THE EFFECTS OF SOIL MOISTURE, MULCH, SLOPE-FACING, AND SURFACE TEMPERATURE ON GRASS SEEDLINGS

by

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INTRODUCTION

The quick establishment of sod cover on highway slopes is essential to prevent damage to roadways and adjacent property by wind, soil and water erosion. When slopes are steep, often at a 30- to 40-degree angle to the horizontal, seeding becomes a problem if conventional agricultural procedures are employed. Therefore slopes are usually seeded hydraulically using a seed-fertilizer-mulch (wood-cellulose fiber) water slurry. This method has sometimes produced a poor vegetative cover under conditions of moisture and temperature stresses, especially on south-facing slopes. Perhaps high bare-soil and mulch-surface temperatures, which occur with high soil moisture tensions and intense solar radiation, reduce grass stands when seedlings are at a young and tender growth stage. Seeds are often sown in the spring and fall when intense solar radiation sometimes strikes steep south-sloping surfaces at nearly perpendicular directions and consequently produces severe heating of the soil surface and a concomitant loss of soil moisture. The combined effects of high temperature and high moisture tension can cause injury to newly-emerged seedlings.

The two experiments presented were designed to ascertain the relative importance of soil surface temperatures with respect to survival of young grass seedlings. Emphasis was placed on the effects of soil moisture tension, wood cellulose mulch, and slope facing on surface temperatures and seedling growth.

LITERATURE REVIEW

The importance of microclimate to plant growth has been stressed by many authors (Bark and Laude 1957; Kinbacher and Jensen 1959; McKee, et al. 1965; Our Crops... 1955; Potzger 1939; Sprague 1959; Sprague, et al. 1955; Sprague and McCloud 1962; Sprague, et al. 1954). The air layer 4 feet above the ground, frequently termed the microclimatic layer, is much more rigorous than the macroclimate (Sprague, et al. 1954). The existence of tender young seedlings, a few centimeters tall, is challenged by severe environments.

Solar "radiation is undoubtedly the most important of all meteorologic elements;" it warms the earth's surface, which in turn warms the air above (Geiger 1965). With cloud cover, wind velocity, and the varied nature of the earth's surface, radiation induces extreme temperature fluctuations (near the soil surface), which have profound effects on plant microclimates (Sprague, et al. 1954).

Close to the soil surface, where temperatures are highest, plants frequently suffer heat injury (Evans 1959). Surface temperatures up to 70^{o}C have been recorded in Germany (Geiger 1965).

Work with tree seedlings has shown that high surface temperatures in some years cause more losses than other environmental factors (Haig 1936; Isaac 1938). Soil surface temperature was the most important factor affecting tree seedling establishment, exceeding drought as a cause of injury and death. McKee, et al. (1965) found that soil surface temperatures increased as grass cover decreased. Reddy and Brentzel (1922) reported surface temperature injuries of flax, buckwheat, wheat, barley and oats. Surface temperature injury was more difficult to detect among grass than tree seedlings. This appeared so because grasses outgrew in a few days the young growth stage when they were most susceptible to injury, while tree seedlings remained in a sensitive growth stage for weeks at a time. There was less injury as plants matured (Baker 1929; Rudolph 1939; Shirley 1936).

Measurement of the actual surface temperatures has been complicated by the theoretical two-dimensional nature of the soil-air interface. Also, steep temperature gradients on both sides of the interface and extreme variation from one location to another have made lethal temperature measurement difficult (Vaartaja 1949).

Man's observation that increased soil covering modified the microclimate led him to use mulches to reduce high surface temperatures (Geiger 1965). Reduction of water loss by evaporation, reduction of weed growth, and promotion of soil productivity are other purposes of mulching (Jacks, et al. 1955). Mulching research has been directed primarily at increasing crop yields, and the effects of mulch on microclimate were rarely determined (Geiger 1965). Modification of surface climate and improvement of the water balance of soils are accompanied by many interactions which complicate mulching investigations. So many soil properties are modified by mulching that it has been difficult to attribute benefits of mulching to any one soil factor (Jacks, et al. 1955).

Temperature is a measure of the potential at which the heat exchange processes (convection, conduction, evaporation, radiation) are in equilibrium. Temperature is not to be confused with either the amount of heat or energy exchange. A surface (plant or soil) temperature is determined by the exchange processes (Raschke 1960).

The major factor among many interacting physical phenomena affecting the heat balance of the earth's surface is the intensity of solar radiation (Shreve 1924) which reaches the earth either directly, as scattered or diffuse radiation, or as cloudlight (Idso, et al. 1966). Soil surface temperatures increase linearly with ft-c light intensity (McKee, et al. 1965). Light intensity is governed by cloud cover, elevation of the sun, latitude, and angle and aspect of sloping topography. Other physical and meteorological phenomena affect the heat balance after the solar energy has reached the ground. Soil water evaporation, eddy diffusion, intermolecular conduction, long-wave reradiation, precipitation, and wind velocity determine the amount of heat retained by the earth or transferred to the atmosphere. Soil properties such as color or reflecting ability (albedo), water content, specific heat, and thermal conductivity also influence the heat balance (Baker 1965; Baker 1929; Geiger 1965).

Measurement of Surface Temperatures

Mercury bulb thermometers and thermocouples have been generally used to measure temperature. These devices, usually 2 to 6 mm in diameter, have been utilized by most investigators. However, reasonably accurate determination of the temperature at the soil-air interface has required thermocouples less than a millimeter in diameter (Baker 1929). Jacob and Hawkins (1957) discussed the problems of surface temperature measurement.

Weather Conditions Conducive to High Surface Temperatures

Since soil surface temperature was not directly related to air temperature (Isaac 1938), other meteorological conditions that lead to surface heating should be considered. Smith (1955) observed 55°C temperatures on a pine litter surface less than ten minutes after complete exposure to the sun. This occurred on a cool, clear August day with a strong northwesterly flow of polar continental air. Such cool polar continental air was normally more transparent than warm tropical maritime air which frequently contained much water vapor, smoke, and haze. In spite of 55°C surface temperatures, Smith (1951) measured 21°C one inch below the surface of mineral soil and 19°C one inch below a pine litter surface.

While cloud cover, horizontal shading, or strong wind had as much as a 20°C cooling effect in a few minutes, highest temperatures were recorded on sites exposed to direct radiation (Vaartaja 1949). Conditions favoring a moist bare mineral soil led to few or no problems with high soil surface temperatures (Smith 1951).

Influence of Soil and Topography on Surface Temperatures

Soil

Physical and chemical properties of soil solids, water content, and air content affected the thermal properties of a soil (Geiger 1965). Various interactions between the soil solids, water and air caused dark soils to heat more than light, loose soils more than compact, and dry soils more than wet soils.

The specific heat, conductivity, and color are terms descriptive of soil properties. The specific heat, a measure of a material's ability to conduct heat, is the number of calories required to raise the temperature of one gram of soil 1°C. Density and water content influence the specific heat of a soil; the effect of air is negligible. The specific heat increases with increasing water content and decreasing particle size and has been shown to be dependent on the chemical composition of the soil particles (Geiger 1965).

To illustrate how specific heat and conductivity of materials affect surface temperatures, Vaartaja (1949) compared sandy soil with rock. The surface temperature of sandy soil was higher than that of the rock because the specific heat and conductivity per unit volume of sand were lower than of the rock, even though no evaporation occurred from the rock. The sun's energy remained concentrated in a thin surface layer of the sandy soil due to its low thermal conductivity and specific heat. The high thermal conductivity and specific heat of the rock caused the heat to be dissipated throughout the material.

The water content at the soil surface varies with rainfall and radiation-induced evaporation. Soil moisture was less important than high surface temperature among factors affecting tree seedling establishment (Isaac 1938). Changes in soil moisture affected (a) color and albedo, (b) density, (c) specific heat, and (d) thermal conductivity of soil. Increases in water content usually darkened the color of a soil, reducing its reflecting ability. Density, specific heat, and thermal conductivity increased with water content, largely because of the reduced number of air spaces. Additions of water decreased soil temperatures because of heat absorbed in evaporation, not because of a low water temperature which soon reached that of the soil.

Soil air, besides depending on water content, varied with structure, texture, organic matter, and state of cultivation; e.g. cultivation increased air content and thus decreased conductivity, thereby permitting greater temperature fluctuations (Baker 1965; Geiger 1965). The high air content of dry organic matter gave it a lower specific heat than that of dry mineral soil. The surface temperature of sun-dried pine litter was raised almost twice as much by a given amount of heat as a bare sandy surface (Smith 1951). When pine litter covered a soil, it acted as an insulator because of its low specific heat and conductivity; little heat was conducted into the soil (Smith 1951). In contrast to poor-conducting materials like pine litter, a good-conducting soil had low daily maximum temperatures and high daily minimum temperatures; it retained heat throughout the soil mass rather than in the surface layer (Geiger 1965). The high specific heat and conductivity of moist bare mineral soils accounted for their moderate temperatures.

Soil color and reflecting ability (albedo) constituted a third major factor affecting soil surface temperature. In addition to water and air content, soil color determined the amount of radiation absorbed or reflected (Geiger 1965). A dark soil absorbed more heat than a light-colored one (Baker 1965). When white powdered lime was spread on the surface of a dark soil, it reduced the surface temperature 15°C below that of bare soil (Isaac 1938). In comparing yellow, gray, and black soils, Isaac (1938) found that the gray soil temperature averaged 5°F higher than that of the yellow soil. At higher air temperatures (above 100°F) the black soil heated most rapidly up to 165°F, which was 15°F and 18°F above the temperatures of the gray and yellow soils, respectively. Surface temperature differences among various soils were usually not greater than 2 to 5°C.

Albedo was influenced by color and moisture content: wet surfaces appeared darker than dry surfaces. If a water layer existed on a soil surface, the albedo may have been influenced by the angle at which the sun's rays struck the inner surface of the water layer. To be absorbed radiation had to strike the inner surface at an angle greater than the critical angle for total reflection. Cloudiness and horizontal shading also affected albedo (Geiger 1965; Isaac 1938).

Topography

The intensity of solar radiation striking a surface is determined by the direction (aspect) and angle of slope of topography, as well as by geographic latitude and declination and altitude of the sun. Maximum intensity occurs on a slope perpendicular to the sun's rays; e.g. a steep south-facing slope would receive more radiation in the winter than in the summer; the reverse is true for a flat surface. Baker (1965) determined that a 30 degree south-facing slope at noon in St. Paul, Minn., was struck by radiation at an altitude and angle of the sun equivalent to a level surface at 15 degrees north latitude. As aspect and angle influenced intensity, intensity in turn affected soil surface temperature and moisture content. The temperature and moisture differences among different slope-facings consequently determined microclimate and vegetational characteristics (Geiger 1965; Shreve 1924). Southwest-facing slopes tended to be the warmest: in the morning the solar energy evaporated and dried the moist soil; in the afternoon the energy was absorbed by the dried soil, causing an increase in soil surface temperatures (Baker 1965; Geiger 1965).

While surface temperatures and evaporation rates were higher and soil moisture content was lower on southern exposures than on others (Isaac 1938), the northerly aspect had an ameliorating effect on temperatures and moisture content (Haig 1936). Thus plant growth was usually better on north slopes than on more severe southern exposures (Aikman 1941; Isaac 1938).

