TRANSPIRATION AND EVAPOTRANSPIRATION WITH ALEPPO PINE (*PINUS HALEPENSIS* MILL.) SEEDLINGS UNDER VARYING SOIL MOISTURE AND SOLAR RADIATION LEVELS

By

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A Thesis Submitted to the Faculty of the

DEPARTMENT OF WATERSHED MANAGEMENT

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

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ACKNOWLEDGMENTS

The author wishes to express his appreciation to Dr. A. L. McComb for his assistance in setting up the study and editing this paper. Professor P. B. Rowe also has the author's gratitude for his assistance in this study.

Appreciation is rendered to Mr. L. P. Hamilton and the personnel of The Plant Materials Center of the University of Arizona for generously providing a location and necessary equipment for this study. Mr. H. L. Silvey also has the author's thanks for his assistance in collecting soil and constructing the bench area.

The author would like to express his appreciation to Dr. H. Tucker for his able assistance in the statistical analysis.

The Institute of Atmospheric Physics must be mentioned for their cooperation in providing solar radiation data.

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INTRODUCTION

There have been few basic studies concerning the rates of transpiration, evapotranspiration, and evaporation as related to soil moisture and solar radiation. Such studies are essential to a more complete understanding of the hydrologic cycle and of its modification by land and vegetation management practices.

In arid regions water is a limiting factor in almost every sphere of human activity. Much interest is centered in obtaining more water for a variety of human uses and purposes. The magnitude of the yields of economic watershed plants is often determined by the amounts of water available to these plants. At the same time the amounts of water occurring as streamflow is dependent in part upon the kinds and density of the vegetation occurring on the watershed. To understand these reciprocal relationships and to make intelligent watershed management decisions, the processes relating to water losses must be studied in both field and laboratory.

The basic purpose of this study was to provide a qualitative index of the relations among water loss, solar radiation, and soil moisture. The study used Aleppo pine as an indicator due to its rapid establishment when transplanted under the climatic conditions at Tucson, Arizona. The study was a fixed model so quantitative applications of results to field conditions or to other populations are not justifiable. This study is part of a larger study designed to study plant-water relations in the pine zones of Arizona.

REVIEW OF LITERATURE

Knowledge of the processes utilizing soil moisture is important in watershed management. There is a large amount of reference material available concerning transpiration and evaporation. In view of this fact only the more pertinent material is presented here as a background.

The question of whether soil water between field capacity and permanent wilting point is equally available to plants for growth has been disputed for nearly 30 years (Stanhill, 1957). Veihmeyer and Hendrickson (1955) proposed the view that water is equally available to plants at any point between field capacity and the permanent wilting point. Their work was done using Aleppo pine sealed in a suspended tank equipped with an automatic weighing device. Graphical results indicated that there was no difference between the rates of transpiration immediately after irrigation and when the soil mass was near the wilting point. Similar results were obtained in subsequent experiments with other plants.

Slatyer (1957) stated that the permanent wilting point was not a soil constant but a plant osmotic characteristic. He further pointed out that the evidence of Veihmeyer and Hendrickson was based on lysimeter studies where results may be altered by uneven root distribution. Therefore, the measurement of plant responses and the interpretation of these data may be in error.

Lane and McComb (1948) using several species of plants reported that a decrease in transpiration with increasing soil moisture tension existed. They also reported that the soil moisture percentage at the permanent wilting point varied between species. However, these differences may have been due to differences in root penetration of the soil mass together with differences in extent of suberization, rate of respiration, and protoplasmic differences in the water absorbing area of the roots of different species.

Stanhill (1957) summarized the results of 80 experiments relating growth to soil moisture and showed that in 65 cases the greatest yields were associated with the wetter soil moisture regime. Only in a carrot seed crop was the greatest yield associated with a dry regime. The 14 experiments that showed no response to soil moisture were older experiments in which fruit growth was the yield criteria. He attributed these results to the ability of the flowering parts to compete with vegetative parts for water during periods of moisture stress.

Kramer and Kozlowski (1960) suggest that much of the confusion relating to water availability and transpiration in relation to soil moisture has resulted from failing to measure the internal water balance of the plant and to quantitatively estimate the factors controlling availability of soil water to the plant and the rate of water loss from the plant.

The work of Richards and Wadleigh (1952) showed that availability of soil moisture to plants depended on the shape of the moisture tension curve. Gingrich and Russell (1957) found that the growth of corn roots at equal moisture stress was greater when the stress was developed osmotically than when it was developed as soil moisture stress. They attributed the lesser growth under soil moisture stress to a rapid change in water transmission rates in their soil as soil moisture stress was increased. The effect was most pronounced in the 1- to 3-atmospheres range.

Slatyer (1957) has attempted to show some of the relationships among transpiration, soil moisture, soil moisture stress, diffusion pressure deficit, osmotic pressure, and relative turgidity. He concluded that since transpiration is primarily a passive plant process it need not cease but may be reduced as soil moisture stress increases due to stomatal closure and reduced rates of water movement in unsaturated soils. Transpiration may continue after the death of a plant, limited by the energy available for evaporation, the resistance to water movement into, through, and out of the plant, and by the rate of flow of soil water into the roots.

Kramer (1937) reported that water absorption lagged behind transpiration during the day but exceeded it at night. He found no differences in the lag between woody, herbaceous, and succulent species. In all cases transpiration changes preceded absorption changes so he concluded water intake was largely governed by water loss.

Bierhuizen (1958) showed that transpiration and evapotranspiration decreased with increasing soil moisture tensions under conditions of high evaporative potentials. Under low evaporative conditions the results were inconclusive. He suggests that some of Veihmeyer's and Hendrickson's experiments may have been conducted under conditions of low potential evaporation. Closs (1958) states that two processes may be involved in determining transpiration. They are: potential transpiration and potential water absorption. The most important one in any given situation depended upon where along the soil moisture tension curve the plant was located.

Bierhuizen (1958) suggested that the transpiration rate is greater at higher light intensities, increases with available soil moisture and may become constant at high moisture levels.

Recently, Kuiper and Bierhuizen (1958) studied the influence of several environmental factors on transpiration of cut leaves in potometers and of entire plants grown in soil. They found that Fick's diffusion law can be applied to transpiration of cut leaves in potometers. They also presented a formula to estimate the transpiration of plants in soil.

Kuiper and Bierhuizen found the effect of soil moisture levels on transpiration was great under conditions of high potential transpiration and small under low potential transpiration conditions. They suggest that soil structure and oxygen content of the soil may become limiting factors in soil moisture absorption under certain conditions. Bierhuizen (1958) states that some of Veihmeyer's early work showing soil moisture to be equally available was done on coarse- to medium-textured soils. On clay soils deep-rooted species may show wilting responses to moisture deficits before the soil moisture reaches the permanent wilting point.

Kuiper and Bierhuizen (1958) found a linear relationship between light intensity and transpiration. At low light intensities (up to

17.5×10^4 ergs/cm.^{2}/sec.) 86 percent of the light effect was due to stomatal changes and decreased diffusion resistance to water. Less than 14 percent was due to a temperature change and the accompanying increased vapor pressure deficit. At high light intensities the linear relationship was thought due mainly to an increase in leaf temperature and vapor pressure deficit.

They stated that in experiments with plants in soil, the soil moisture tension affects the total diffusion resistance of leaves independent of light intensity. The effect of soil moisture on diffusion resistance may be due partly to incipient drying and partly to an osmotic stomatal reaction.

Abd el Rahman, Kuiper, and Bierhuizen (1959) found a linear relationship existed between transpiration and incident light intensity with the exception of the lowest light intensity under controlled temperature and relative humidity conditions. They attributed the deviation of transpiration at the low light intensity to morphological differences in the plants grown at these light intensities.

Tests on 25 sample trees showed that light and soil moisture were the most prominent factors affecting transpiration (Rothacker, 1949). A decreased transpiration rate occurred with increased soil dryness. Plants in sealed containers placed on a tower at the crown levels of a forest stand and exposed to full solar radiation lost twice as much moisture as similar plants at the ground level in the same length of time. Hendrickson (1942) stated that quantitative results from container experiments such as those Rothacker reported cannot be applied to watershed areas.

Wiegand and Taylor (1961) stated that evapotranspiration, the sum of transpiration plus evaporation, must be analyzed on the basis of certain plant factors. Two such factors are the adaptations of land plants for maximum photosynthetic advantage and development of xylem which provides a supply of water to the mesophyll cells of the leaf. The effectiveness of stomata in control of transpiration is much debated. Stomata do occur at the only point at which protection against transpiration would be effective, namely at the plant-air interface.

These authors also discuss three stages or periods in the drying of porous solids by evaporation. During the constant rate period evaporation is limited by external conditions. The two distinct falling rate periods of drying can be separated. The first is controlled by the rate of surface evaporation and the second is controlled by the rate of internal liquid diffusion.

