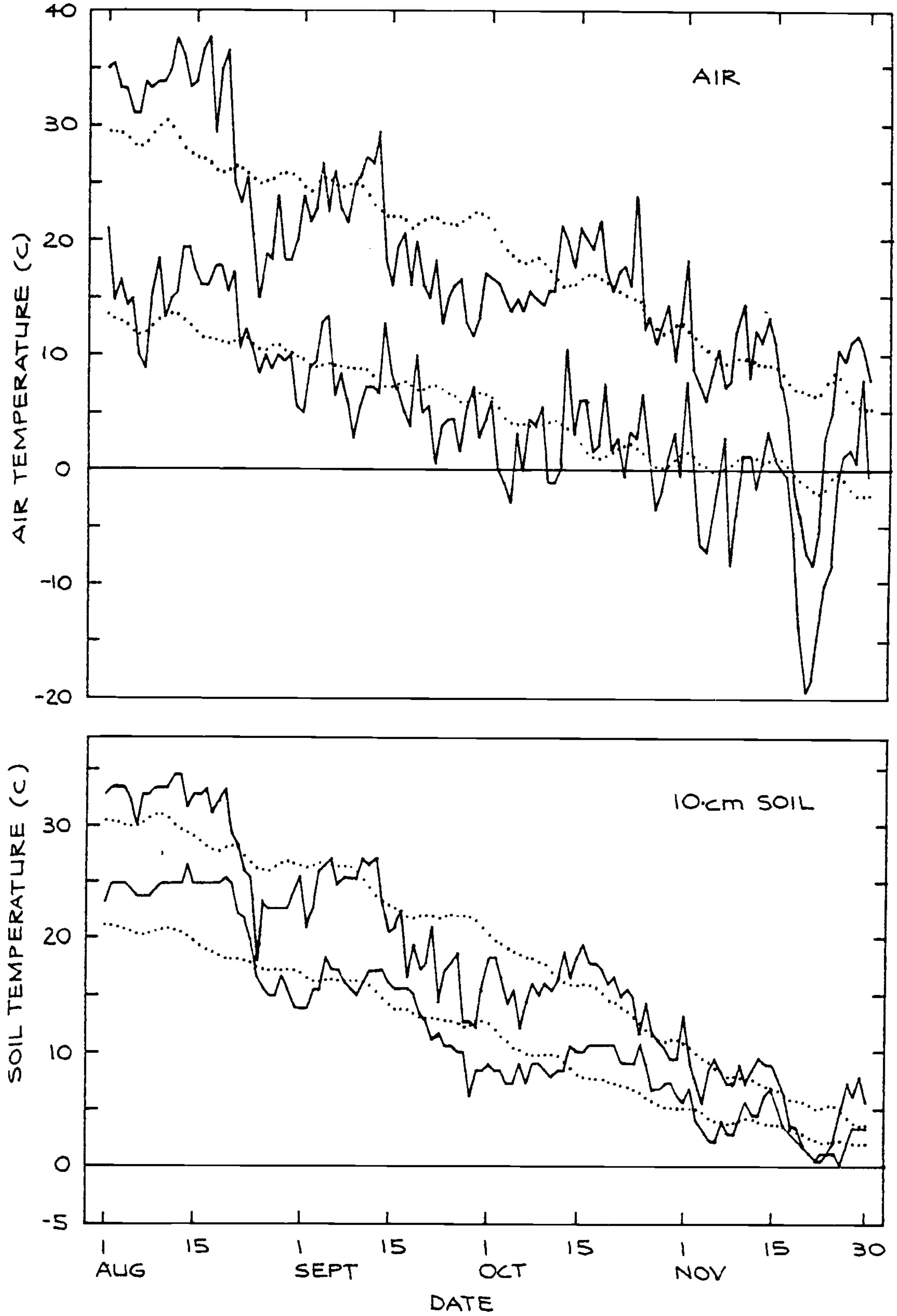
OCT
15
1
NOV
15
30
DATE

Figure 7. Daily maximum and minimum air and 10-cm soil temperatures as a function of time in 1977 (solid lines), compared to the 15-year (1963-1977) running average of these daily temperatures (dotted lines). See Appendix Figure 6 for further explanation.


AIR
AIR TEMPERATURE (C)
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10-cm SOIL
SOIL TEMPERATURE (C)
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Table 5. Average gravimetric soil water content (g-g^{-1}) by depth for four fallow tillage treatments on different dates in 1976. Each value is the mean of two or three replications, two to three samples per replication. (Note: Sampling increments for 21 Aug and 4 Sept were 0-4, 4-9, 9-15, 15-21, 21-27, and 27-33 cm; for other dates the increments were 0-4.5, 4.5-7.5, 7.5-10.5, 10.5-13.5, 13.5-16.5, 16.5-19.5, 19.5--25.5, and 25.5-31.5 cm.)