Processes of Heat Transfer

Four physical processes transfer heat from the ground surface to the air. In order of importance they are (a) evaporation, (b) eddy diffusion, (c) intermolecular conduction, and (d) long-wavelength reradiation (Gates 1964; Geiger 1965; Idso, et al. 1966; Jakob and Hawkins 1957; Raschke 1960; Smith 1951). Heat conducted or radiated from the earth's surface is the primary source of warmth in the atmosphere. The irregularity of the processes transferring this heat makes the density of the air masses near the ground highly variable, actually optically inhomogeneous (Geiger 1965). Observation of optical phenomena near the surface illustrates the inhomogeneity and the temperature gradient.

Evaporation is a diffusion process and also one of latent heat loss. The amount of heat lost from a surface cannot exceed the magnitude of energy gained by radiation and convection. Water molecules absorb heat from air and soil particles, thus reducing soil temperatures. Upon reaching the heat of vaporization, water changes its physical state from liquid to gas. A transport of energy into the atmosphere as water vapor results (Raschke 1960). The intensity of evaporative heat exchange depends on the resistance of the surface's boundary layer (discussed below). Usually the temperature depression for given conditions is proportional to the evaporation rate (Wiegand and Namken 1966).

Eddy diffusion, turbulent as opposed to laminar flow of air, is the sum of two processes: (a) frictional exchange and (b) convectional exchange. Frictional exchange of heat is caused by variations in the roughness of natural surfaces and by changes in wind speed with height. It is a shear or forced convection as the name "friction" implies and is the only kind that occurs at night (Geiger 1965).

During the day convectional exchange usually masks the effect of the lesser process frictional exchange. Convection is macroscopic heat transfer, as opposed to conduction which is considered microscopic (Jakob and Hawkins 1957). Convectional exchange is caused by solar heating; it is more important than, although aided by, wind in heat transfer (Clum 1926). Convection involves overheated parcels of air rising from the ground into the atmosphere and cold heavy air sinking downward to occupy the vacant space (Geiger 1965; Smith 1951; Vaartaja 1949). The intensity of convective transfer is proportional to the temperature difference between a surface and the air above and is dependent on the resistance of the boundary layer (Raschke 1960). Jakob and Hawkins (1957) consider convection to be affected by the following: (a) shape, dimensions, and roughness of the surface involved, (b) direction and velocity of air flow, and (c) temperature, density, specific heat, and thermal conductivity of the air. Smith (1951) considers convection to be most active above surfaces interrupted by large pores.

Processes of eddy diffusion do not extend to solids. Adhering with great tenacity to solid surfaces is a layer of air that is characterized as the atmosphere's lowermost edge, from which eddy diffusion increases rapidly with height, Fig. 1. The boundary layer is both a transfer and insulating zone, which affects the intensity of all heat transfer processes. Its width (1-10 mm) depends on wind velocity and the nature of the surface it covers. The thicker the layer, the smaller the temperature fluctuations (Raschke 1960). Geiger's (1965) observations indicated that this layer does not reach a height of 1 cm: in wintertime the temperature at 1 mm above the surface ranged from 6-9°C while the temperature at 1 cm fluctuated from 0-4°C. Although eddy diffusion had little effect on this "formidable surface barrier" (Geiger 1965), intermolecular conduction was responsible for most of the heat transfer from the surface to the boundary layer (Vaartaja 1949).

Intermolecular conduction is a relatively slow process (Jakob and Hawkins 1957; Vaartaja 1949); its rate depends on the temperature difference (gradient) between the air and the ground surface (Jakob and Hawkins 1957; Raschke 1960; Smith 1951).

The fourth heat transfer process is long-wavelength reradiation. Its rate is proportional to the fourth power of the absolute temperature of the radiating surface and to the temperature difference between the radiating surface and the surrounding medium (Raschke 1960). For radiation to be emitted from a surface there must be a radiation-absorbing body of equal or lower temperature than the radiating body.

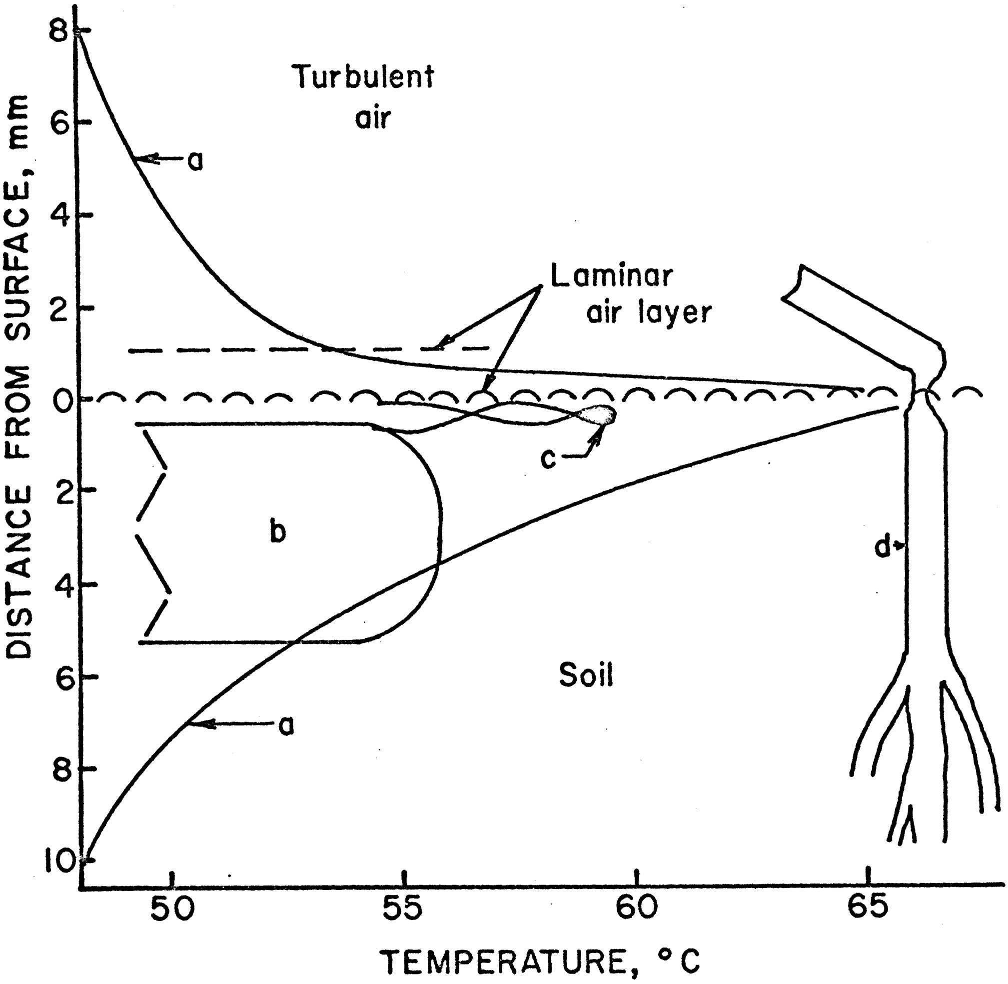

Fig. 1. Surface soil and its temperature measurement (schematic): a) temperature distribution curves in the neighborhood of the soil surface; b) part of a mercury bulb thermometer; c) part of a thermocouple; d) base of a damaged seedling. In a case like this the mercury bulb thermometer would show approximately 58°C and the thermocouple approximately 67°C. (Vaartaja, 1949)

The absorbing body could be outer space or cold gases like CO_2 and water vapor, i.e. clouds (Curtis 1936). The medium through which the radiation flows (usually air) is perfectly permeable and does not become heated. Only when the wave-motion energy is absorbed by a cold body is it converted to thermal energy (Jakob and Hawkins 1957). Net loss of infrared radiation is usually greatest during the day owing to high surface temperatures (Raschke 1960), but is most evident at night (dew formation and frost damage) because it is the primary cooling process occurring at that time (Idso, et al. 1966). The absence of the cooling effect by reradiation can cause severe overheating in greenhouses which are opaque to infrared radiation.

Surface Heat Injury of Seedlings

Commonly known as stem girdle or heat girdling, soil surface heat injury of seedlings occurs in a narrow band at the base of the plant stem, either at the level of the interface where heated soil particles cause the injury or within the first two millimeters above the surface where the superheated laminar air layer may cause the injury (Smith 1951).

Heat girdling of succulent conifer seedlings involves formation of tiny white lesions on the south side of the stem base, darkening of the tissue giving a bruised appearance, followed by longitudinal wrinkling. A well-developed constriction may appear immediately or hours after water is lost from the dead cells (Baker 1929). The plant may die or recover from the injury. Only when starving roots cannot support the needs of the aerial portion is injury fatal. Heat girdling often weakens the plant, making it susceptible to secondary injury from drought and/or plant disease.

The literature (Carroll 1943; Geiger 1965; Isaac 1938; McKee, et al. 1965; Reddy and Brentzel 1922; Rudolph 1939; Vaartaja 1949; Vaartaja 1954) has been inconsistent in specifying the lowest temperature at which girdling occurs. Variation is perhaps due to numerous methods of measurement and the variability of the earth's surface, which causes inconsistent surface temperatures, i.e. a standard deviation of 4.03°C in Vaartaja's (1949) work. Small temperature and exposure time differences may cause major differences in extent of injury, i.e. between no injury and slight injury and between slight injury and fatality (Lorenz 1939). Investigators have often lost the significance of some results by not accounting for exposure time in data interpretation. Lorenz (1939) summarized work of several researchers indicating injury, temperature, and exposure time.

Working with a temperature-controlled water bath, Lorenz obtained an hyperbolic curve when lethal temperature (56-66°C) was plotted versus time of exposure (0-30 mins.). The lowest surface temperatures at which injury occurred seemed to be 120-125°F (Baker 1929; Carroll 1943; Isaac 1938; Toumey and Neethling 1924); the highest lethal surface temperatures have been measured about 65°C (Hide 1943; Rudolph 1939; Vaartaja 1949). Vaartaja (1949) measured 56.6°C and 59°C at the surface of a dry heath in Finland, while 33.5°C and 26.3°C temperatures were observed 10 cms above the ground. Hide (1943) in Kansas measured maximum surface temperatures of 144-156°F with maximum air temperatures of 100-104°F. Soil temperature maxima increased gradually with air temperature maxima. Differences between air and soil temperatures were not always proportional to increases in maximum air temperature (Isaac 1938).

Influence of the Plant on Its Temperature

Flax (Reddy and Brentzel 1922), Douglas fir (Isaac 1938), white pine (Smith 1951), Kentucky 31 fescue (McKee, et al. 1965), and conifers (Vaartaja 1954) are a few plants studied in relation to surface temperature injury, the extent of which was partially determined by the plant itself.

Six phenomena help reduce a plant's ground level temperature below that of the surrounding milieu. These include (a) eddy diffusion, (b) conduction, (c) reradiation, (d) transpiration, (e) shading, (f) stem angle, (g) age. Eddy diffusion (mostly convection), conduction, and reradiation affect the heat balances of the earth and of plants similarly, except for a few qualifications and interactions unique to plants.