Rowe (1948) found that evaporation losses from the upper 12-inch depth of soil of annually burned plots in California chaparral were greater than evapotranspiration losses from undisturbed plots. He also stated that bared soil surfaces showed more rapid drying between storms than undisturbed plots.

Zahner (1958) found that a hardwood understory increased the rate of soil moisture depletion in pine stands. A chemical treatment of the understory was more efficient than a controlled burn in preventing moisture loss. By the end of the growing season the soil in both treated and untreated areas had reached the wilting point and moisture loss had almost ceased. These results agree with those of Hendrickson and Veihmeyer (1955). These authors stated that the greatest water loss occurred during the growing season. Water loss decreased rapidly at the end of the growing season.

Metz and Douglass (1959) working with a 66-inch depth of Piedmont soil found that evapotranspiration losses from a pine plantation were greater than evaporation losses from a barren area. These authors found that evaporation from the surface 5-inches of soil was greater than evapotranspiration during a 40-day drying period. They concluded that moisture loss is related to soil depth. Under vegetation it is a reflection of root concentration and from bare soils it is a reflection of the characteristics of evaporation.

Koshi (1959) found that no differences in soil moisture retained throughout the growing season existed in the top 12-inches of soil under an undisturbed oak stand, a thinned oak stand, and a cleared area in Texas. In the 12- to 24-inch horizon the moisture losses on the cleared plots were distinctly less than for the other two treatments.

Failure to calculate interception losses when estimating soil moisture depletion by soil sampling under field conditions may alter the results of an experiment (Lull and Axley, 1958). Interception losses may amount to as much as 10 percent of the total rainfall. This may account for part of the differences in water loss between forested and bared plots.

Zahner (1955) found that the rate of water loss between oak and pine stands was little different for corresponding depths. The upper 3-feet of soil lost water twice as fast as the layers below three feet.

Gardner and Fireman (1958) stated that there are two maximum soil moisture evaporation rates: one is the potential rate as determined by external conditions, and the other is determined by the rate at which water can be transmitted in the soil. Water will be limited by the lesser of the two and may very nearly equal the lesser.

Measurements of transpiration of intact five-stamen tamarisk (Tamarix pentandra Pall.) plants by using an infrared gas analyzer (Decker and Wetzel, 1957) showed that transpiration increased linearly with increasing light intensity up to 600 foot-candles. Light saturation was reached between 600 and 3,000 foot-candles. Arizona cypress (Cupressus arizonica Greene) gave results essentially the same as those obtained with tamarisk. These authors also found that transpiration decreased with increasing humidity and increased with increasing temperature.

In a study of diurnal variations of transpiration (Parker, 1957) the evening drop of transpiration seemed clearly related to decreases in light intensity. Occasional periods of cloudiness during the day had no apparent effect in depressing transpiration rates.

Janes (1954) noted that even though leaves may absorb some water from a saturated atmosphere, this water did not replace soil moisture in promoting growth. He also pointed out that leaves under a partial moisture stress may have reduced rates of photosynthesis.

Peters and Russell (1959) reported that the relative water losses from field corn by transpiration and evaporation from 1954 through 1957 resulted in the conclusion that transpiration accounted for only 30 to 50 percent of the total water loss. The remainder was attributed to evaporation.

Harrold et al. (1959) using plastic covered lysimeters reported that evaporation accounted for over half of the total water loss from field corn.

Holt and Van Doren (1960) used plastic covered plots to estimate the water losses from field corn. Evaporation accounted for 40 to 50 percent of the total water loss. The low water loss on bare plots indicated a low rate of evaporation when the soil surface was dry.

Recent gains have been made in research regarding the relative magnitudes of evaporation, evapotranspiration, and evaporation. However, more research is needed before the effects of vegetation manipulation and land management practices can be fully evaluated.

RESEARCH METHODS

Soil Moisture Depletion Study

The first part of this study of the relations among soil moisture, solar radiation, and water loss involved deriving a soil moisture depletion curve. The study was designed to investigate the rates of water loss by transpiration, evapotranspiration, and evaporation over a range of soil moisture and solar radiation levels. The results may help explain the magnitudes of the processes involved in water loss.

Seedlings of Aleppo pine (*Pinus halepensis* Mill.), two years old, grown in plastic pots were used for part of these determinations. Transpiration was studied by using pots that contained a tree seedling with the soil protected from evaporation; evapotranspiration, by pots that contained a tree seedling with the soil exposed; and evaporation, by pots that contained soil only.

Soils. Four groups of 15 pots were filled with a forest soil from the Bear Wallow area of the Santa Catalina Mountains of Arizona. The soil used in this experiment was collected under a mixed stand of ponderosa pine (*Pinus ponderosa* Laws.) and douglas fir (*Pseudotsuga taxifolia* (Poir) Britt.). It was screened through a quarter-inch mesh to remove rocks. The soil had a field capacity of 26 percent soil moisture using 1/3-atmosphere of tension as a simulator, and a wilting point of nine percent soil moisture using 15-atmospheres of tension. Other soil moisture tests were run at 3.4- and 5-atmospheres of tension (Table 1, Appendix). The mechanical composition of the screened soil was 48 percent sand, 47 percent silt, and 5 percent clay (Table 2, Appendix). The oven-dry weight of the soil was determined for each pot and proved to be in the range of 4000 to 5000 grams.

Climate. A continuous record of relative humidity and temperature was obtained during the experimental period by placing a hygrothermograph in the experimental area. Day temperatures ranged from 96° F. to over 110° F. and night temperatures from 56° F. to 84° F. Although some of the day temperatures were high for plant growth, they did not extend over long periods of time (Table 3, Appendix).

During the experimental period the daily maximum temperature increased from a high of 100° F. during the last two weeks of May to a daily maximum of over 110° F. during the period from June 13 until June 27, 1961. Another period of maximum daily temperatures over 110° F. prevailed from July 7 until July 22, 1961. After July 27, the daily maximum temperature dropped to approximately 100° F. for the remainder of the experimental period.

Daily minimum temperatures averaging 60° F. were recorded from May 15 until June 8, 1961. The minimum daily temperature increased to an average of 80° F. within 10 days and remained at this level until the end of the experiment on August 22, 1961.

Relative humidity during the experimental period ranged from 5 percent to 100 percent. A minimum daily relative humidity of less than 15 percent prevailed from May 15 until June 9, 1961. The highest minimum relative humidity was 42 percent recorded on August 15, 1961.

Maximum relative humidity never exceeded 65 percent between May 15 and June 17, 1961. After June 17 maximum daily relative humidity increased steadily until July 28, 1961. After July 28 relative humidity values above 85 percent were recorded almost every day until August 22, 1961. High relative humidity values were obtained during summer convectional storms but lasted for only a short time. A record of total solar radiation in gram-calories/cm.^{2}/day was obtained from the Institue of Atmospheric Physics, The University of Arizona (Table 3, Appendix).

Pot Treatment. In this part of the study treatments were replicated five times; each replication consisting of the following three treatments. To study evapotranspiration, seedlings of Aleppo pine were planted in five randomly selected pots out of each group of 15. To study transpiration five other pots were treated by planting a seedling in the pot and then covering the soil surface with 4 mil neutral polyethylene film and sealing it to the tree trunk with grafting wax to minimize evaporation. The remaining five pots in each group of 15 were left as a bare soil check on evaporation. For convenience, the pots were numbered in such an order that the first five pots out of each group of 15 held a tree with the soil covered with polyethylene, the second five pots held a tree seedling, and the remaining five pots contained soil only.

Each pot in the experiment was 10-inches in diameter and allowed 78.54 square inches of surface area when filled with soil. Each pot was 10-inches deep and filled with 7 to 9 inches of soil. The pot was equipped with a bottom liner of one-inch thickness fiberglass to minimize water loss through the bottom of the pot and two plastic tubes leading into the soil to allow uniform watering throughout the soil depth. The two tubes were placed 3-inches and 6-inches below the surface of the soil, respectively. The buried end of each tube consisted of a circular section with several holes punched along this length to allow uniform lateral watering throughout the soil mass. The weight of each pot with equipment, oven-dry soil, and tree was determined to the nearest gram and soil moisture changes were determined by weighing.

Tree seedlings were planted in the plastic pots on February 12, 1961 and allowed an establishment period under field capacity soil moisture conditions until May 15, 1961.

On May 15, 1961 the pots were moved to The Plant Materials Center of the University of Arizona. They were randomly placed by groups on a prepared bench two and one-half feet above the ground with a roof of 4 mil neutral polyethylene four feet above the bench surface to prevent normal summer precipitation from entering the pots. The sides of the bench were not enclosed so normal air temperatures prevailed throughout the measurement period. To prevent solar radiation from striking the sides of the pots, thus increasing soil temperatures, a 6-inch border was constructed around the edge of the bench and the interval between the pots on the bench was filled with excelsior.