Treatment	Depth	Sampling Date						
	(cm)	21 Aug	4 Sept	16 Sept	2 Oct	16 Oct	30 Oct	12 Nov
Bare fallow, shallow mulch	2.0	0.044	0.023	0.028	0.030	0.026	0.045	0.050
	6.0	0.092	0.098	0.076	0.073	0.051	0.069	0.067
	9.0			0.120	0.105	0.093	0.104	0.099
	12.0	0.128	0.133	0.132	0.119	0.119	0.116	0.116
	15.0			0.131	0.125	0.125	0.121	0.123
	18.0	0.133	0.137	0.135	0.125	0.124	0.122	0.129
	21.5	0.135	0.137	0.134	0.127	0.123	0.124	0.127
	28.5	0.133	0.133	0.131	0.126	0.124	0.122	0.122
Bare fallow, deep mulch	2.0	0.039	0.024	0.024	0.028	0.027	0.040	0.046
	6.0	0.085	0.076	0.041	0.045	0.052	0.056	0.061
	9.0			0.081	0.085	0.095	0.086	0.093
	12.0	0.135	0.129	0.125	0.125	0.123	0.118	0.116
	15.0			0.135	0.131	0.131	0.124	0.123
	18.0	0.140	0.137	0.138	0.131	0.135	0.125	0.126
	21.5	0.140	0.138	0.136	0.133	0.136	0.127	0.125
	28.5	0.138	0.134	0.135	0.131	0.132	0.123	0.120

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Table 5. (Continued)

Treatment	Depth (cm)	Sampling Date						
		21 Aug	4 Sept	16 Sept	2 Oct	16 Oct	30 Oct	12 Nov
Stubble fallow, shallow mulch	2.0	0.041	0.021	0.026[a]	0.026	0.022	0.037	0.049
	6.0	0.068	0.070	0.050[a]	0.043	0.041	0.045	0.059
	9.0			0.098[a]	0.074[a]	0.081	0.079	0.085
	12.0	0.117	0.115	0.121[a]	0.112	0.108	0.107	0.110
	15.0			0.127[a]	0.128[a]	0.121	0.119	0.118
	18.0	0.136	0.133	0.131[a]	0.130	0.125	0.123	0.122
	21.5	0.137	0.135	0.133[a]	0.131	0.123	0.121	0.120
	28.5	0.136	0.132	0.130[a]	0.134	0.124	0.123[a]	0.122
Stubble fallow, deep mulch	2.0	0.038	0.023	0.024	0.024	0.026	0.038	0.047
	6.0	0.069	0.055	0.044	0.033	0.031	0.040	0.052
	9.0			0.074	0.055	0.051	0.057	0.066
	12.0	0.103	0.125[a]	0.118	0.096	0.090	0.094	0.093
	15.0			0.131	0.120	0.119	0.119	0.114
	18.0	0.133	0.131	0.135	0.131	0.133	0.125	0.123
	21.5	0.139	0.134	0.136	0.136	0.135	0.123	0.122
	28.5	0.135	0.137	0.135	0.134	0.132	0.124	0.123

[a] These values are means of two replications only.

Table 6. Mean squares from the analysis of variance for soil water content ($g\text{-}g^{-1}$) at 6, 12, and 18 cm in 1976.

Source of Variation	df	6 cm	12 cm	18 cm
Block	2	2.18	4.46	5.79
Primary Tillage	1	62.06	55.53*	0.60*
Prim x Block (Error A)	2	7.47	2.92	0.01
Rod Depth	1	28.82*	4.53*	1.36
Prim x Rod	1	3.44	6.80*	0.26
Rod x Block + Prim x Rod x Block (Error AB)	4	2.41	0.58	0.35
Date of Sampling	6	20.67**	6.15**	2.83**
Date x Prim	6	1.02	0.73	0.23
Date x Rod	6	1.72	0.35	0.36
Date x Prim x Rod	6	1.24	1.45	0.12
Date x Block + Date x Prim x Block + Date x Rod x Block + Date x Prim x Rod x Block (Error ABC)	48	0.86	0.82	0.44
Total	83			
CV Error A		0.47	0.15	0.01
CV Error AB		0.26	0.07	0.05
CV Error ABC		0.16	0.08	0.05

*Significant at 5% level.

**Significant at 1% level.

Table 7. Mean squares from the analysis of variance for soil water content (g-g^{-1}) at 9, 15, and 22.5 cm in 1976.

Source of Variation	df	Depth (cm)		
		9	15	22.5
Block	2	7.93	4.26	3.59
Primary Tillage	1	86.16	3.60	0.16
Prim x Block (Error A)	2	5.24	0.50	0.25
Rod Depth	1	57.04**	0.04	3.13**
Prim x Rod	1	1.44	1.63*	0.00
Rod x Block + Prim x Rod x Block (Error AB)	4	1.02	0.18	0.09
Date of sampling	4	4.36*	2.44**	3.08**
Date x Prim	4	1.68	0.16	0.35
Date x Rod	4	1.97	0.20	0.73*
Date x Prim x Rod	4	2.04	0.35	0.05
Date x Block + Date x Prim x Block + Date x Rod x Block + Date x Prim x Rod x Block (Error ABC)	32	1.20	0.50	0.22
Total	59			
CV Error A		0.27	0.06	0.04
CV Error AB		0.12	0.03	0.02
CV Error ABC		0.13	0.06	0.04

*Significant at 5% level.

**Significant at 1% level.

Table 8. Soil water content ($g\text{-}g^{-1}$) by depth and date, 1976, averaged over tillage treatments. Dashes indicate that those depths were not sampled separately from the adjacent depths.