Convection seems to cool stem bases indirectly by inducing temperature gradients in the above-ground portions of plants. By cooling leaves, convection establishes the gradient necessary for conduction and transpiration to help cool the stem. Horizontally-oriented leaves survive primarily because of the cooling effect of convection. Transpiration is second in importance; it reduces temperatures when convection is not operative. The amount of convectional energy loss depends on leaf size and the consequent thickness of the leaf's boundary layer: the smaller the leaf, the more easily is heat convected to the atmosphere (Idso, et al. 1966; Raschke 1960). Convection and radiation together cause sudden and wide temperature fluctuations (5-7°C in less than a min.), believed more effective in minimizing overheating than transpiration. The acceptability of this belief is based on the small temperature differences between dried (non-transpiring) and green leaves (Clum 1926; Watson 1934).

Heat loss by conduction and reradiation is practically independent of any special plant features (Idso, et al. 1966), although water content and color have some effect (Watson 1934). Heat is conducted into the ground via stems and roots (Baker 1929) and to air with the aid of wind (Watson 1934). Stem bases tend to be cooler than the surfaces of poor-conducting, high radiation absorbing soils because of high specific heat and conductivity of stems (Baker 1929; Vaartaja 1954). Baker's (1929) within-stem-base (coniferous seedlings) thermocouple (0.18 mm diameter) measurements showed stems 15-20°F cooler than surrounding surface materials. Lethal in-seedling temperatures were lower than those measured at the soil surface (Vaartaja 1954).

As with convection, reradiation primarily cools leaves. Leaf temperatures changed rapidly by either permitting or preventing radiation to cold objects or to space (Curtis 1936).

A plant has little effect on the amount of heat exchanged with its environment, but it influences to some extent the allotment of energy to different heat transfer processes (Raschke 1960). The relative importance of transpiration in cooling leaves and stems is uncertain. While Shirley (1936), Tanner (1963), Gates (1964), Geiger (1965), Pallas and Harris (1964), and Wiegand and Namken (1966) considered transpiration the most important leaf-cooling process, Baker (1929), Curtis (1936), Idso, et al. (1966), Raschke (1960), and Watson (1934) indicated that other processes (convection and radiation) are of equal or greater importance. Clum (1926) believed these factors varied with climate and geography. Transpiration was most important in hot dry southern (U.S.) climates and of secondary importance in humid northern regions.

Gates (1964) stated that transpiration is the primary force cooling leaves; cooling is due to the large latent heat of vaporization of water relative to the heat capacity (Wiegand and Namken 1966). That transpiration cooled leaves and stems up to 10°C below air temperature under strong radiation and calm air led Geiger (1965) and Shirley (1936) to rate transpiration the principle role in cooling. In Georgia leaf temperatures were highly correlated with transpiration under most conditions (Pallas and Harris 1964). Tanner (1963) explained how plant temperatures increased if transpiration decreased, when radiation and wind balances were static.

Since large leaf temperature changes occur in seconds, transpiration cannot be the major factor producing such changes (Baker 1929;

Watson 1934). Because transpiration lowered plant temperatures only 2-5°C, Curtis (1936) considered other temperature-lowering phenomena. Clum (1926) in New York found no correlation between transpiration rate and the leaf-air temperature difference, nor between transpiration rate differences and leaf temperature differences of two leaves. Transpiration seemed to play a major cooling role, by a few degrees C, only at leaf temperatures close to the thermal death point (Clum 1926). Only after convection and radiation effects were accounted for did transpiration seem to respond to leaf-air temperature differences. The larger the difference, the larger was the drop in leaf temperature (Idso, et al. 1966). Clum (1926) pointed out that more energy is lost by transpiration and leaf temperatures are lower in semi-arid states like Arizona and Kansas than in humid New York. This supported his conclusion that convection is more important than transpiration in New York. In interpreting several workers' results, Raschke (1960) judged the importance of transpiration versus convection to be relative to numerous resistances to the transpiration process. As resistances increased there was less transpirational and more convectional heat loss.

The angle of exposure to radiation (i.e. leaf or stem orientation) influences the absorption-reflection properties of a stem or leaf, sometimes having as much effect on plant temperature as transpiration (Clum 1926; Curtis 1936). Vertically-oriented leaves and stems have a low heat load (Idso, et al. 1966).

Self-shading was second to leaf angle in affecting the amount of solar energy absorption (Idso, et al. 1966). The self-and mutual-shading effects depended on leaf and stem number (growth stage). A shading effect on surface temperature within grass stands was demonstrated (McKee, et al. 1965). Grass stands below 30-40% cover deteriorated more rapidly than stands with denser cover; this was related to high soil surface temperatures.

Age of tissues influences a plant's ability to resist damage from heat stresses (Baker 1929; Haig 1936; Reddy and Brentzel 1922; Rudolph 1939; Smith 1951). Heat mortality of tree seedlings decreased with age (Rudolph 1939; Shirley 1936); this was attributed to the development of protective devices (Baker 1929). Young succulent flax seedlings were more susceptible to girdling than older plants 3-5 inches tall (Reddy and Brentzel 1922). Plants more than 5 inches tall were rarely injured. Decreasing mortality with age in trees was related to cortical development. Hardening of exterior stem tissues increased high temperature resistance (Haig 1936). Development of intra-cortical air spaces impeded heat conduction to living succulent tissues within the stem (Smith 1951).

Plant resistance to high temperatures may vary with the condition of the protoplasm (Baker 1929; Evans 1959; Levitt 1956). Increased high temperature hardiness can be induced in plants by subjecting them to less-than-fatal doses of very low temperatures, high temperatures, and/or drought. Under such moisture and/or temperature stresses the growth rate is reduced, and salts and sugars accumulate in cells. As the osmotic pressure of the cell vacuoles increases and water is withdrawn from the cytoplasm, increased hydrophily and heat resistance of the proteins results (Evans 1959).

Mulches

Organic mulching materials are characteristically good insulators and therefore do not conduct heat well. Stagnant air spaces within a mulch contribute to its insulating and conducting properties (Baker 1965). Effects of shading and wind protection have been discussed by several persons (Geiger 1965; Loupo 1951; Russell 1939). Color determines some radiative properties, a light colored mulch possessing a greater capacity to reflect solar energy than a dark one.

Insulating properties and albedo influence average temperatures and temperature fluctuations of soil beneath a mulch (Baker 1965; Jacks 1955; Loupo 1951). Evaporation is reduced due to lower temperatures and wind protection (Jacks 1955; Loupo 1951; Richardson and Diseker 1961; Willard 1962). Mulches also reduce water runoff, enhancing moisture supply (Loupo 1951); runoff reduction and wind protection help hold seeds and fertilizer in place (Richardson and Diseker 1961).

Although mulches favorably modify soil temperatures and moisture relations, they also increase mulch surface temperatures; i.e. while a mulch reduces temperature fluctuations beneath it, the fluctuations within and immediately above the mulch are greater than those occurring on a bare soil surface (Vaartaja 1949). Smith (1940) observed that lethal temperatures occurred more frequently on insolated pine litter than on bare mineral soil. He attributed this to the stable moisture supply of the bare soil. When using mulches investigators should consider the severe microclimate in-and-above a mulching material as well as the mulch's effects on seeds within the mulch and on succulent seedlings growing through the mulch (Smith 1951).

EXPERIMENT I. EFFECTS OF MULCH, SOIL MOISTURE, SLOPE-FACING, AND THE RESULTING MICROCLIMATE TEMPERATURES ON GROWTH OF KENTUCKY 31 FESCUE SEEDLINGS

Objectives of this experiment were: (a) to study effects of wood cellulose mulch, soil moisture, and slope-facing on the microclimate temperatures near the soil surface; and (b) to study effects of these treatments and temperatures on the dry weights, percent secondary leaf development, population and heights of Kentucky 31 fescue seedlings.

Methods and Materials

Thirty-two metal greenhouse flats, filled with soil and seeded with Kentucky 31 fescue (*Festuca elatior*, var. *arundinacea*), were assigned factorial treatment combinations of two mulch rates (0 and 2000 lbs./acre: M_1 and M_2), two slope facings (north and south each at approximately a 45^o angle to the horizontal), and two levels of soil moisture (unwatered and watered: W_1 and W_2), Fig. 2. For each treatment combination there were four trials, two of which were used as replicates in statistical analyses.

The soil, a "C" horizon of a cut slope along a highway near Blacksburg, was dried, shredded and 27 pounds were weighed into each flat. The soil's moisture content at field capacity was 29.5%. Based on soil test data, N, P, and K were added as a 10-8.8-8.3 fertilizer at a 1000 lbs./acre rate.

On July 14, 1965, Kentucky 31 fescue seed, commonly used for sod establishment on subsoils in Virginia, was space planted on 1.5 inch

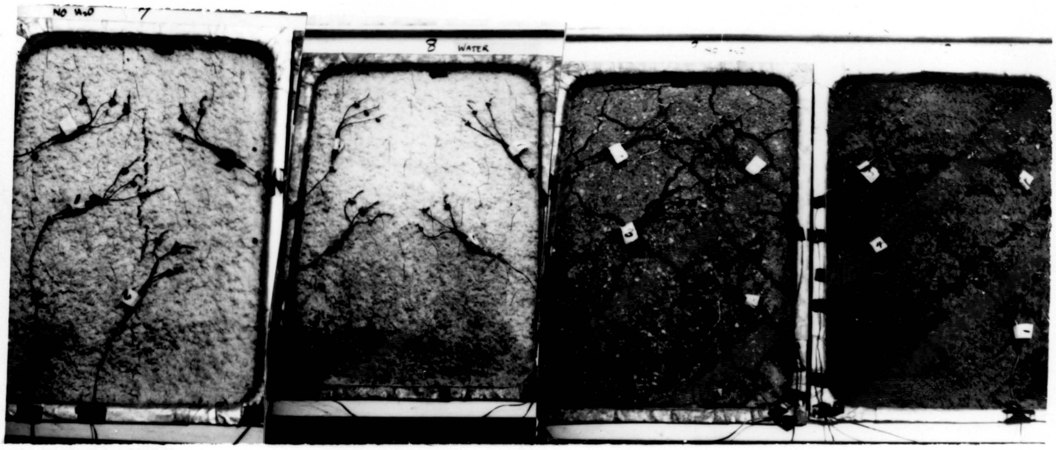

Fig. 2. Treatment effects and thermocouple placement for south-facing flats. Treatments are (left to right): (a) high soil moisture tension, mulch, (b) low tension, mulch, (note seedlings) (c) high tension, no mulch, (d) low tension, no mulch.

centers to minimize mutual shading. Dry wood cellulose mulch (Conwood, Wood Conversion Co., St. Paul, Wis.) was applied at a 2000 lbs./acre rate. Seeds were covered with about 1/16 inch of soil. All flats were watered daily in the greenhouse until seedlings emerged on July 18. Flats were then placed outdoors on special frames to attain north and south slopes, simulating highway conditions.