At the start of the measurement period each randomly selected group of 15 pots was placed under one of four solar radiation levels. Solar radiation levels were 100 percent, 70 percent, 49 percent, or 6 percent solar radiation. For convenience, the pots were numbered in groups of 15. Pot numbers 61 to 75 were placed under six percent solar radiation, 76 to 90 were placed under 49 percent solar radiation, 91 to 105 were placed under 70 percent solar radiation, and 106 to 120 were left under full incident solar radiation. For a diagram of the design see Figure 1, Appendix.

The soil in each pot was watered to 26 percent which corresponded to field capacity as determined by 1/3-atmosphere of tension. Daily water losses were determined by weighing each pot to the nearest gram from the time the soil was brought to field capacity until the seedlings were permanently wilted. This required about 30 days.

Analysis. Daily water losses were not related to leaf area but were left on a per pot basis due to the difficulty of determining the actual internal leaf area involved in transpiration and to allow a direct comparison of transpiration, evapotranspiration, and evaporation (Decker, 1955).

Wilting Point Study

When the plants were permanently wilted at the termination of the soil moisture depletion study the moisture percentages in each pot were determined from the total pot weight. The wilting behavior of the Aleppo pine seedlings was noted on the experimental plants by a change in hue and a dessicated and curled appearance of the juvenile needles and from the daily water loss values. These served as guides to determine when permanent wilting had occurred.

The purpose of this work was to determine the soil moisture percentage when the tree seedlings reached permanent wilting over a range of incident solar radiation levels. The results may help explain failures in tree reproduction under restricted light conditions.

Analysis. Evaluation of this part of the experiment was supplemented by using analysis of variance.

Soil Moisture and Solar Radiation Study

The second major section of this study of the relations among soil moisture, solar radiation, and water loss involved establishing daily water loss averages under different pot treatments, soil moisture, and solar radiation combinations. The results may add some information on the processes involved in soil moisture loss.

Similar two-year-old seedlings of Aleppo pine (*Pinus halepensis* Mill.) were used for this work. Transpiration studies were conducted by planting a tree in a plastic pot and covering the soil surface with polyethylene. Evapotranspiration was studied by using a tree seedling with an exposed soil surface contained in a plastic pot. Plastic pots containing soil only were used to study evaporation.

Soil. Four groups of 15 plastic pots were filled with a forest soil from the Bear Wallow area of the Santa Catalina Mountains of Arizona. The soil used in this part of the study was collected under a mixed stand of ponderosa pine (*Pinus ponderosa* Laws.) and douglas fir (*Pseudotsuga taxifolia* (Poir) Britt.). It was also screened through a quarter-inch mesh to remove rocks. Moisture tension analysis of this soil at 1/3-atmosphere revealed a "field capacity" moisture content of 22 percent. A similar test at 15-atmospheres of tension showed the permanent wilting point to be at nine percent soil moisture. Other soil moisture values were determined at 3.4- and 5-atmospheres of tension (Table 4, Appendix). Mechanical analysis of the screened soil showed 50 percent sand, 46 percent silt, and 4 percent clay (Table 5, Appendix). The oven-dry weight of the soil in each pot ranged from 4000 to 5000 grams.

Climate. This section of the experiment was run concurrently with the other sections so climatic conditions were the same (Table 3, Appendix).

Pot Treatment. Each of three treatments in this part of the study was replicated five times. Evapotranspiration was studied by planting seedlings of Aleppo pine in five randomly selected pots out of each group of 15. Five other pots received a treatment to study transpiration consisting of planting a tree seedling in the pot and covering the soil surface with a 4 mil neutral polyethylene film and sealing the polyethylene to the seedling stem with grafting wax to minimize water loss by evaporation. The remaining five pots of each group were left as bare soil surfaces to study evaporation. The same pot numbering scheme was again adopted as was previously employed. The first numbered five pots of each group of 15 contained a tree seedling with the soil covered, the second numbered five pots held a tree seedling, and the remaining numbered pots held soil only. The pots used in this experiment contained fiberglass bottom liners and watering tubes identical with those described earlier.

Tree seedlings were transplanted to the plastic pots on February 2 and February 3, 1961 and allowed an establishment period under field capacity soil moisture conditions until May 15, 1961. On May 15, 1961 these post were also transferred to The Plant Materials Center and placed on the bench that was previously described.

At the start of the measurement period each group of 15 pots was brought to a selected soil moisture level (22 percent, 18 percent, 14 percent, or 10 percent) as indicated by pot weight and placed under full solar radiation conditions in a completely randomized design. Pot numbers 1 to 15 were watered to 22 percent soil moisture, 16 to 30 were watered to 18 percent soil moisture, 31 to 45 were watered to 14 percent soil moisture, and 46 to 60 were watered to 10 percent soil moisture. The design of the experiment is shown in Figure 2, Appendix. This measurement combination was continued for 16 days. Pots were weighed to the nearest gram daily and were rewet to the selected soil moisture level each day by adding water to the pots as described hereafter.

After each pot was weighed and the proper amount of water measured into a graduated cylinder the water was added to the pot by thirds. One third was placed into the tube leading 6-inches below the soil surface, one third was placed into the tube leading 3-inches below the surface and the remainder was added evenly to the surface of the soil. This method was used to insure that the soil mass in each pot was watered equally throughout the soil depth.

After the full solar radiation measurements had been completed various screens were erected over groups of pots to allow various incident solar radiation (70 percent, 49 percent, and 6 percent of the total) levels and measurements including watering were continued in the same manner and for the same length of time as previously described. At the end of the experiment measurements had been recorded for all soil moisture and solar radiation combinations with the exception of the groups of pots having

10 percent soil moisture and an incident solar radiation level of 70 percent and 49 percent of total solar radiation. The experimental seedlings did not survive at this low soil moisture level.

Tree growth during the period was not measured but appeared to be negligible.

Analysis. Analysis of this section of the experiment was supplemented by using analysis of variance of unweighted means.

RESULTS

Soil Moisture Depletion Study

<u>Transpiration</u>. To obtain a measure of the rate at which transpiration was depleting soil moisture each pot was weighed daily. A correction was made for the green weight of the pine seedling. The average weights of soil moisture lost for five replicates during the first eight days of the wilting period, during the remaining 11 to 24 days before the tree seedlings were permanently wilted, and during the entire period are presented in Table 1. Moisture losses in relation to soil moisture are displayed graphically in Figure 1. When solar radiation treatments are listed according to the amounts of water lost during the first eight days, from the largest to the smallest, they show the following order: 100 percent, 70 percent, 49 percent and 6 percent. The results showed that transpiration decreased as soil moisture decreased under all levels of incident solar radiation. However, after the first eight days or when the soil moisture had reached approximately 22 percent the decline was fairly constant regardless of the solar radiation level.

Table 1. Mean water losses by transpiration for different levels of incident solar radiation

Solar Radiation percent	Solar Radiation cal./cm.^{2}/day	First 8 days grams	Remaining Period grams	Remaining Period days	Total grams
100	775	240	145	11	385
70	542	228	195	24	423
49	380	132	194	24	326
6	47	109	181	24	290

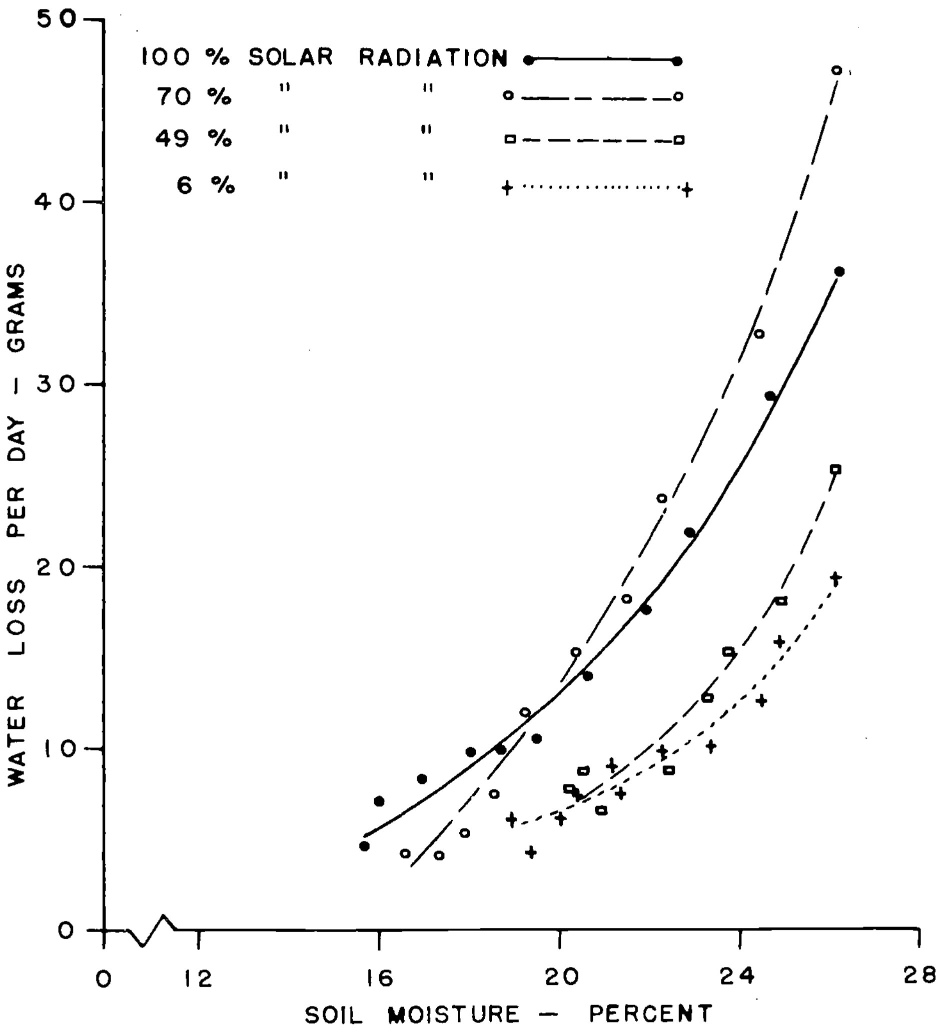

Figure 1. Mean daily water losses in grams by transpiration for different levels of soil moisture and solar radiation.