Sampling Date	Depth (cm)				
	6	9	12	15	18
21 August	.078	-	.120	-	.136
4 September	.074	-	.125	-	.134
16 September	.053	.094	.124	.131	.135
20 October	.049	.079	.113	.127	.129
16 October	.044	.080	.110	.124	.129
30 October	.053	.082	.109	.121	.124
12 November	.060	.086	.109	.120	.125
$ASD_{.05}$	.009	.011	.009	.007	.006

Table 9. Interaction of sampling date and rodweeding depth on soil water content ($g\text{-}g^{-1}$) during 1976 at 22.5 cm.

Sampling Date	Rodweeding Depth		$\bar{x}$
	Shallow	Deep	
16 September	.134	.136	.135
2 October	.129	.135	.132
16 October	.123	.136	.130
30 October	.123	.125	.124
12 November	.123	.124	.123
$\bar{x}$	.127	.131	
$ASD_{.05}$	.003		

Table 10. Interaction of primary tillage and rodweeding depth on soil water content ($g\text{-}g^{-1}$) at 12, 15, and 18 cm. Values are averaged over replications and sampling dates in 1976. At 18 cm, there was a significant effect of primary tillage only.

Mulch Depth	12 cm			15 cm			18 cm	
	Bare	Stubble	$\bar{x}$	Bare	Stubble	$\bar{x}$	Bare	Stubble
Shallow	.123	.113	.118	.129	.129	.129	-	-
Deep	.124	.103	.113	.131	.130	.130	-	-
$\bar{x}$	.124	.108		.131	.130		.127	.122
$ASD_{.05}$	.009			.007			.006	

Table 11. Average gravimetric soil water content ($g\text{-}g^{-1}$) by depth for four fallow tillage treatments on different dates in 1977. Each value is the mean of three replications, two samples per replication, of soil cores with centers at the indicated depths.

Treatment	Depth	Sampling Date						
	(cm)	13 July	4 Aug	1 Sept	16 Sept	4 Oct	12 Oct	27 Oct
Bare fallow, shallow mulch	0.5	0.015	0.012	0.028	0.020	0.033	0.027	0.031
	2.0	0.019	0.017	0.083	0.028	0.081	0.051	0.039
	4.0	0.027	0.025	0.114	0.051	0.108	0.086	0.060
	6.0	0.045	0.044	0.114	0.070	0.111	0.101	0.083
	8.0	0.083	0.071	0.098	0.089	0.108	0.106	0.100
	10.0	0.110	0.101	0.093	0.099	0.107	0.112	0.113
	12.0	0.123	0.112	0.099	0.115	0.110	0.116	0.116
	14.0	0.131	0.121	0.111	0.109	0.110	0.118	0.120
	16.5	0.134	0.121	0.114	0.112	0.114	0.119	0.125
	21.0	0.139	0.125	0.116	0.116	0.114	0.117	0.127
	27.0	0.141	0.127	0.121	0.116	0.118	0.122	0.126
Bare fallow, deep mulch	0.5	0.016	0.013	0.022	0.021	0.032	0.029	0.030
	2.0	0.018	0.019	0.067	0.027	0.072	0.056	0.039
	4.0	0.024	0.027	0.107	0.039	0.107	0.089	0.056
	6.0	0.035	0.046	0.111	0.059	0.111	0.100	0.077
	8.0	0.066	0.065	0.086	0.080	0.101	0.101	0.092
	10.0	0.097	0.090	0.073	0.096	0.093	0.100	0.100
	12.0	0.116	0.110	0.087	0.105	0.101	0.106	0.111
	14.0	0.124	0.122	0.098	0.114	0.110	0.111	0.117
	16.5	0.130	0.126	0.107	0.114	0.115	0.113	0.118
	21.0	0.136	0.128	0.116	0.118	0.118	0.114	0.120
	27.0	0.136	0.127	0.118	0.119	0.118	0.116	0.122

Table 11. (Continued)

Treatment	Depth (cm)	Sampling Date 13 July	4 Aug	1 Sept	16 Sept	4 Oct	12 Oct	27 Oct
Stubble fallow, shallow mulch	0.5	0.015	0.016	0.023	0.022	0.047	0.031	0.032
	2.0	0.020	0.022	0.074	0.029	0.094	0.065	0.044
	4.0	0.029	0.038	0.108	0.048	0.115	0.096	0.069
	6.0	0.064	0.076	0.115	0.077	0.118	0.107	0.093
	8.0	0.107	0.100	0.113	0.093	0.120	0.114	0.105
	10.0	0.110	0.110	0.105	0.101	0.120	0.115	0.109
	12.0	0.110	0.111	0.102	0.105	0.118	0.111	0.112
	14.0	0.115	0.113	0.102	0.110	0.117	0.111	0.113
	16.5	0.121	0.118	0.106	0.110	0.119	0.113	0.116
	21.0	0.131	0.120	0.112	0.115	0.118	0.117	0.121
	27.0	0.133	0.125	0.117	0.118	0.118	0.119	0.124
Stubble fallow, deep mulch	0.5	0.014	0.016	0.024	0.020	0.043	0.029	0.034
	2.0	0.020	0.021	0.082	0.027	0.097	0.060	0.043
	4.0	0.033	0.033	0.111	0.044	0.116	0.094	0.064
	6.0	0.064	0.076	0.112	0.071	0.116	0.103	0.085
	8.0	0.107	0.111	0.098	0.090	0.110	0.107	0.098
	10.0	0.117	0.117	0.099	0.098	0.107	0.107	0.103
	12.0	0.118	0.117	0.099	0.101	0.106	0.105	0.106
	14.0	0.121	0.118	0.098	0.105	0.107	0.106	0.108
	16.5	0.125	0.122	0.103	0.108	0.107	0.108	0.111
	21.0	0.131	0.125	0.110	0.111	0.111	0.116	0.116
	27.0	0.132	0.128	0.116	0.114	0.116	0.115	0.118