Realizing the necessity of water for plant growth and its modifying effect on microclimate temperatures, half the flats were watered to field capacity (by weight) daily; the remaining 16 received no water. To maintain this moisture differential the area was covered with plastic at night and during rainfall.

Temperature data were obtained from each flat of one replication. Thus, second and third order interactions were pooled with the error term to test significance. Based on previous work (Vaartaja 1949; Geiger 1965), five positions on each flat were used to characterize the surface temperature gradients above and below the soil-air interface. Temperatures were measured at (a) 50 mm below the surface, (b) 0-2 mm beneath the surface, (c) 0-1 mm above the surface, (d) 2-4 mm above the surface, (e) 5-8 mm above the surface. Air temperature, 1.83 M above the ground, was also determined. Temperatures were measured with three copper-constantin thermocouples (0.5 mm diameter of 36-gauge wire) in parallel circuitry (Barkley 1963), randomly placed for each position. Thermocouples located near the surface were held in place with plastic stakes, while the soil temperature thermocouples were inserted in the soil. Moist burlap hung beneath the flats to reduce irradiation.

The average temperature of the three thermocouples at each position was recorded by a Leeds & Northrup 24-point temperature recording potentiometer (Burrows 1959), and quick coupling devices permitted rapid switching from one point to another.

Seedling counts of all flats were noted initially, July 18, and prior to termination of the experiment, July 28. This final count indicated additional germination or plant losses among the flats; therefore, data were coded to give non-negative numbers.

Secondary leaf development was noted at harvest time and was expressed as the ratio of the number of plants with secondary leaves to the total number in each flat as a percent. Plant height was measured at random on ten seedlings in each flat. Ten plants were harvested at random from each flat by clipping at the soil surface, dried at 70°C for 24 hours, and weighed.

The results were subjected to analysis of variance, and linear correlations were made on temperature and growth data; coefficients of variation were determined for the growth factors.

Results

Seedling Data

Low soil moisture tension (W_2) produced better seedling growth than high soil moisture tension (W_1); mulching had variable effects on seedlings, Tables 1 and 2. Dry weights for the low soil moisture tension (W_2) treatment were several fold higher than for the high moisture tension (W_1) treatments except for the mulched, north slope, Fig. 3. Mulch (M_2) gave lower seedling weights than no mulch (M_1) when used with W_2 on both slopes. Mulch did not increase growth for the W_1 treatment.

Secondary leaf development was decidedly improved by M_2 with W_1 on both slopes, Fig. 4, Table 2, but M_2 gave no increase with W_2. When considering treatment means, leaf development was better with W_2 as compared with W_1. Under W_1 values were higher for north than south slopes.

Mulch (M_2) caused large improvements in seedling populations with W_1, but the differences were small with W_2 on both slopes, Fig. 5. Seedling stands were especially poor with W_1M_1 on south slopes; however, W_1M_1 values were higher for north than south slopes.

Temperatures

Analyses of variance for temperature data are presented in Tables 3 and 4. Soil and near surface temperatures during two days were higher on south as compared to north slopes, Figs. 6 and 7. Recorded temperatures on both slopes were lowest at a 50 mm depth and generally highest at 1 mm above the soil. When considering all locations temperatures with W_1 were higher than for W_2 on both slopes. Soil temperatures at 50 mm were lower for M_2 than for M_1, but these differences were small for the north as compared with the south slope.

On the south slope the highest temperatures generally occurred with W_1M_1, Fig. 6. With high moisture tension (W_1), temperatures were higher with M_1 than M_2; the reverse occurred with W_2. Soil temperatures with W_2 were lower for M_2 than M_1. Soil and near surface temperature ranges were lowest (88-94°F) for W_2M_1 and highest (83.5-107°F) for W_1M_2.

For the north slope W_1M_2 had the highest temperatures with the largest ranges, Fig. 7. The temperatures for the other treatments were quite similar except at 1 mm where W_1M_1 was highest and W_2M_2 was lowest.

Daytime temperatures averaged for two days and five positions near the surface were higher for the south slope than the north, Figs. 8 and 9. On both slopes for all treatments temperatures increased from 9:30 am until maxima were attained, the time of which varied with treatment.

South slope W_1 temperatures were higher than W_2 at all times, Fig. 8. M_1 was higher than M_2 for W_1 except at 9:30 am; the reverse resulted for W_2, except at 9:30 am, 3:30 pm, and 5:00 pm. The magnitudes of the differences of the above exceptions were small. Highest temperatures were measured for W_1M_1 and the lowest for W_2M_1. At 3:30 pm maximum values were observed for W_1M_1 W_1M_2, and W_2M_1; but for W_2M_2 2:00 pm was the hottest. The treatment with highest overall temperatures (W_1M_1) also had the largest range.

North slope temperatures were more moderate than south, there being small differences among treatments except for W_1M_2 which had the highest

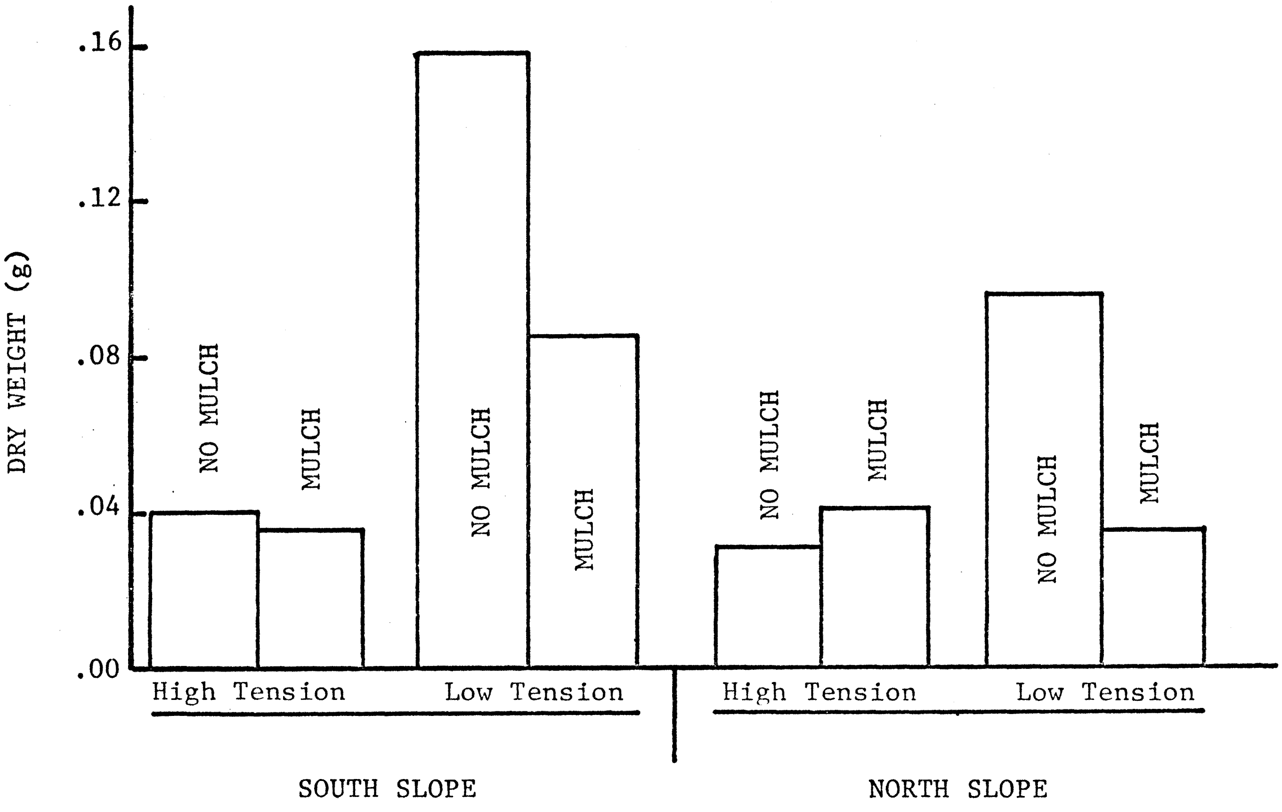

Fig. 3. Effects of slope-facing, moisture tension, and mulch on seedling dry weight.

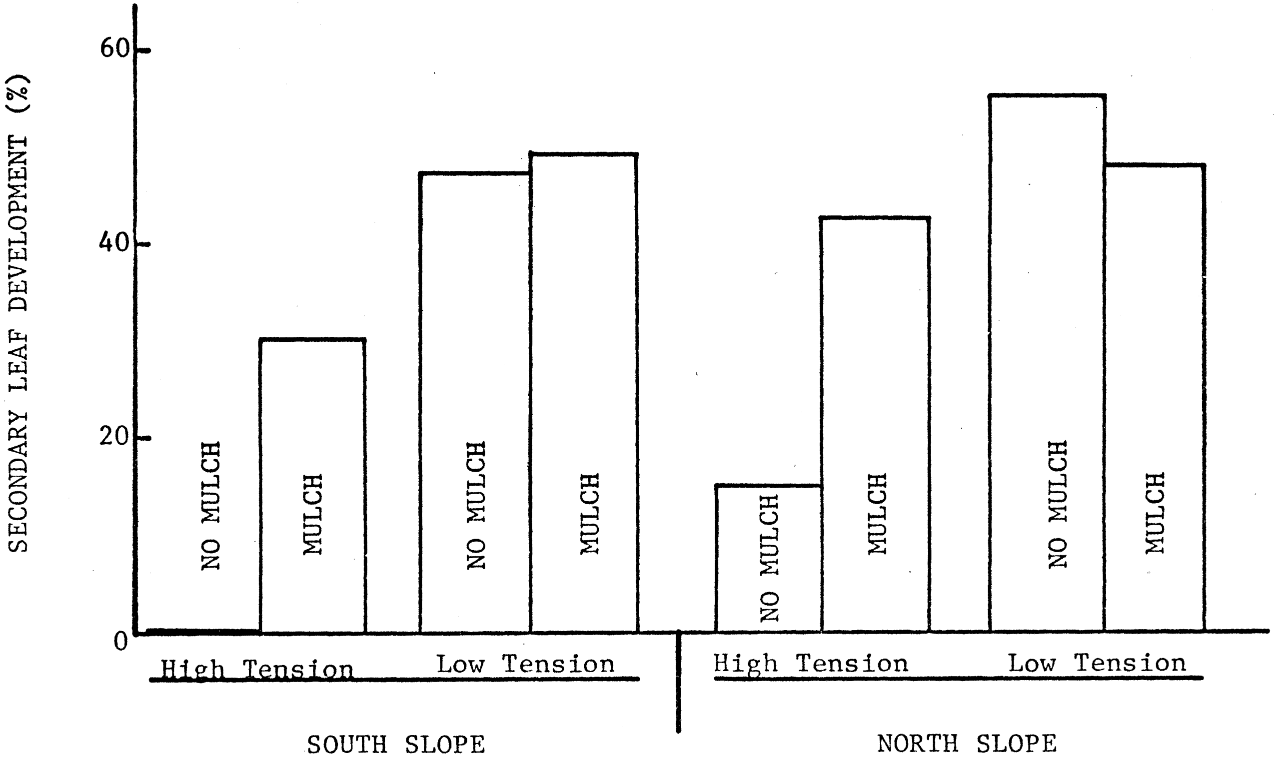

Fig. 4. Effects of slope-facing, moisture tension, and mulch on secondary leaf development (%).