<u>Evapotranspiration</u>. The same procedures were used in measuring evapotranspiration as described for transpiration.

The average weights of soil moisture lost during the first eight days of the wilting period, during the remaining 17 to 20 days before the seedlings were permanently wilted, and during the entire period are presented in Table 2. When the solar radiation treatments are listed according to the amounts of water used during the first eight days, from greatest to smallest, they fall in the order 100 percent, 49 percent, 70 percent and 6 percent. After the first eight days of the wilting period the soil moisture losses were approximately the same regardless of incident solar radiation. Therefore, after the soil moisture had dropped to 19 percent, solar radiation did not affect water loss. Moisture losses in relation to soil moisture percentage are displayed in Figure 2. The curves did not follow the same pattern as did the tabulated water loss values. This effect was due to high water losses during the first two days under 70 percent solar radiation. Water loss decreased rapidly during the next six days. The curves showed that water loss decreased both with decreasing soil moisture and decreasing solar radiation during a period when no water was added.

Table 2. Mean water losses by evapotranspiration for different levels of incident solar radiation.

Solar Radiation percent	cal./cm.^{2}/ day	First 8 days grams	Remaining Period grams	days	Total grams
100	775	448	225	18	673
70	542	333	229	17	562
49	380	346	234	17	580
6	47	274	264	20	538

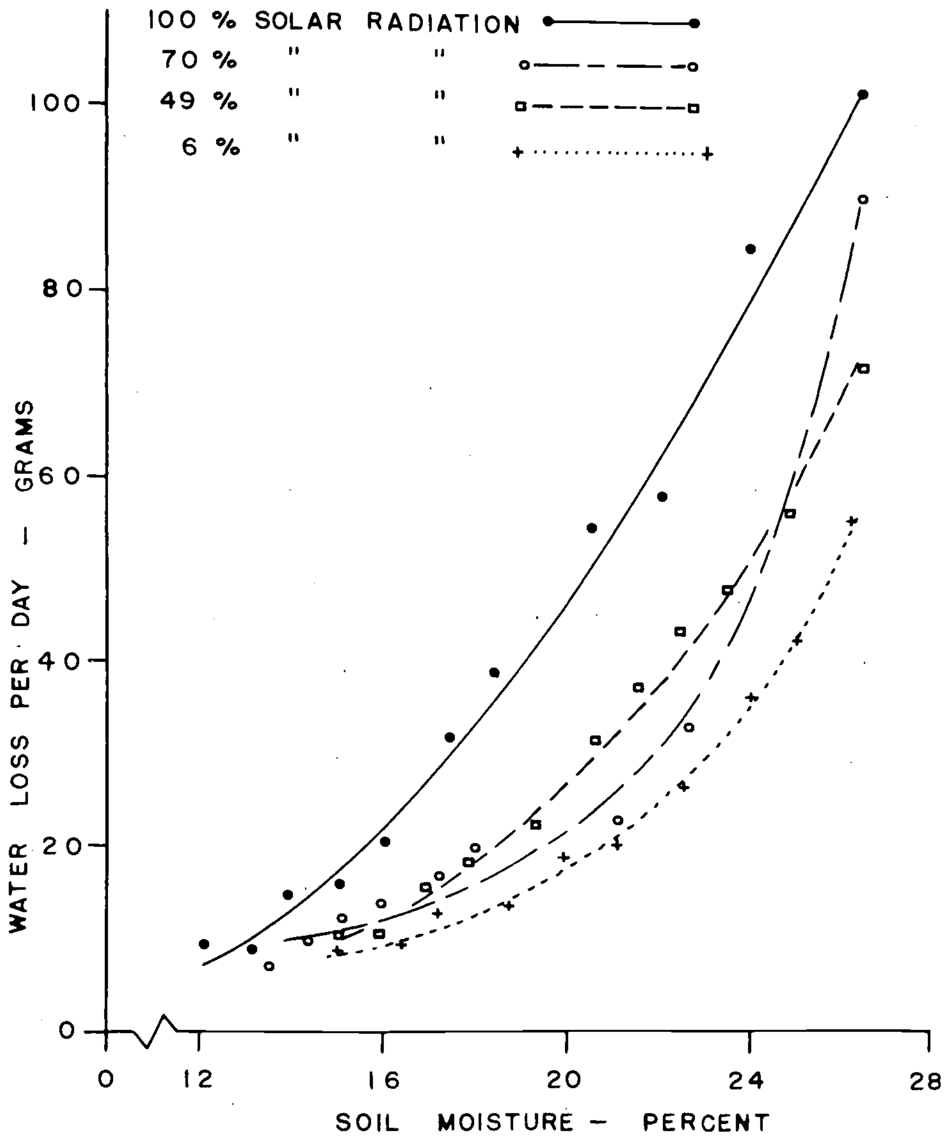

Figure 2. Mean daily water losses in grams by evapotranspiration for different levels of soil moisture and solar radiation.

Evaporation. With the exception of correcting water loss values for the weight of a tree seedling the same procedures were used as described for transpiration.

The average weights of soil moisture lost during the first eight days of the moisture depletion period, the remaining 24 days, and for the entire period are presented in Table 3. Water loss under different solar radiation treatments, when listed from the largest to the smallest over the first eight days follows an order of 70 percent, 100 percent, 49 percent, and 6 percent incident solar radiation. The same order is followed for total water loss. The differences are probably not large enough to be significant.

Moisture loss in relation to soil moisture percentage is shown graphically in Figure 3. Moisture losses by evaporation decreased with decreasing soil moisture but were not related to incident solar radiation. The curves and data show the rate at which soil moisture was depleted by evaporation during the period when no water was added.

Table 3. Mean water losses by evaporation for different levels of solar radiation.

Solar Radiation percent	Solar Radiation cal./cm.^{2}/ day	First 8 days grams	Remaining Period grams	Remaining Period days	Total grams
100	775	426	239	24	665
70	542	463	254	24	717
49	380	382	206	24	588
6	47	377	194	24	571