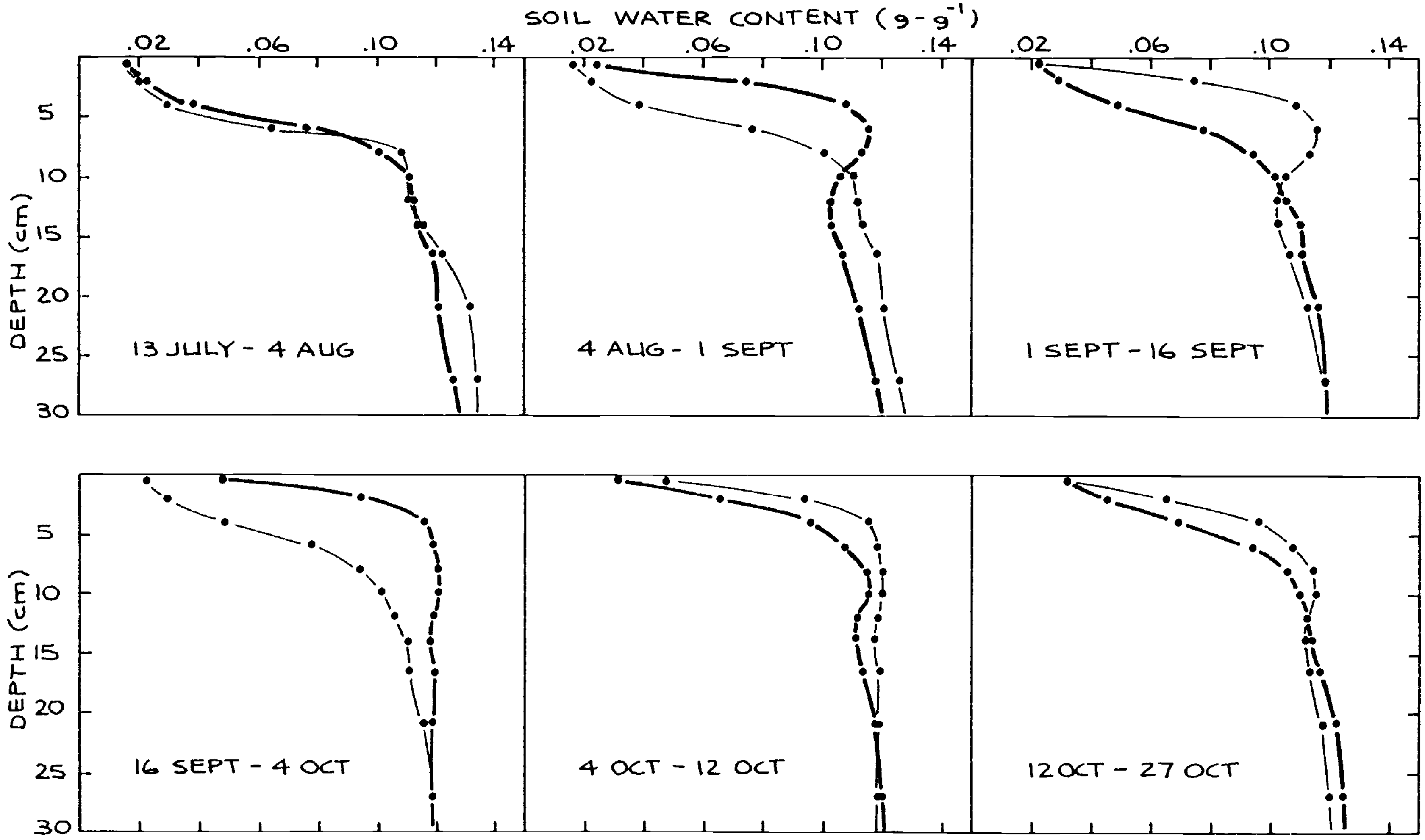

Figure 8. The pattern of change in water distribution in the upper soil profile of the stubble fallow, shallow mulch treatment, 1977. The light line in each graph represents the water content profile on the early date, the heavy line represents the later date. Increases in water content near the surface were due to rainfall.