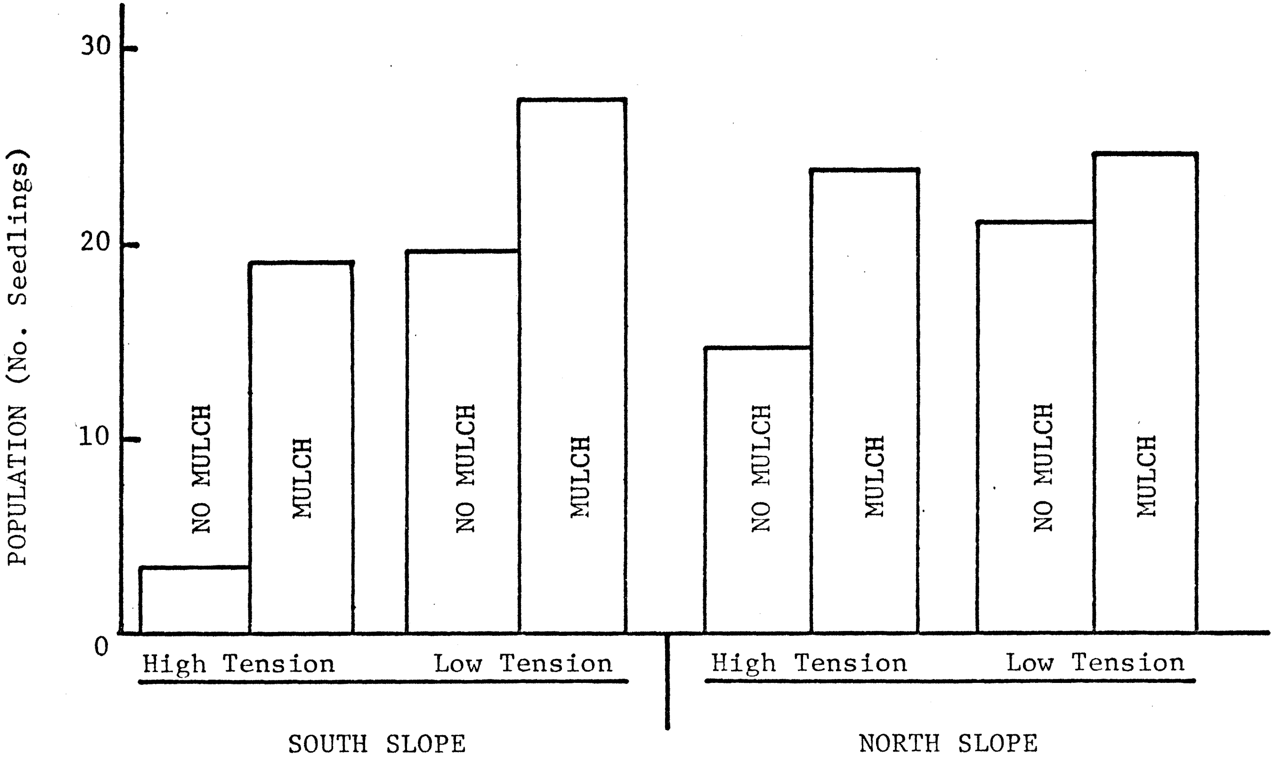

Fig. 5. Effects of slope-facing, moisture tension, and mulch on seedling populations per flat.

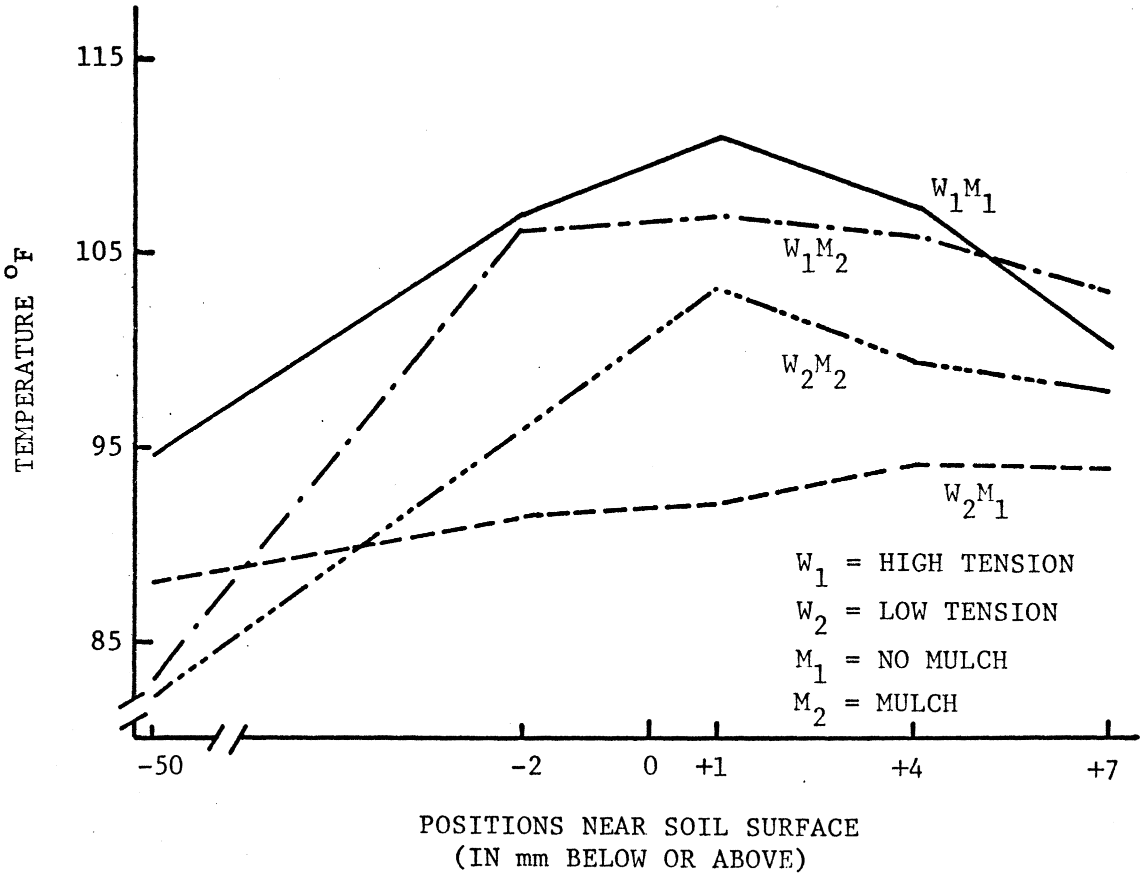

Fig. 6. Effects of moisture tension and mulch on the average surface temperature gradients for the south slope (Measurements taken every one and one-half hours from 9:30 a.m. to 5:00 p.m. and averaged over two days).

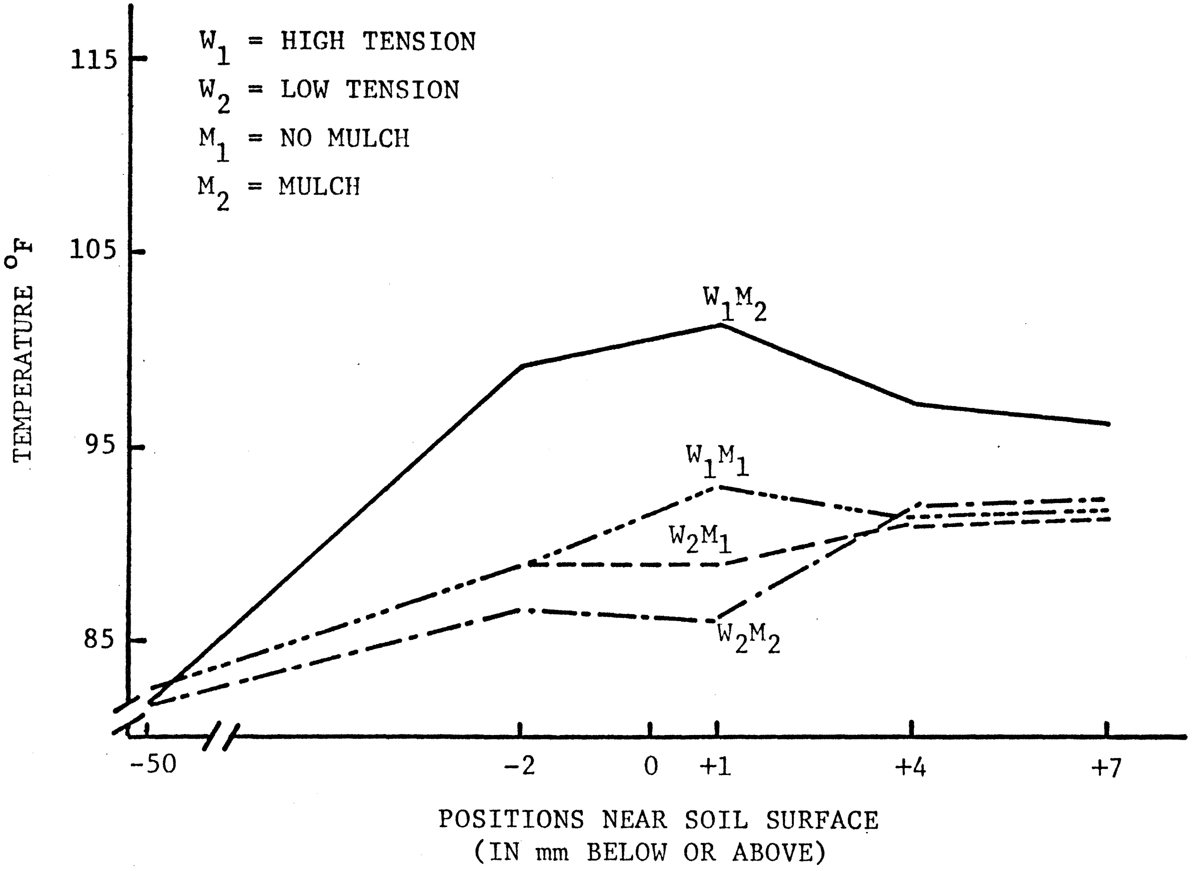

Fig. 7. Effects of moisture tension and mulch on the average surface temperature gradients for the north slope (Measurements taken every one and one-half hours from 9:30 a.m. to 5:00 p.m. and averaged over two days).