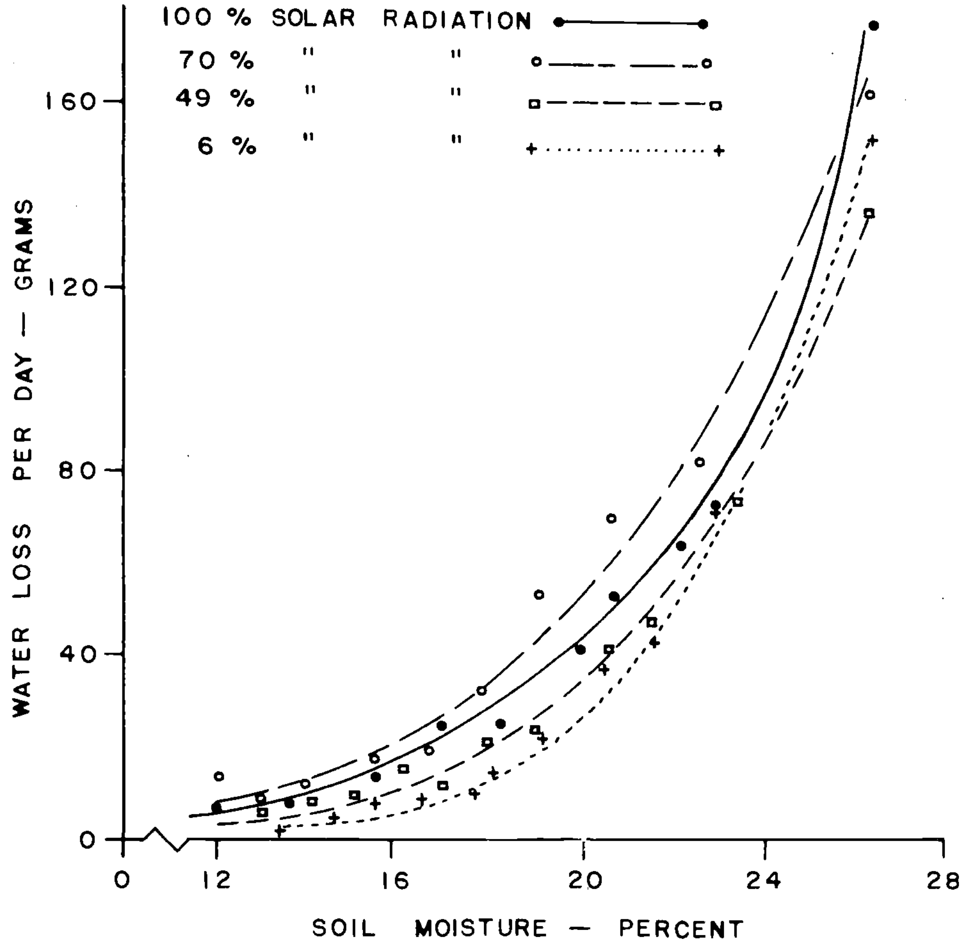

Figure 3. Mean daily water losses in grams by evaporation for different levels of soil moisture and solar radiation.

Comparison of Transpiration, Evapotranspiration, and Evaporation. In all solar radiation treatments evaporation exceeded either transpiration or evapotranspiration at high soil moisture percentages. Evaporation remained the greatest cause of water loss until the soil moisture dropped to 18 percent where evapotranspiration became the greatest. Although evaporation losses were the greatest at all levels of soil moisture under 70 percent solar radiation this was probably not significant due to experimental error. The high evaporation losses at soil moistures above 18 percent were probably due to direct absorption of radiation and heat and to the high temperatures and low relative humidities under which the experiment was conducted. The temperature effects could be more pronounced when small pots containing only a small volume of soil were used such as in this experiment. In all cases evaporative losses decreased sharply with decreases in available soil moisture indicating that the surface soil moisture was governing water loss (Wiegand and Taylor, 1961).

Evapotranspiration losses were intermediate between evaporation and transpiration losses at soil moisture percentages above 18 percent. This may have been due to a change in the microenvironment at the soil surface in the pot brought about by the addition of a tree seedling. At soil moisture percentages below 18 percent evapotranspiration became the greatest method of water loss except at the 70 percent solar radiation level. Evapotranspiration did not decrease as sharply as evaporation indicating that moisture removal from the soil by transpiration became more important as evaporation was restricted by a dry surface layer.

Transpirational water loss was the lowest of the three and in all cases did decrease as soil moisture decreased. Low transpirational water losses under low levels of incident solar radiation may have been due partly to depletion of food supplies within the plant and eventual starvation (Abd el Rahman, Kuiper and Bierhuizen, 1960) but mainly to less available energy.

Transpiration, evapotranspiration and evaporation under different levels of incident solar radiation are compared in Figures 4, 5, 6, and 7.

A comparison of transpiration, evapotranspiration and evaporation averaged over all incident solar radiation levels is presented in Figure 8. In this case evaporation was the greatest source of water loss at high soil moisture levels but assumes a position intermediate between transpiration and evapotranspiration after the eighth day of measurement. The eighth day of measurement corresponds to about 18 percent soil moisture.

The effect of solar radiation appeared to be greatest on transpiration and least on evaporation. This may have been caused by direct absorption of solar energy by tree seedlings which were highly sensitive to this form of energy. Evaporation may have been controlled by air temperature to such an extent that the effects of solar radiation were obscured. Evapotranspiration would show both effects.

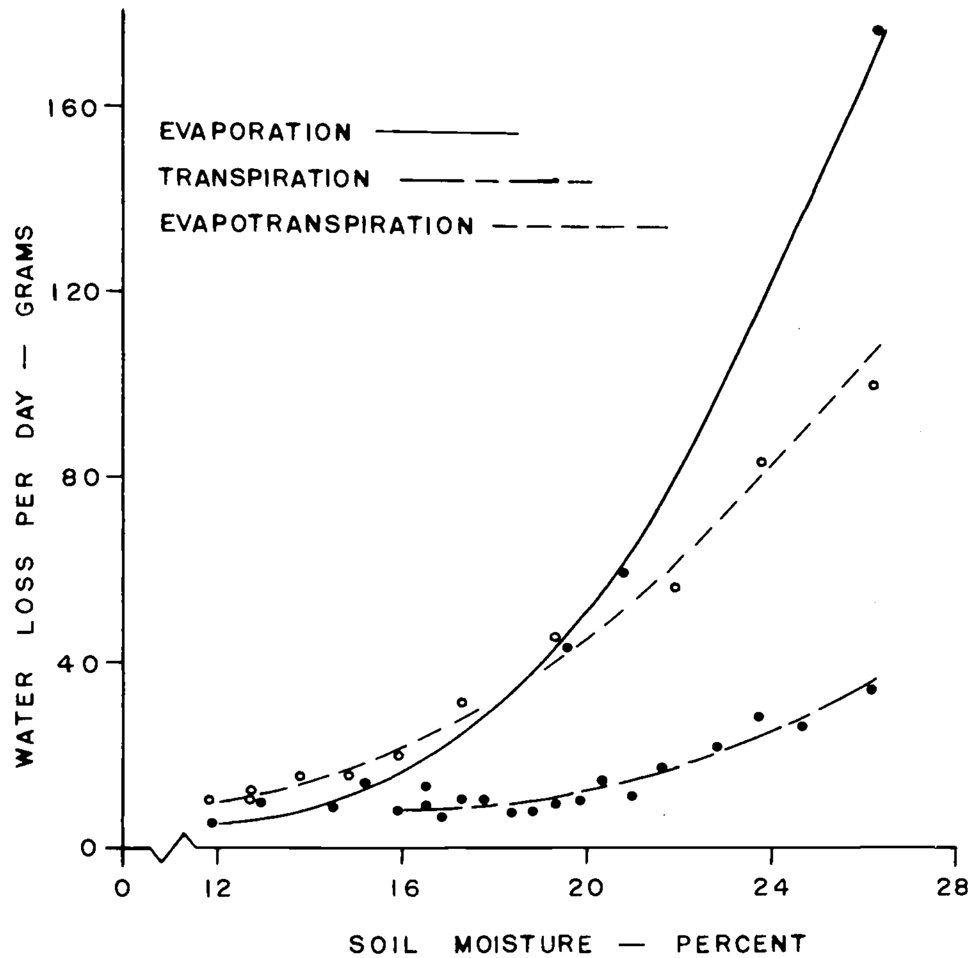

Figure 4. Mean daily water losses in grams by transpiration, evapotranspiration, and evaporation at different levels of soil moisture under 100 percent solar radiation.

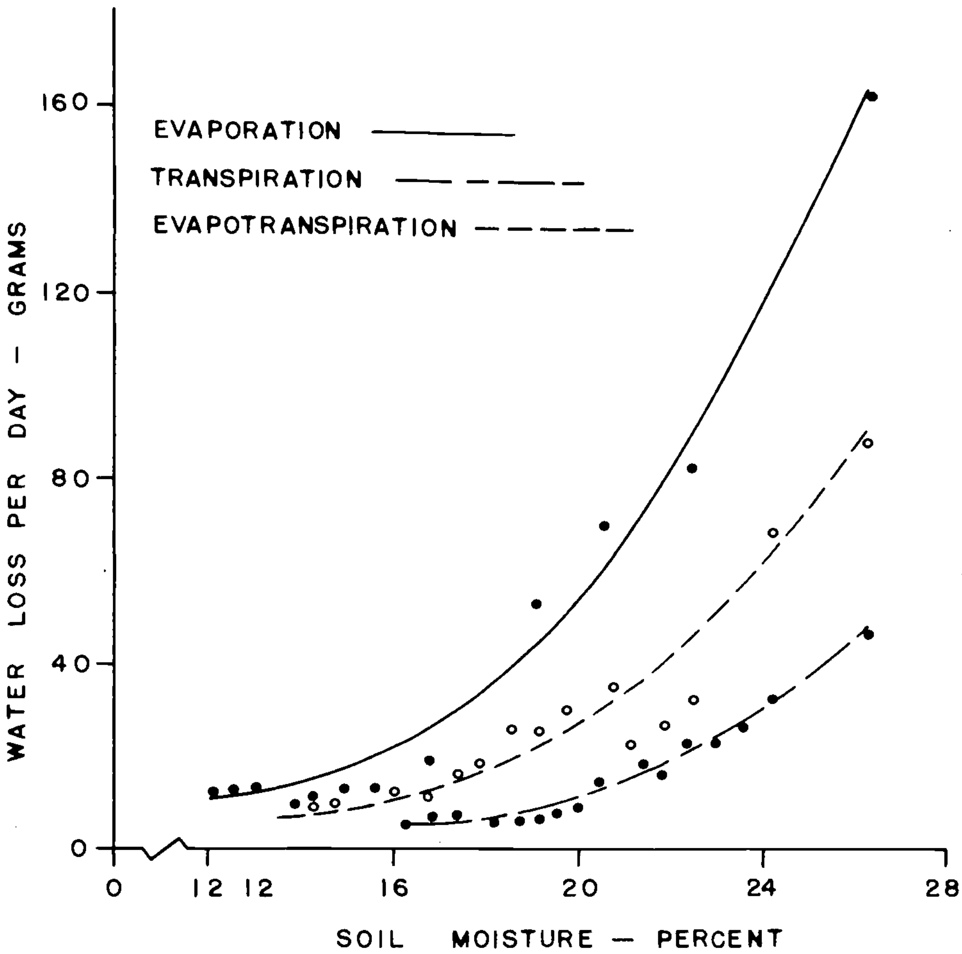

Figure 5. Mean daily water losses in grams by transpiration, and evaporation at different levels of soil moisture under 70 percent solar radiation.