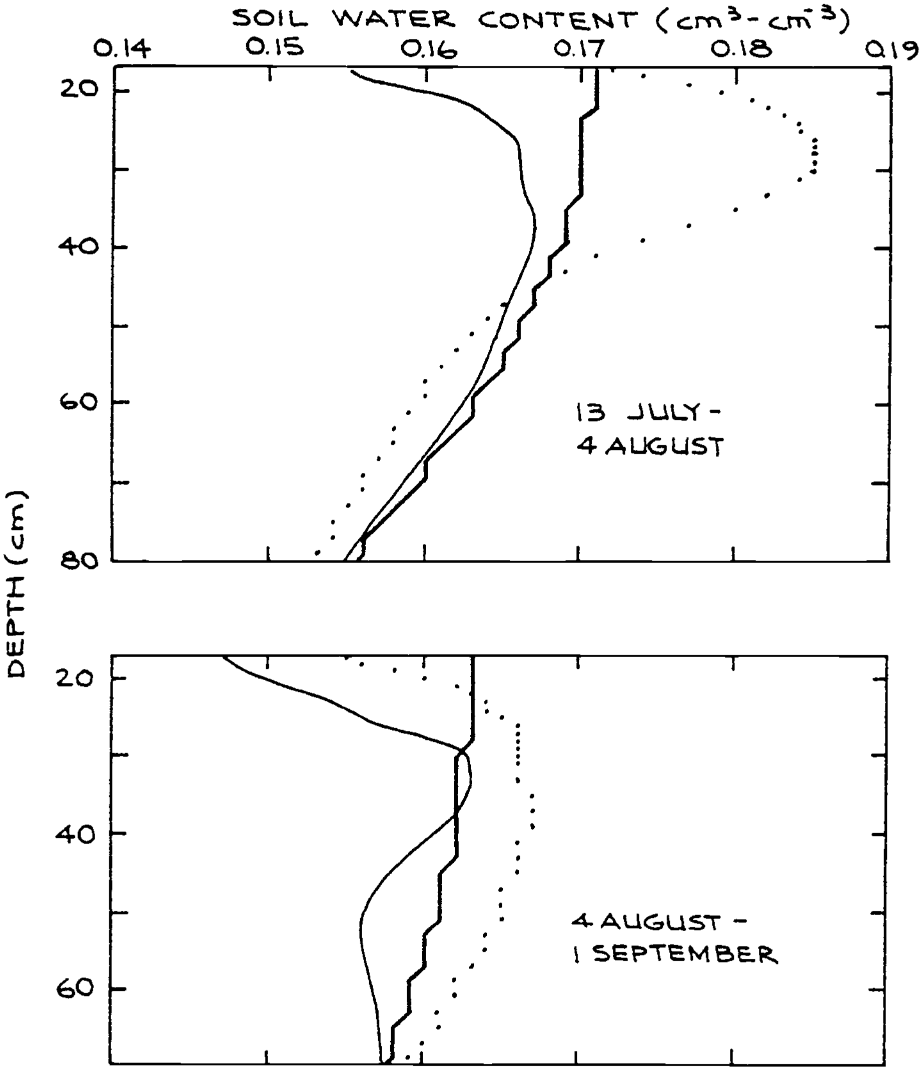

Figure 9. Results of the simulation program-- soil water content by depth. The dotted curves are the initial measured values of the indicated period, the thin solid curves are the final measured values of the period, and the heavy solid curves are the results of simulating redistribution in the profile.

Table 12. Gravimetric soil water content ($g\text{-}g^{-1}$) under two tillage treatments on six dates during 1976. P = bare fallow; S = stubble fallow. Values are averages of two or three replications.

Depth (cm)	26 May[a]		1 July		7 Aug		4 Sept		2 Oct		30 Oct	
	P	S	P	S	P	S	P	S	P	S	P	S
0-15	.144	.145	.136	.139	.106	.108	.090	.107	.091	.083	.100	.094
15-30	.154	.154	.147	.144	.132	.134	.134	.135	.131	.128	.122	.124
30-45	.147	.149	.142	.138	.128	.136	.131	.130	.125	.128	.122	.126
45-60	.142	.143	.136	.134	.132	.133	.128	.128	.124	.128	.122	.126
60-75	.134	.135	.131	.129	.128	.130	.129	.128	.124	.127	.120	.126
75-90	.126	.123	.125	.121	.120	.126	.128	.127	.125	.124	.118	.120
90-105	.113	.115	.118	.113	.114	.121	.130	.127	.126	.129	.114	.118
105-120	.106	.106	.114	.103	.114	.119	.129	.128	.124	.128	.120	.122
120-135	.119	.115	.113	.104	.123	.119	.129	.128	.124	.126	.120	.122
135-150	.121	.117	.113	.110	.124	.118	.130	.129	.123	.128	.126	.124

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[a] Samples taken in 15-cm increments beginning at 5 cm under the bare fallow and 10 cm under the stubble fallow.

Table 13. Soil water content ($g\text{-}g^{-1}$) by date and depth for the 0-150-cm soil profile, 1976. The top 15 cm was not analyzed because of high variability between samples. The data for 26 May were not included in the analysis of variance because the samples were taken for different increments (see Table 12). In this table, the values for 26 May have been adjusted to correspond to the indicated depth increments, but should not be compared to other dates using the LSD values.