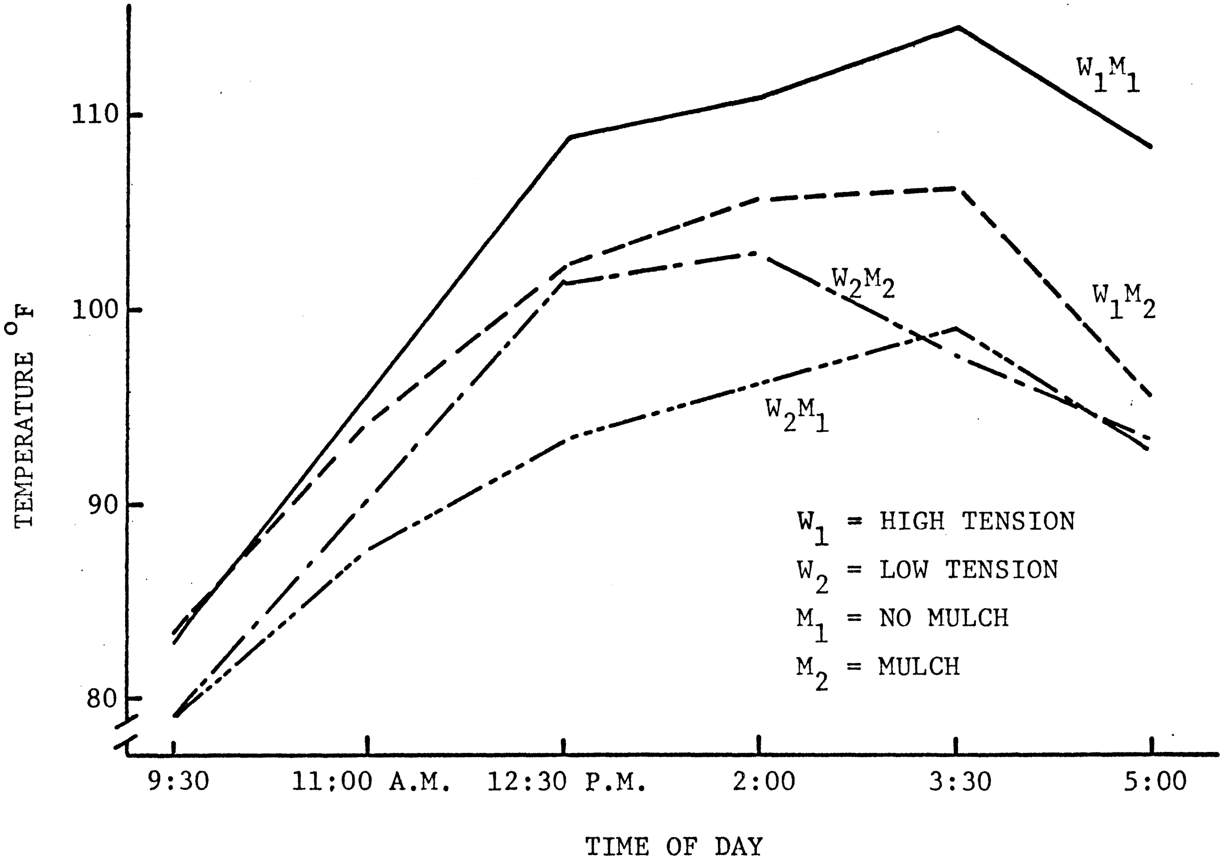

Fig. 8. Effects of moisture tension and mulch on the diurnal temperatures for the south slope.

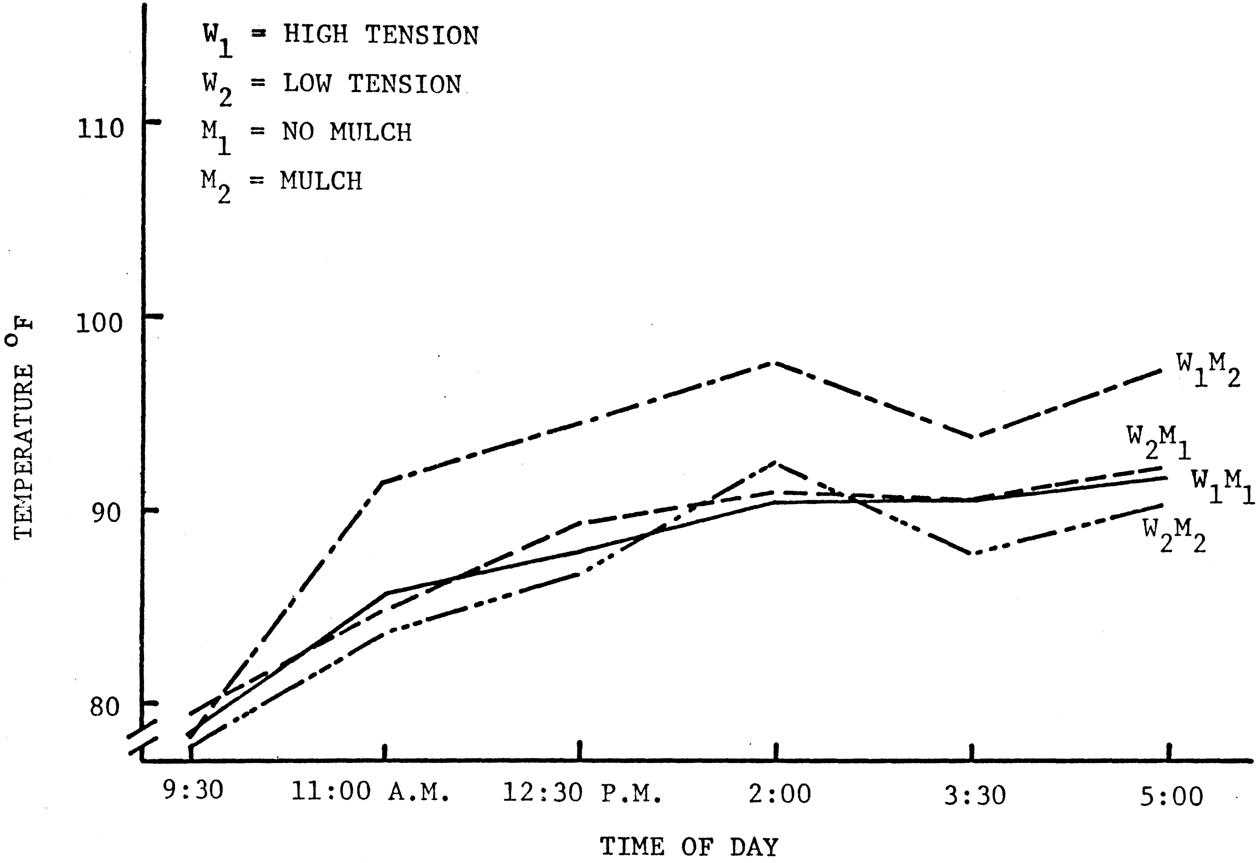

Fig. 9. Effects of moisture tension and mulch on the diurnal temperatures for the north slope.

values after the early morning low for all treatments, Fig. 9. After 9:30 am the W_1M_2 temperatures generally paralleled W_2M_2, which remained 5-8°F below W_1M_2. The M_1 treatments were similar at different times during the day. The highest temperatures for all treatments were generally at 2:00 and 5:00 pm; the M_2 treatments declined at 3:30 pm.

Table 1. Analysis of variance and coefficients of variation for dry weight, % secondary leaf development, seedling population, and plant height.

Source	Dry Weight	% Secondary Leaf Development	Seedling Population	Plant Height
Slope (S)	22.07	3.82	11.6	4.17
Coefficients of Variation (%)	19	23	8	12.3
Treatment (T)	64.0**	29.62**	7.17*	3.17
Mulch (M)	35.5**	12.89*	11.13*	4.46
Water (W)	115.1**	56.93**	8.75*	3.38
M x W	41.4**	19.04**	1.63	1.66
T x S	8.8*	1.05	0.89	0.09
S x M	---	0.75	0.67	0.04
S x W	25.0**	2.12	1.85	0.22
T x S x W	---	0.30	0.03	0.01
Coefficients of Variation (%)	16	20	31	20

* $0.01 < \alpha \leq 0.05$

** $\alpha \leq 0.01$

Table 2. Effects of slope, mulch, and moisture tension on dry weight of shoot material, secondary leaf development, height, and population of Kentucky 31 fescue seedlings.

Treatments	Dry Weight (g)		Secondary Leaf Development (%)		Height (cms)		Population	
	North	South	North	South	North	South	North	South
High Moisture Tension (W_1)								
No Mulch (M_1)	0.030	0.040	22.0	0.0	3.75	2.90	29.5	7.0
Mulch (M_2)†	0.040	0.035	64.0	45.5	5.25	4.50	48.0	38.5
Low Moisture Tension								
No Mulch (M_1)	0.095	0.155	82.5	70.5	5.00	4.50	42.5	39.5
Mulch (M_2)†	0.035	0.085	70.5	74.0	5.25	5.00	49.0	57.5

† 2000 lbs./acre wood cellulose.

Table 3. Analysis of variance for temperatures recorded at 10:00 a.m., 12:00 noon, 2:00 p.m., and 4:00 p.m. and averaged over July 23, 24, and 25, 1965.

Source	F Ratio
Treatment (T)	4.05
Mulch (M)	--
Water (W)	9.58*
Slope (S)	14.37*
Positions (P)	47.86**
P x T	2.24*
P x M	4.45*
P x W	4.93**
P x S	2.24
Days (D)	--
D x T	1.76
D x M	4.40*
D x W	4.98*
D x S	--
Hours (H)	--
H x T	--
H x M	1.93
H x W	--
H x S	86.72**
H x P	4.28**
H x D	5.78**

* $0.01 < \alpha \leq 0.05$

** $\alpha \leq 0.01$

Table 4. Analysis of variance for temperature measurements taken on the south-facing slope on July 23, 1965, every one and one-half hours from 9:30 a.m. to 5:00 p.m.

Source	F Ratio
Treatments (T)	1.55
Mulch (M)	--
Water (W)	3.56
Positions (P)	32.65**
P x T	2.84
P x M	4.89
P x W	2.63
Hours (H)	212.08**
H x T	5.87**
H x M	6.52**
H x W	4.88**
H x P	2.92**

* $0.01 < \alpha \leq 0.05$
** $\alpha \leq 0.01$

Discussion

Soil Moisture Tension

Soil moisture tension was the most important factor affecting seedling growth and soil surface temperatures. Low moisture tension (W_2) produced more seedling growth than high tension (W_1) as evidenced from dry weight, secondary leaf development, seedling population, and plant height data. Also, low tension resulted in lower temperatures than occurred with high tension. Reduced growth at high tension appears to be due to insufficient moisture to support growth. The high temperatures—induced as the cooling effects from evaporation and conduction were restricted by very low moisture—probably had a secondary effect.

Several reasons seem to justify temperature as a secondary factor affecting seedling growth. (a) The highest recorded temperatures were only 125-130^{o}F, which are about the lowest temperatures at which heat girdling has occurred (Baker 1929; Carroll 1943; Isaac 1938; Toumey and Neethling 1924); also, time of exposure was not accounted for since measurement was neither frequent nor continuous. (b) Observation of seedlings was not detailed enough to detect heat girdling and easily could have been confused with wilting. (c) The cooler north slope temperatures should have resulted in seedling growth differences between north and south slopes among the flats at high moisture tension (W_1). Dry weight results, however, showed slight differences between slopes for W_1, and secondary leaf development and seedling population data did not show outstanding differences. Peculiar dry weight results indicated that the south slope outyielded the north slope at low moisture tensions (W_2). It seems that solar radiation, influenced by slope, has produced neither optimal south slope temperatures nor too cool, growth-inhibiting north slope temperatures. Only small differences between slopes at W_2 occurred for secondary leaf development and seedling population, further substantiating the importance of moisture and the subordinate role of temperature. Lowest temperatures occurred at 50 mm beneath the surface for low moisture tensions (W_2) with mulch (M_2) on both slopes.