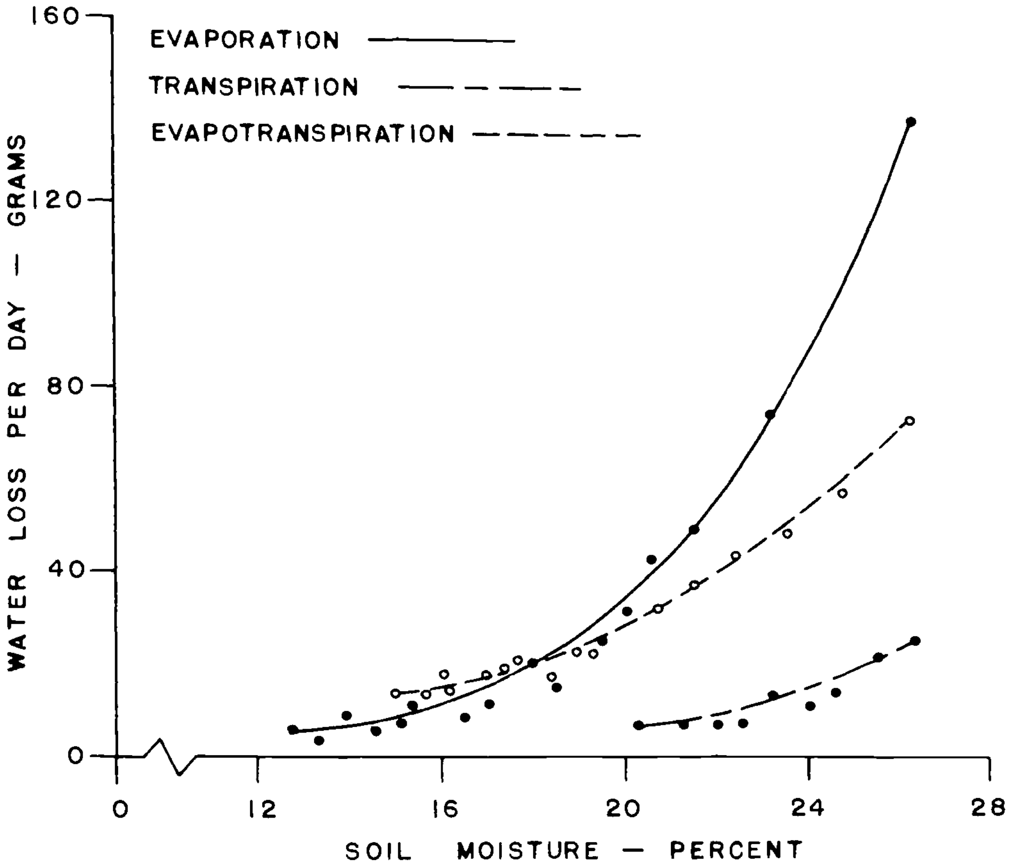

Figure 6. Mean daily water losses in grams by transpiration, evapotranspiration, and evaporation at different levels of soil moisture under 49 percent solar radiation.

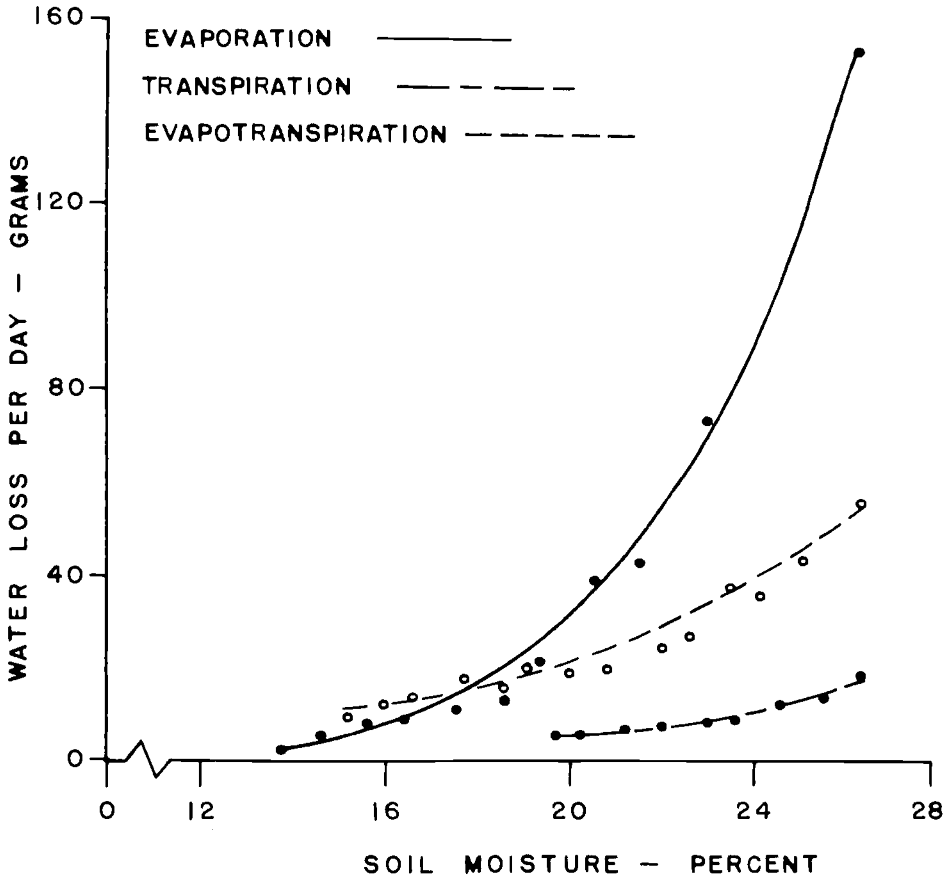

Figure 7. Mean daily water losses in grams by transpiration, evapotranspiration, and evaporation at different levels of soil moisture under 6 percent solar radiation.

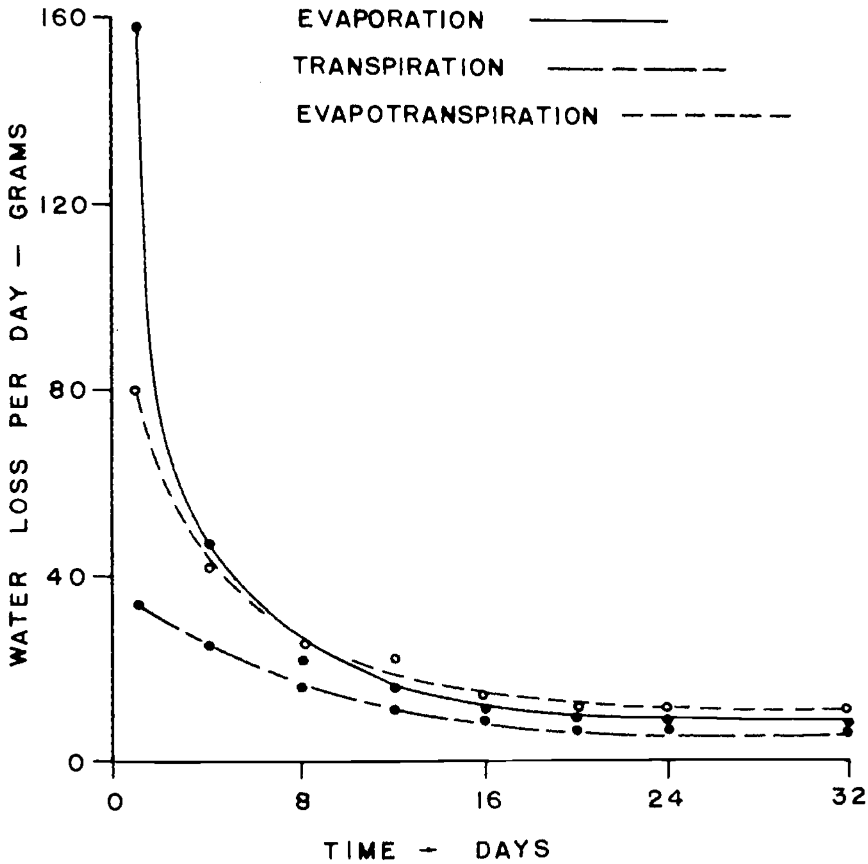

Figure 8. Mean daily water losses by transpiration, evapotranspiration, and evaporation during a soil moisture depletion study.