	Depth increment (cm)									
Date of Sampling	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	120-135	135-150
26 May	.137	.153	.152	.144	.138	.128	.118	.108	.114	.120
1 July	.134	.145	.140	.135	.132	.124	.116	.110	.110	.112
7 August	.108	.133	.132	.132	.129	.123	.118	.117	.121	.121
4 September	.103	.134	.131	.128	.129	.128	.128	.128	.128	.129
2 October	.087	.130	.127	.126	.126	.124	.128	.126	.126	.125
30 October	.097	.122	.124	.126	.123	.119	.118	.122	.121	.125
LSD$_{.05}$	-	.006	.005	.003	.003	NS	.006	.006	.008	.010
LSD$_{.01}$	-	.008	.007	.004	.004	NS	.009	.008	.012	.014

NS = F test nonsignificant.

Table 14. Mean squares from the analysis of variance for soil water content (g-g^{-1}) at the indicated depths in the 0-150-cm soil profile, 1976. This analysis excludes the 26 May sampling because of sampling method differences.

Source of Variation	d.f.	Depth increment (cm) 15-30	30-45	45-60	60-75	75-90	90-105	105-120	120-135	135-150
Blocks	1	0.364	0.084	0.338	0.242	0.760	0.612	1.458	1.984	3.042
Treatments	9	1.260**	0.758**	0.426**	0.249**	0.218	0.733*	1.202**	1.016*	0.799
Primary tillage	1	0.000	0.220	0.098	0.162	0.012	0.000	0.008	0.180	0.072
Date of sampling	4	2.755**	1.443**	0.843**	0.459**	0.407	1.441**	2.253**	1.993**	1.595*
Tillage x date	4	0.088	0.207	0.092	0.061	0.080	0.209	0.449	0.247	0.184
Treatment x Block	9	0.121	0.093	0.034	0.026	0.140	0.141	0.135	0.264	0.358
Total	19									
CV		0.03	0.02	0.01	0.01	0.03	0.03	0.03	0.04	0.05

*Significant at 5% level.

**Significant at 1% level.

Table 15. Days to first emergence and 70% stand establishment for barley and wheat planted on various dates in 1976 and 1977. Values in parentheses are averages of less than the full number of replications, and were not included in the calculation of the approximate significant difference values. Dashes indicate that emergence or stand establishment had not been reached by mid-December, 1976.

Planting	1976				1977	
	Barley		Wheat		Wheat	
Date	Emergence	70% Stand	Emergence	70% Stand	Emergence	70% Stand
20 August	5.6	10.8	7.0	11.1		
1 September					6.5	8.2
4 September	6.4	9.4	7.6	11.4		
16 September	7.2	10.5	8.4	11.8	9.3	12.8
30 September					12.6	19.2
20 October	10.1	12.4	11.1	13.1		
12 October					10.4	14.5
17 October	23.5	27.5	23.3	28.6		
27 October					32.7	35.8
30 October	(45.6+)	-	(35.8)	-		
12 November	-	-	-	-		
Between species & years						
ASD $_{.05}$	1.4	2.4	2.0	3.5	3.1	14.3
Between species, 1976						
ASD $_{.05}$	2.8	7.9	2.8	7.9		

Table 16. Mean squares from the analysis of variance for days to emergence and 70% stand of wheat and barley, 1976.

Source of Variation	d.f.	Wheat		Barley	
		Emergence	70% Stand	Emergence	70% Stand
Block	3	0.55	7.75	2.15	11.35
Primary Tillage	1	10.51*	36.45	2.45	19.01
Prim x Block (Error A)	3	0.48	8.35	0.42	6.61
Rod Depth	1	0.01	1.80	0.05	0.31
Prim x Rod	1	0.01	0.80	0.05	0.11
Rod x Block + Rod x Prim x Block (Error AB)	6	0.15	0.57	0.10	0.18
Date of Planting	4	745.25**	907.08**	881.82**	913.82**
Date x Block (Error C)	12	0.40	5.99	0.69	7.53
Date x Prim	4	0.58	3.11	0.08	4.64
Date x Prim x Block (Error AC)	12	0.38	4.88	0.71	5.95
Date x Rod	4	0.14	0.39	0.05	0.12
Date x Prim x Rod	4	0.14	0.27	0.05	0.11
Date x Rod x Block + Date x Rod x Prim x Block (Error ABC)	24	0.15	0.47	0.07	0.21
Total	79				
CV Error A		0.06	0.19	0.06	0.18
CV Error AB		0.03	0.05	0.03	0.03
CV Error C		0.06	0.16	0.08	0.19
CV Error AC		0.05	0.15	0.08	0.17
CV Error ABC		0.03	0.05	0.03	0.03

*Significant at 5% level

**Significant at 1% level.

Table 17. Mean squares from the analysis of variance for days to emergence and 70% stand of wheat, 1977.