Mulch

Mulch effects were more variable than moisture effects. That dry weights were lower for M_2 than M_1 at low tension (W_2) and that mulch did not enhance growth at high tension (W_1) on both slopes might be caused by the high mulching rate with uniform soil coverage, which may have aggravated soil moisture relations. The water-holding capacity of the mulch layer was not accounted for in the watering method at low tension (W_2). Even though flats were usually watered at night, some water did not penetrate the soil since it was retained by and soon evaporated from the mulch. Because less water may have been in soil with mulch than without, this fact might explain the higher dry weight yields of the no mulch (M_1) than the mulch (M_2) for W_2 on both slopes. Also, the uniformity of the mulch layer and the moisture in it may have reduced aeration in the soil below, thereby inhibiting growth.

Secondary leaf development and seedling population data showed growth enhancement by mulch on both slopes at high moisture tension, but at low tension the mulch was less effective. The growth enhancement at high tensions is accounted for by the water-conserving ability of the high mulch rate. The lack of significant growth enhancement by mulch at low tension (W_2), as shown in secondary leaf development and seedling population data, may be explained by the discussion of similar dry weight results stated above.

Mulch seemed to have unique effects on temperature regimes of several treatments. At W_1 mulch seemed to conserve some moisture, perhaps enough to allow for evaporation to cool the mulch surface temperatures below those of the bare soil, but not enough to enhance seedling growth. That evaporation is the major factor cooling W_1M_2 below W_1M_1 seems to be supported by the fact that if no moisture were present, the mulch (M_2) should have had higher temperatures than bare soil (M_1). Thus, without water in the mulch the heat would not be dissipated from the insulating layer, giving higher mulch (M_2) surface temperatures than for bare soil (M_1). Because the clayey compacted soil had a high water-holding capacity and a high specific heat and thermal conductivity, heat should have been conducted away from the soil surface and into the soil mass. An argument against evaporation being the major cooling factor for W_1M_2 is the possible infrared radiation absorption effect of the dark soil color. This effect may have caused temperatures for M_1 to be higher than M_2.

On the north slope the W_1M_2 treatment had higher temperatures than W_1M_1. Less radiation on the north slope reduced evaporative water loss. This was especially evident because of the low W_1M_1 temperatures. Although not great enough to affect surface temperatures, the water loss from W_1M_1 apparently was sufficient to reduce plant growth more for M_1 than M_2. For W_1M_2 heat was apparently not dissipated from the insulating mulch layer as moisture was retained in the cool soil. The mulch layer was dry enough so that evaporation had less of a cooling effect than it did on bare-soil (W_1M_1) surface temperatures.

Although the uniform mulch layer probably permitted less of a convective cooling effect on surface temperatures than a porous, broken surface of straw mulch, the few pores and surface roughness of wood-cellulose mulch seem likely to have caused a thinner air layer above it than occurred above the smooth, bare soil surface at high soil moisture tension (W_1) on the south slope. The light mulch color could also have accounted for the W_1M_2 temperatures being less than W_1M_1.

Results from low soil moisture tension (W_2) on the south slope show an effect similar to that occurring on the above-described north slope at high tension (W_1): M_2 had higher temperatures than M_1, except at 50 mm beneath the surface. Mulch (M_2) retained heat at the surface, preventing both conduction to the cool, moist soil below and evaporation to the air above. On bare soil (M_1) heat was apparently conducted throughout the soil mass and lost primarily by evaporation to the atmosphere, giving low surface but high soil (-50 mm) temperatures.

Apparently the mulch-surface temperatures for the north, W_1M_2 and the south, W_2M_2 were not high enough to injure seedlings, because except for dry weight all measurements show that mulch produces more growth than no mulch under these conditions.

Slope-Facing

The angle and direction of slope determine the intensity of solar radiation striking a surface. The radiation intensity is the major factor affecting soil moisture tension through water loss by evaporation. Radiation effects on soil temperatures become apparent as soil moisture tension increases.

The principle effect of slope seems to be on the soil moisture tension, especially at high tension. Dry weight results, showing only slight differences between slopes at W_1 and higher yields for south than north slopes at W_2, appear unusual. The lack of dry weight differences between slopes at W_1 is due to a sub-critical water level for growth. Higher yields on the south slope at W_2 may be due to a confounding of the mulch-water interactions as described above under "Mulch".

Secondary leaf development and seedling population data showed more growth on north than south slopes at W_1, because of lower radiation intensity and thus less water loss from the north slope. At W_2 slope differences were less striking since moisture was not limiting.

Temperatures

Temperatures were generally lower on north than south slopes for each treatment. This reflects the effect of slope-induced radiation intensity on surface temperature. Temperature differences between slopes were usually secondary to soil moisture and mulch effects on seedling growth.

Temperature measurements at five positions, one 50 mm below the surface and four near the soil-air interface, were intended to pinpoint the gradient level or air layer of maximum injury to seedlings *vis a vis* high temperature.

One reason temperature differences were striking is the sparse seeding rate (space-planted on 1.5 inch centers) that did not permit seedlings, as in normal stands, to alter the surface environment by self and mutual shading. Transpiration and humidity near the surface would also be higher for normal than sparse stands. Higher than normal temperatures and water loss were probably associated with the sparse populations in this experiment.

The young, single-leaf growth stage, at which seedlings were expected to be most susceptible to surface temperature injury, prevented the small, thin stems from cooling either themselves or the surrounding surface material by conduction of heat to the soil below or leaves above. On the other hand, the small leaf size would tend to aid heat loss via convection and transpiration by minimizing the width of the leaf surface's boundary air layer. Leaf angle is not likely to have been important in cooling by reflection and reradiation since the single leaves grew perpendicular to the earth's surface, even though they were at an angle to the mulch or soil surface due to the tilted flats.

Internal stem anatomy differences may have led to the more frequent fatalities among tree than grass seedlings--a fact seemingly evident from data in the literature, although no comparison of such has been made therein. The cambium, phloem, and xylem of the fibrovascular bundles scattered throughout the grass stem may comprise a structure more resistant to stem girdling than the concentric arrangement of growth and conductive tissues in trees.

Weather conditions were not optimal for maximum surface temperatures by standards in the literature (Smith 1951; Vaartaja 1949). Occasional cloud cover, high humidity and dust particles in the air, and an erratic southwest wind are believed to have influenced surface temperatures by reducing light intensity and increasing convection and conduction of heat from the surface to the air. Measurements of these phenomena were not taken.

Surface temperatures (1 mm above the surface) correlated negatively with dry weight ($r = -0.825$), % secondary leaf development ($r = -0.72$), plant population ($r = -0.23$), and plant height ($r = -0.467$) at 1% significance level; likewise, soil temperatures (50 mm beneath surface) correlated negatively with dry weight ($r = -0.288$), secondary leaf development ($r = -0.771$), and plant height ($r = -0.785$). Although high negative correlations with surface temperatures and low correlations with soil temperatures (dry weight only) would seem to indicate the importance of surface temperatures relative to plant growth, the -0.771 and -0.785 r values for leaf development and plant height would indicate that this conclusion may not be valid. Also, since only twelve points were used in correlations, this conclusion seems questionable.

Inconsistent results, as in this research, have sometimes led to seemingly ambiguous explanations. With so many interacting environmental factors affecting seedling growth, correct data interpretation is difficult. Efforts have been made to present the most likely causes; the reader is cautioned that these explanations are not absolute and others may be equally plausible.

EXPERIMENT II. CHARACTERIZATION OF SOIL SURFACE TEMPERATURES LETHAL TO RYEGRASS SEEDLINGS MULCHED WITH WOOD CELLULOSE AT TWO MOISTURE TENSIONS

The objective of this experiment was to characterize soil surface temperatures lethal or injurious to ryegrass seedlings, grown in flats with wood-cellulose mulch at two soil moisture tensions. To determine if heat girdling is caused by superheated mulch or a laminar air layer was a secondary objective to be achieved by detection of the location of stem injury--above, at, or below the mulch surface.

Methods and Materials

In six flats filled with greenhouse potting mixture (22% field capacity), ryegrass seeds were space-planted on one-inch centers and covered with about 1/16 inch of soil. Wood-cellulose mulch (Conwood, Wood Conversion Co., St. Paul, Wisconsin) was applied in dry form at 2000 lbs./acre; all flats were watered to field capacity and placed on greenhouse benches. After seedling emergence, the flats were tilted at a 45° angle facing south to simulate a highway roadbank; high and low soil moisture tensions were imposed, those at low tension watered to field capacity by weight twice daily. Flats at high tension received no water. Five days after sowing, with seedlings in a single-leaf stage, flats were given radiation treatments.

Each flat was placed in a 40-inch high plywood chamber, open at the top and bottom to facilitate convection and positioning of lights above flats. Aluminum foil lined the four sides, Fig. 10. Thermocouples

Fig. 10. Aluminum-lined chamber (right) in which seedlings were subjected to radiation levels. Motorized worm gear is shown beside flat in chamber.

(36-gauge Cu-Constantin) were attached to each flat prior to placement in the chamber. Using a Leeds and Northrup 24-point potentiometric temperature recorder, a Honeywell Electronik 18 millivolt recorder, and a Leeds and Northrup Speedomax H millivolt recorder, five temperature measurements were taken: (1) in the soil, (2) within the mulch (beneath mulch-air interface but above soil surface), (3) at the mulch surface; and utilizing a vertically mobile (0-20 mm) thermocouple attached to a motorized worm gear, additional positions, (4) at the mulch surface and (5) in the air, 20 mm above the surface, were obtained.

Three predetermined radiation levels, using two 500-watt flood lamps placed 22", 33", and 39¼" above each flat's mulch surface for 13, 30, and 50 minutes respectively, were imposed--one level for each flat. Thermocouples were removed following treatment of each flat, and plant data were then obtained from two randomly placed circular quadrats (10 cm in diameter). Injury measurements were obtained by counting the number of seedlings in each quadrat that (1) were not standing erect (erectness being rated on a 4-point scale) and (2) showed evidence of stem girdling (rated on a 3-point scale), Fig. 11. Injury data were later converted to percentages-of-seedlings-injured per quadrat and analyzed statistically. The above-described procedure was performed three times to give three replications.

To facilitate computer analyses for linear correlations between temperatures and seedling injury, data transformations were imposed.