Wilting Point Study

The percentages of soil moisture at permanent wilting for the indicator plants used in the moisture depletion study are presented in Table 4. Overall statistical analysis of these data (Table 5) showed that differences, significant at the five percent level, existed between transpiration and evapotranspiration with evapotranspiration reducing the soil moisture percentage to a lower level in all cases. Solar radiation levels were also significant.

Soil moisture was reduced to a lower level by evapotranspiration than by transpiration alone. These data are mean values for five experimental plants each having the same treatment. With the exception of the 49 percent solar radiation treatment with polyethylene covered soil all means decrease, aligned in an order of increasing solar radiation.

Comparisons among individual wilting percentages showed that in both transpiration and evapotranspiration the 6 percent and 49 percent incident solar radiation levels gave permanent wilting points significantly higher than the wilting points under greater levels of solar radiation. This may have been due to restricted root growth, water absorption, and photosynthate production.

Table 4. Soil moisture percentages at permanent wilting of tree seedlings under two sources of water loss and four levels of solar radiation.

	Solar Radiation (Percent)					
Source	100	70	49	6	Total	Average
Transpiration	15.78	16.15	20.39	19.25	71.57	17.89
Evapotranspiration	11.96	12.69	14.81	15.31	54.77	13.69

Table 5. Analysis of variance of wilting point data.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Pot treatment	1	173.98	173.98	35.72*
Solar radiation	3	106.68	36.23	7.44*
Interaction	3	12.81	4.24	0.87
Error	32	155.91	4.87	
Total	39	451.38		

* Significant at the five percent level.

Soil Moisture and Solar Radiation Study

Measurements were made of the rates at which soil moisture was depleted by transpiration, evapotranspiration, and evaporation under four different levels of solar radiation and four soil moisture percentages. Each value reported is an average of from 29 to 75 individual observations.

Soil moisture exerted a definite influence on daily transpirational losses but the role of solar radiation was obscure although greatest loss appeared to occur at full solar radiation. As soil moisture became limiting transpiration decreased in the same manner as in the moisture depletion study. The decrease was present under all levels of incident solar radiation. The actual incident solar radiation probably did not greatly influence the average daily water loss due to the high temperatures and low relative humidities of the environment under which the determinations were made.

Data for mean daily water losses by transpiration under different levels of soil moisture and solar radiation are presented in Table 6 and Figure 9.

Table 6. Average daily rates of water loss in grams by transpiration under different levels of solar radiation and soil moisture.

Solar Radiation (Percent)	Soil Moisture (Percent) 22	18	14	10	Total	Average
100	52	34	12	5	103	26
70	37	27	18	6*	88	22
49	40	36	19	5*	100	25
6	41	24	13	6	84	21
Total	170	121	62	22		
Average	42	30	16	6		

* Measurements not taken, values added for computation assuming that actual observations would be intermediate to other observed values at 10 percent moisture.

Evapotranspirational water losses followed the same pattern as transpirational losses. Soil moisture levels exerted the greatest influence on daily water loss. The results showed a decreasing rate of water loss as soil moisture was depleted under constant solar radiation. This was the same result pattern as was obtained in the soil moisture depletion study. A solar radiation effect was present between full solar radiation and the reduced levels of solar radiation at all soil moisture levels. The 100 percent solar radiation level allowed a much greater rate of daily water loss than did the lower levels of solar radiation. This may have been partially due to the experimental procedure of taking all the observations under 100 percent solar radiation during the same period of time. The observations of evapotranspiration under

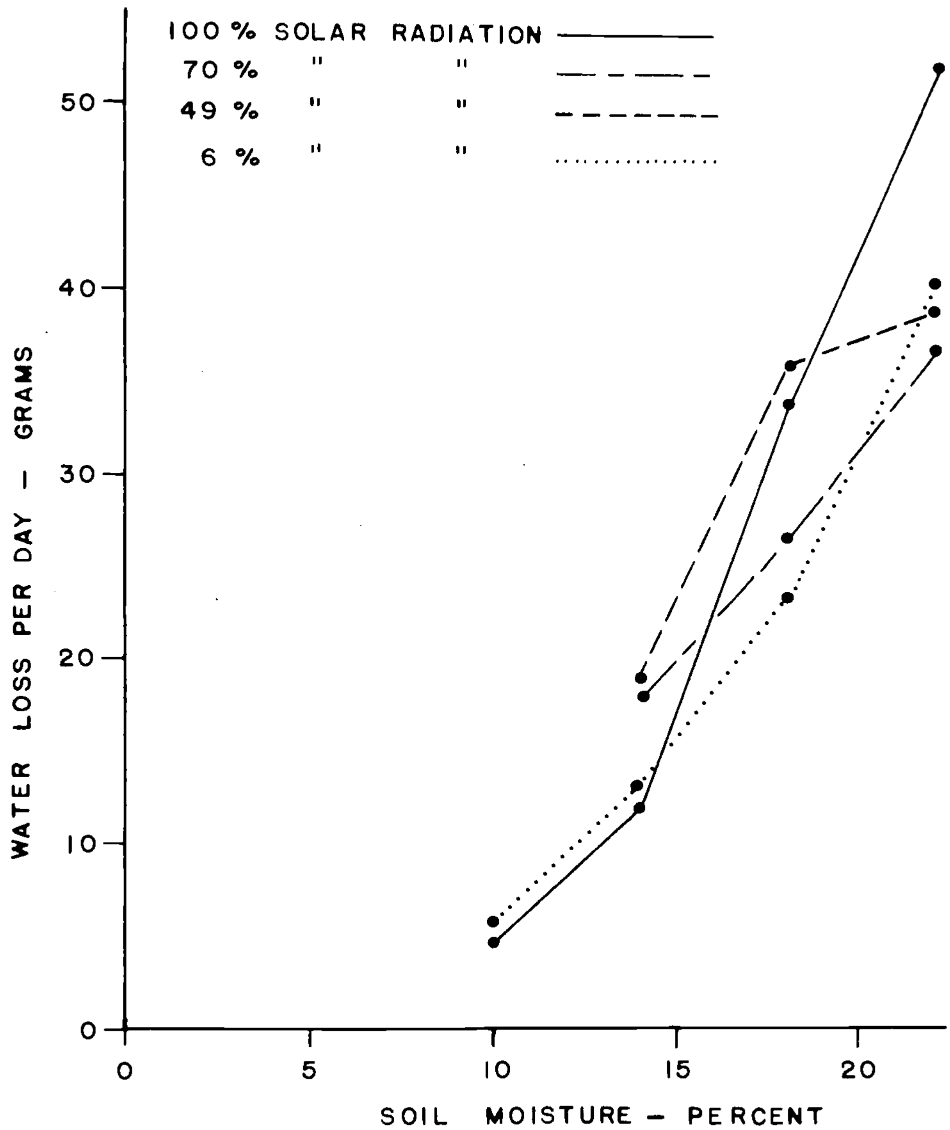

Figure 9. Mean daily water losses in grams by transpiration under four different levels of soil moisture and solar radiation.

the other three levels of solar radiation were taken over the next two months. Thus a variation in climatic conditions over the measurement period may have altered the results. At low solar radiation levels the effect may have been obscured by high temperatures and low relative humidities. Daily evapotranspiration losses under different levels of soil moisture and solar radiation are presented in Table 7 and Figure 10.

Table 7. Average daily rates of water loss in grams by evapotranspiration under different levels of solar radiation and soil moisture.

Solar Radiation (Percent)	Soil Moisture (Percent) 22	18	14	10	Total	Average
100	209	177	83	26	495	124
70	139	93	39	23*	294	74
49	139	87	30	20*	276	69
6	143	73	36	17	269	67
Total	630	430	188	86		
Average	158	108	47	22		

* Measurements not taken, values added for computation assuming that actual observations would be intermediate to other observed values at 10 percent moisture.