Source of Variation	d.f.	Emergence	70% Stand
Block	2	0.15	5.02
Primary Tillage	1	2.40	4.82
Prim x Block (Error A)	2	0.65	1.52
Rod Depth	1	0.67	0.42
Prim x Rod	1	0.27	2.02
Rod x Block + Rod x Prim x Block (Error AB)	4	0.47	3.37
Date of Planting	4	1322.61**	1324.89**
Date x Block (Error C)	8	0.73	6.89
Date x Prim	4	0.44	11.02
Date x Prim x Block (Error AC)	8	0.82	7.10
Date x Rod	4	0.19	6.71
Date x Prim x Rod	4	0.39	11.64
Date x Rod x Block + Date x Rod x Prim x Block (Error ABC)	16	0.34	7.14
Total	59		
CV Error A		0.06	0.07
CV Error AB		0.05	0.10
CV Error C		0.06	0.14
CV Error AC		0.06	0.15
CV Error ABC		0.04	0.15

**Significant at 1% level.

Table 18. Mean squares from the analysis of variance for days to emergence and 70% stand of wheat and barley, 1976. Data were averaged for different mulch depths, since previous analysis showed them not to be significantly different.

Source of Variation	df	Emergence	70% Stand
Block	3	1.05	7.00
Crop	1	15.31**	24.02*
Block x Crop (Error A)	3	0.21	2.20
Primary Tillage	1	6.61	26.45
Crop x Tillage	1	1.01	1.25
Block x Till + Block x Crop x Till (Error AB)	6	0.31	3.12
Date of Planting	4	807.26**	911.96**
Crop x Date	4	1.69**	1.48
Block x Date + Block x Crop x Date (Error AC)	24	0.32	3.36
Tillage x Date	4	0.36	1.48
Crop x Tillage x Date	4	0.14	2.53
Block x Till x Date + Block x Crop x Till x Date (Error ABC)	24	0.29	2.81
Total	79		
CV Error A		0.04	0.10
CV Error AB		0.05	0.12
CV Error AC		0.05	0.13
CV Error ABC		0.05	0.11

*Significant at 5% level.

**Significant at 1% level.

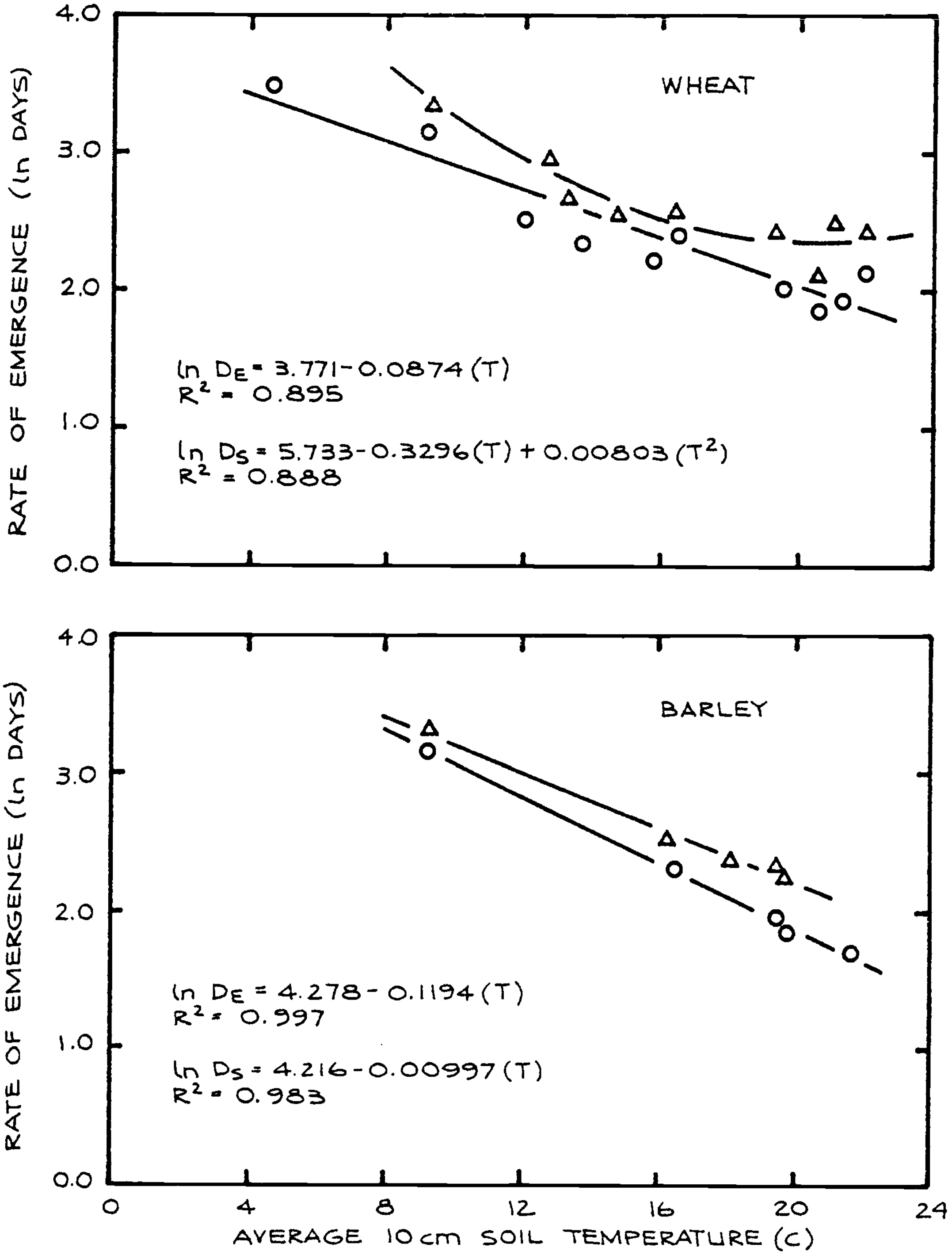

Figure 10. The relationship between average 10-cm soil temperature and the natural logarithm of days to first emergence (D_E) and 70% stand (D_S) for wheat and barley. The open circles represent emergence; the triangles represent stand. Note that, for barley, the very high coefficients of determination for the regression equations may be due to the extreme data points. These relationships are presented so that comparisons with other predictive equations will be easier.