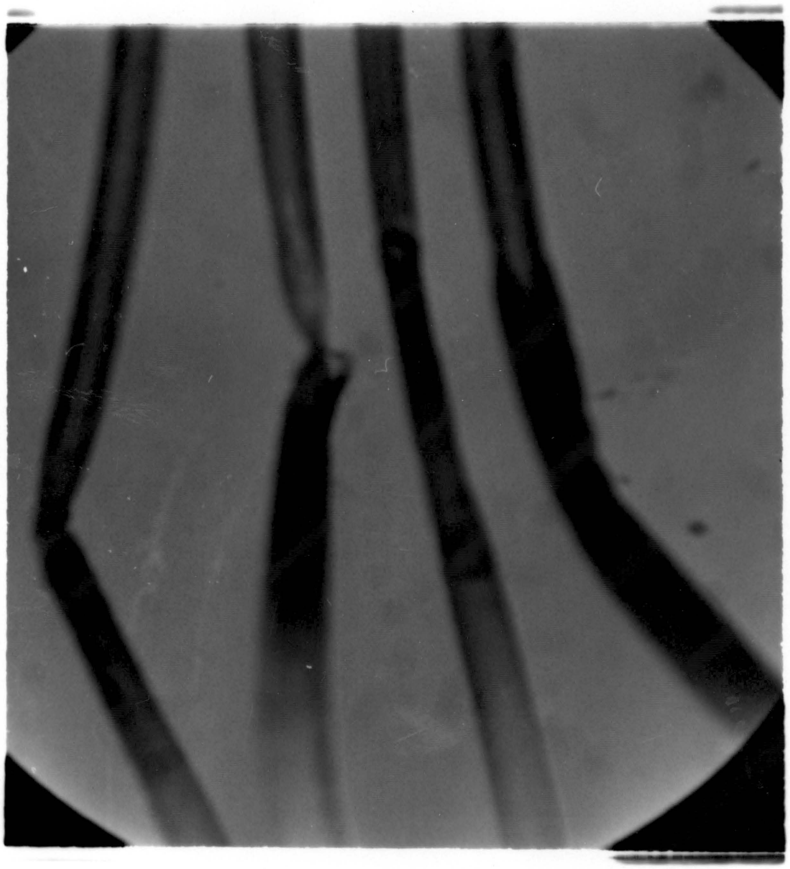

Fig. 11. Magnified view of stem girdling of ryegrass seedlings due to high mulch-surface and in-mulch temperatures. Stems from left to right are (a) moderately girdled, (b) severely girdled, (c) not injured, and (d) slightly girdled.

In the analysis of variance for temperature measurements as related to treatments (Table 7), the degrees of freedom and sums of squares for Reps x Moisture and Reps x Radiation were pooled, giving a 10 degrees of freedom error term; both of these interactions were not significant.

Results

Results analyzed by the V.P.I. Computer Center show significant positive linear correlations between surface and in-mulch temperatures and seedling injury based on erectness and girdling, Table 5. Soil and air temperatures were not significantly correlated with injury. Table 6 shows mean temperatures at which injury occurred at the three radiation levels and two moisture tensions. Only slight differences in percent injury (especially girdling) occurred for the high radiation level versus the low level at both moisture tensions. Surface temperatures exceeded air and soil temperatures.

Analyses of variance for each of the five temperature measurements show that radiation levels had significant effects on all temperatures, Table 7. Soil moisture tension had significant effects only on surface temperatures, although some F ratios indicate that mean differences for other temperatures were greater than those due to random variance, Table 8. None of the F ratios for the Moisture x Radiation interaction were significant, all except for air temperature being less than 0.5. Mean differences among replications were significant only for in-mulch temperatures. F ratios for motor-surface and air temperatures were not significant but were large enough to indicate that the three runs of the experiment did not produce identical responses probably because of moisture tension variability. Surface and soil temperatures showed no differences among replications.

Table 5. Correlation coefficients for temperature and seedling injury measurements

Measurement	r values	
	Erectness	Girdling
Surface Temperature	0.525*	0.508*
Motor-Surface Temperature	0.632**	0.599**
In-Mulch Temperature	0.539*	0.567*
Air Temperature	0.305	0.159
Maximum Soil Temperature	-0.102	0.031

* $0.01 < \alpha \leq 0.05$

** $\alpha \leq 0.01$

Table 6. Mean temperature and injury data

	Temperatures °C					Percent Injury	
	Surface	Motor-Surface	In-Mulch	Air	Max. Soil	Erectness	Girdling
High Moisture Tension							
High Radiation	70.23	62.47	61.60	52.23	25.00	44.3	48.0
Medium Radiation	65.37	57.17	54.63	44.40	26.50	27.5	46.5
Low Radiation	56.50	50.73	50.77	42.73	27.97	32.5	49.0
Low Moisture Tension							
High Radiation	63.83	55.73	53.17	49.73	22.77	18.7	22.0
Medium Radiation	60.06	56.40	52.50	49.60	24.60	18.5	30.1
Low Radiation	49.06	49.33	44.43	42.13	27.07	21.0	23.7

High Radiation = Lamps 22" above surface; exposure 13 mins.
Medium Radiation = Lamps 33" above surface; exposure 30 mins.
Low Radiation = Lamps 39¼" above surface; exposure 50 mins.

Table 7. Analysis of variance for each temperature measurement

SOURCE	D.F.	MEAN SQUARES	F RATIO	SIGNIFICANCE
Surface Temperature				
Reps	2	19.75	0.917	
Soil Moisture Tension	1	183.04	8.499	*
Radiation Levels	2	320.37	14.875	**
Error	10	21.54		
Motor-Surface Temperature				
Reps	2	61.71	3.04	
Soil Moisture Tension	1	39.60	1.462	
Radiation	2	133.13	6.578	*
Error	10	20.24		
In-Mulch Temperature				
Reps	2	175.66	5.170	*
Soil Moisture Tension	1	142.80	4.205	
Radiation	2	145.88	4.296	*
Error	10	33.96		
Air Temperature				
Reps	2	22.37	2.915	
Soil Moisture Tension	1	2.20	0.287	
Radiation	2	109.82	14.310	**
Error	10	7.67		
Maximum Soil Temperature				
Reps	2	0.65	0.150	
Soil Moisture Tension	1	12.67	2.937	
Radiation	2	19.85	4.602	*
Error	10	4.31		

* $0.01 < \alpha \leq 0.05$
** $\alpha \leq 0.01$

Table 8. Effects of soil moisture tension on seedling injury

	Extent of Injury - %	
	Erectness	Girdling
High Tension	34.7	47.8
Low Tension	19.4	25.2

Discussion

Table 6 presents the soil surface temperatures injurious to ryegrass seedlings; this was an experimental objective. Table 5 data, however, lead one to question the acceptability of data in Table 6.

The three radiation levels were ideally intended to produce nearly equal amounts of total radiation on each flat. Although temperatures were supposed to decrease with the distance of the lights from each flat, the concomitant increasing exposure times were expected to equalize the effects on seedling injury at all radiation levels. The girdling data at high and low moisture tensions and the erectness data at low tensions illustrate this relatively uniform injury.

Correlations of surface temperatures with injury in Table 5 show injury increasing with surface temperatures. Significant relationships between radiation levels and surface temperatures (Table 7) also involve the proximity of lights and exposure times with injury data: more injury occurred with high temperatures at short exposures than with low temperatures at long exposures. This apparent trend of increased injury with surface temperature leads one to question the conclusions of uniform injury in Table 6. However, the relatively small r values (0.508 to 0.632) (in Table 5, although significant, do not seem high enough to serve as a meaningful argument against Table 6 data). Although Lorenz (1939) stressed the time factor as being essential to temperature injury data, soil moisture variability hampered accurate measurement of the times of exposure to specific temperatures. Moisture differences within the same flat, and the highly variable temperature environment thus produced, may be attributed to the erratic and non-uniform seedling injury observed.

In spite of somewhat contradictory results in Tables 5, 6, and 7, the experimental objective seems to have been achieved to a limited degree. The most acceptable conclusions seem to be (1) that at high moisture tension injury was more severe with temperatures caused by the "high" radiation level (13 min. exposure; 22-inch height) than the "low" level (50 min. exposure; 39¼-inch height), (2) that injury increased with temperature, and (3) that high soil moisture tension results in more surface injury than low tension.

The location of stem injury (above, at, or below the mulch surface) varied among seedlings, perhaps due to the variation in surface and in-mulch temperatures. Surface, motor-surface, and in-mulch temperatures correlated positively with each other (r = 0.800, 0.653, and 0.896) indicating that the treatments affected them similarly. Correlations of the three surface temperature measurements with air temperatures gave r values of 0.700, 0.573, and 0.313, and correlations of surface with soil temperatures were negative (r = -0.371, -0.376, and -0.208) and not significant. Thus, as also shown in Table 5, air and soil temperatures showed little relation to surface temperatures and injury. Extreme variations in the surface environment, even under the controlled conditions of this experiment, resulted in variations between the two surface and the in-mulch temperatures and consequently made evaluation of the location of injury difficult.

SUMMARY

The influences of soil surface temperatures on the growth of young grass seedlings were determined in one outdoor and one laboratory experiment. In the outdoor experiment soil moisture tension, wood-cellulose mulch, and slope-facing were varied and their effects on seedling growth and surface temperatures observed. Moisture had the most profound effect on seedlings and temperatures, giving more growth and lower temperatures at low tension than at high tension. Mulch and slope effects were secondary to moisture and sometimes ambiguous. Mulch did not always produce more growth at high moisture tensions than no mulch and at low tensions seemed to have little effect. Slope effects were especially evident at high moisture tensions, the south slope having higher temperatures and less growth than the north. Temperatures at or within a millimeter above the soil-air interface were judged the most critical, although measurements immediately below the surface of, yet within, the mulch layer also seemed significant. Several factors, such as a high mulching rate, a sparse seeding rate, inadequate moisture control, and less than ideal weather conditions, complicated the control of environmental factors and interpretation of experimental results.

The laboratory experiment attempted to characterize surface temperature injury to grass seedlings grown with wood-cellulose mulch at two soil moisture tensions. Three artifically induced radiation levels produced temperatures that showed seedling injury to increase with surface temperature while air and soil temperatures had no significant effect. Low moisture tension generally produced lower surface temperatures and less injury than high tension.

From both experiments one might conclude that soil surface temperatures were injurious to grass seedlings at high soil moisture tensions. Wood cellulose mulch seemed to prolong the time period during which surface temperatures might have been detrimental to seedlings before death resulted from drought. South-facing slopes receiving intense radiation seem to be requisite for these high moisture tensions and high surface temperatures.

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THE EFFECTS OF SOIL MOISTURE, MULCH, SLOPE-FACING, AND SURFACE TEMPERATURE ON GRASS SEEDLINGS

by

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ABSTRACT

Soil moisture tension had a greater effect on both soil surface temperatures and growth of young Kentucky 31 tall fescue (*Festuca arundinacea*) seedlings under solar radiation than either wood-cellulose mulch or slope-facing. More growth and lower temperatures occurred at low than high moisture tensions. Mulch did not consistently benefit growth. Slope effects were evident primarily at high tensions: higher temperatures and less growth occurred on south than north slopes. Temperatures (a) within a millimeter above the soil-air interface and (b) below the surface of, yet within the mulch layer seemed the most critical to seedling growth. Inadequate moisture control, a sparse seeding rate, a high mulching rate, and below optimal weather conditions complicated environmental control and produced some ambiguous results.

A characterization of surface temperature injury to perennial ryegrass (*Lolium perenne*) seedlings grown with wood-cellulose mulch at two moisture tensions showed seedling injury to increase with surface temperature while air and soil temperatures had no significant effect. Low moisture tension produced lower surface temperatures and less injury than high tension.