Table 19. Mean squares and coefficients of determination for the regression of average 10-cm soil temperature on the reciprocal of days to first emergence and 70% stand of wheat and barley.

Source	Wheat				Barley			
	df	Emergence	df	Stand	df	Emergence	df	Stand
Total	9		8		4		4	
Regression	1	0.01314**	1	0.00354**	1	0.01153**	1	0.00292**
Residual	8	0.00020	7	0.00018	3	0.00015	3	0.00002
R^2		0.890**		0.735**		0.962**		0.983**

**Significant at the 1% level.

Table 20. Mean squares and coefficients of determination for the regression of average 10-cm soil temperature on the natural logarithm of days to first emergence and 70% stand of wheat and barley. For 70% stand of wheat, the regression equation includes the second-order term of temperature squared.

Source	Wheat				Barley			
	df	Emergence	df	Stand	df	Emergence	df	Stand
Total	9		8		4		4	
Regression	1	2.22810**	2	0.45699**	1	1.32084**	1	0.73569**
Residual	8	0.03256	6	0.01919	3	0.00150	3	0.00431
R^2		0.895**		0.888**		0.997 **		0.983**

**Significant at the 1% level.

Table 21. Relative stand prior to harvest of wheat and barley planted on seven dates in 1976 in four fallow tillage treatments. Values are means of four replications with two independent determinations per replication, and are expressed as percent of the best plots.

Planting Date		Bare fallow		Stubble fallow		Mean
		Shallow mulch	Deep mulch	Shallow mulch	Deep mulch	
20 Aug	Wheat	87	79	82	76	81
	Barley	52	34	57	25	42
4 Sept	Wheat	96	91	93	87	92
	Barley	91	87	82	80	85
16 Sept	Wheat	91	87	82	80	85
	Barley	92	89	91	82	88
2 Oct	Wheat	97	95	92	86	92
	Barley	92	90	88	84	88
17 Oct	Wheat	92	92	90	76	88
	Barley	65	46	36	25	43
30 Oct	Wheat	86	84	78	60	77
	Barley	14	8	2	2	6
12 Nov	Wheat	73	67	57	33	58
	Barley	0	0	0	0	0
	Mean	73	68	66	57	

Table 22. Grain yield (g-m^{-2}) of wheat and barley planted on seven dates in 1976 in four fallow tillage treatments. Values are means of four replications.

Planting Date		Bare fallow		Stubble fallow		Mean
		Shallow mulch	Deep mulch	Shallow mulch	Deep mulch	
20 Aug	Wheat	87	73	100	89	87
	Barley	71	54	56	42	56
4 Sept	Wheat	171	178	179	213	186
	Barley	217	184	172	192	191
16 Sept	Wheat	376	319	306	228	307
	Barley	375	327	333	348	346
2 Oct	Wheat	402	347	334	320	351
	Barley	414	368	340	355	369
17 Oct	Wheat	308	318	248	243	279
	Barley	239	230	168	130	192
30 Oct	Wheat	222	182	180	130	178
	Barley	54	28	0	0	20
12 Nov	Wheat	164	152	114	81	128
	Barley	0	0	0	0	0
	Mean	222	181	197	169	

Table 23. Mean squares from the analysis of variance for plot yield (g-m^{-2}) of wheat and barley, 1976. The last two planting dates were omitted from the ANOVA for barley, because no yield was obtained in most treatments on those dates.

Source of Variation	d.f.	Wheat	d.f.	Barley
Block	3	36969.46	3	24016.21
Primary Tillage	1	40698.44	1	23632.81
Prim x Block (Error A)	3	7026.68	3	49773.41
Rod Depth	1	14789.01	1	4851.61
Prim x Rod	1	0.01	1	4636.01
Rod x Block + Rod x Prim x Block (Error AB)	6	5021.41	6	9044.31
Date of Planting	6	152098.70**	4	264182.74**
Date x Block (Error C)	18	7074.18	12	33621.00
Date x Prim	6	6466.08	4	3899.00
Date x Prim x Block (Error AC)	18	2486.35	12	6841.52
Date x Rod	6	3491.78	4	147.74
Date x Prim x Rod	6	639.40	4	1711.33
Date x Rod x Block + Date x Rod x Prim x Block (Error ABC)	36	1926.77	24	2075.66
Total	111			
CV Error A		0.39		0.97
CV Error AB		0.33		0.41
CV Error C		0.39		0.79
CV Error AC		0.23		0.36
CV Error ABC		0.20		0.20

**Significant at 1% level.