Daily water losses by evaporation were related to soil moisture and solar radiation as in the soil moisture depletion study. Evaporative losses were definitely influenced by decreasing soil moisture but followed no definite pattern with regard to incident solar radiation. As soil moisture became limiting evaporation was retarded. A dry soil surface was not present in this study because water losses were replaced daily by watering. The reduction in evaporative loss was due to an

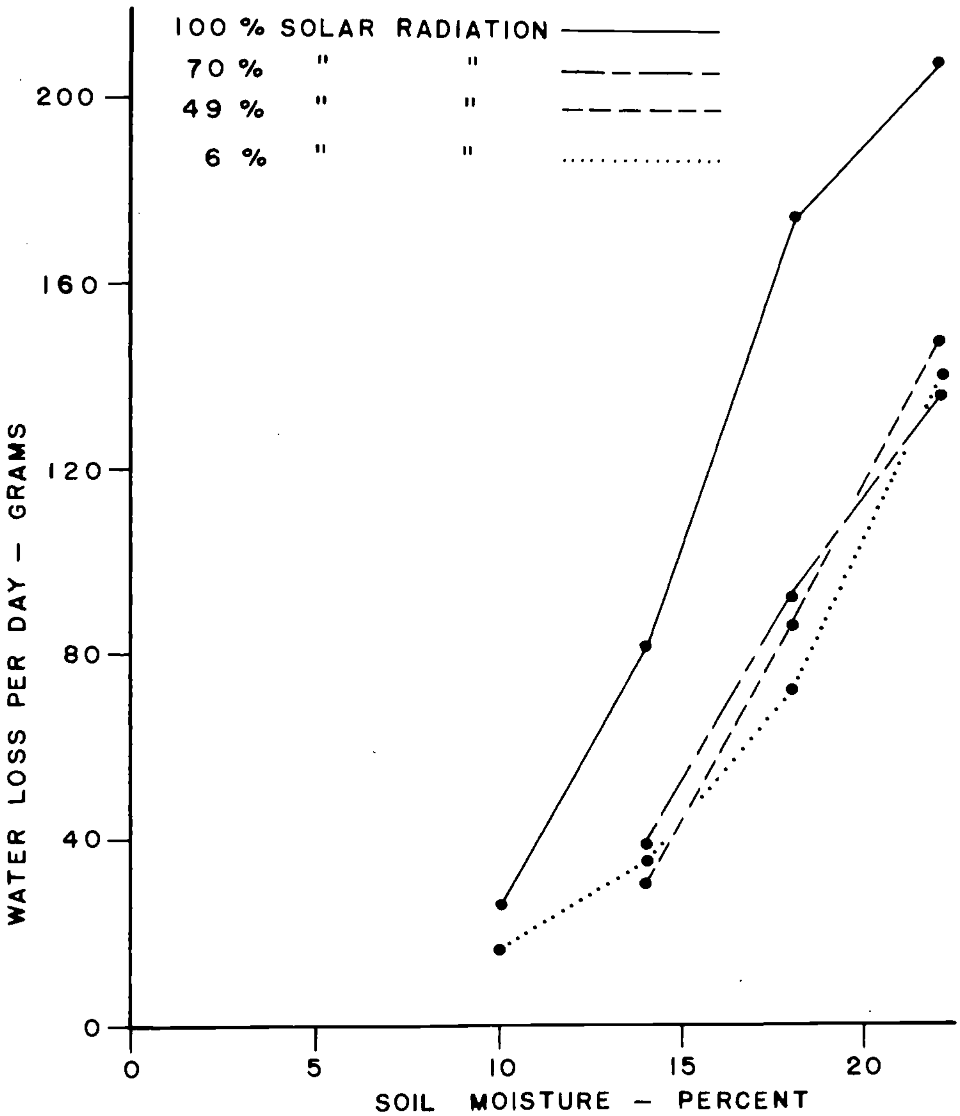

Figure 10. Mean daily water losses in grams by evapotranspiration under four different levels of soil moisture and solar radiation.

increased resistance to evaporation as soil moisture decreased (Table 8 and Figure 11).

Table 8. Average daily rates of water loss in grams by evaporation under different levels of solar radiation and soil moisture.

Solar Radiation (Percent)	Soil Moisture (Percent) 22	18	14	10	Total	Average
100	175	99	54	6	334	84
70	45	30	51	5*	131	33
49	62	68	22	5*	157	39
6	106	21	34	4	165	41
Total	388	218	161	20		
Average	97	55	40	5		

* Measurements not taken, values added for computation assuming that actual observations would be intermediate to other observed values at 10 percent soil moisture.

Analysis of variance of unweighted means of all soil moisture loss data are presented in Table 9. The pot within treatment sum of squares was divided by the harmonic mean to obtain a testing term. The F test showed that the interaction was non-significant but that pot treatments and soil moisture-solar radiation levels were significant at the five percent level. A comparison of the data showed that water losses by transpiration, evapotranspiration, and evaporation were significantly different. The order exhibited by the water losses, from largest to smallest, was evapotranspiration, evaporation, and transpiration. In this section the magnitudes of water loss by evapotranspiration and evaporation were reversed from those found in the moisture depletion study ; evapotranspiration was the greater in this case. A comparison

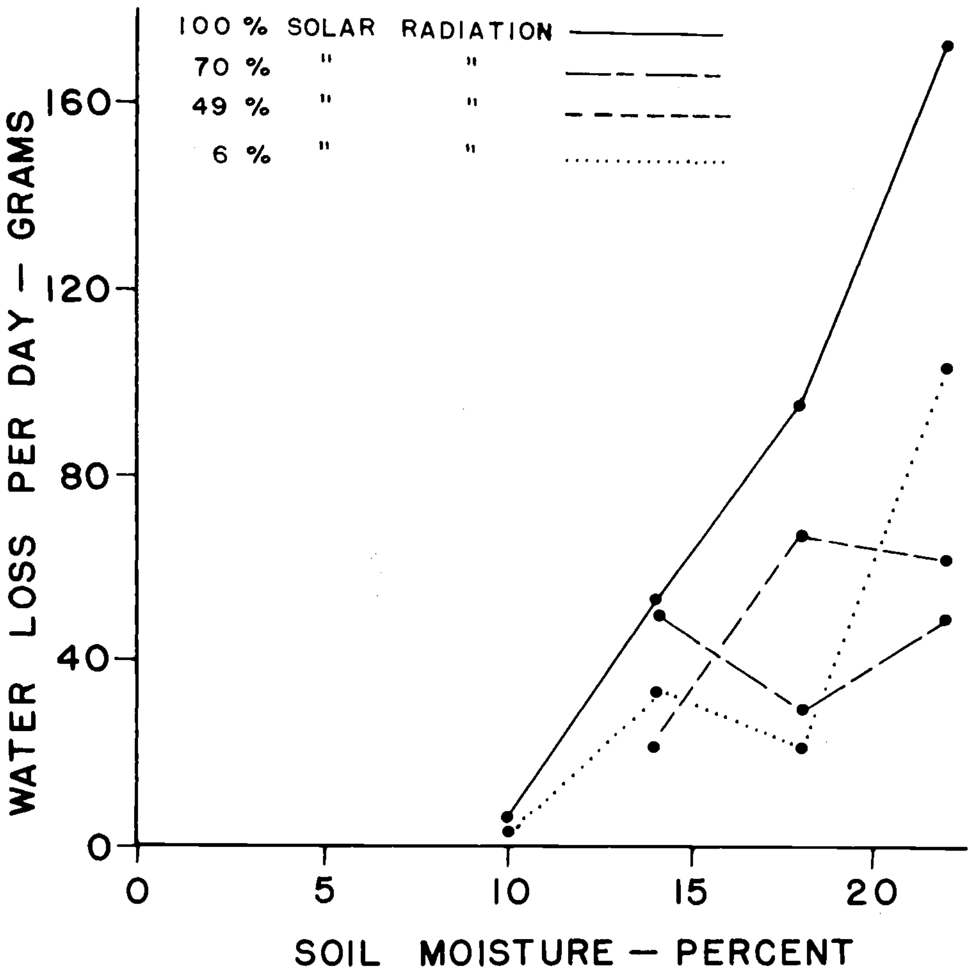

Figure 11. Mean daily water losses in grams by evaporation under four different levels of soil moisture and solar radiation.

of the mean water losses under the soil moisture-solar radiation treatments showed that only two significant groups of water loss values existed. The water losses attributed to transpiration, evapotranspiration, and evaporation under all incident solar radiation levels at 22 percent soil moisture and under 100 percent and 49 percent incident solar radiation at 18 percent soil moisture were significantly greater than the rest of the means. High soil moisture and incident solar radiation will increase water loss. Comparisons of individual means were not performed since the interaction was not significant.

Table 9. Analysis of variance of unweighted means of moisture loss data from soil moisture and solar radiation study.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Pot treatment	2	29,149	14,575	7.36*
Soil moisture-Solar radiation treatment	13	70,140	5,375	2.72*
Interaction	26	22,024	847	0.42
Pot within treatment	151	1,291,857	1,979#	

* Significant at the five percent level.

\# Pot within treatment sum of squares was divided by the harmonic mean of 4.322 to obtain a testing term.

A comparison of the results of this experiment with the results from the soil moisture depletion study showed one difference. In this study evapotranspirational water loss exceeded the water loss by evaporation alone. This reversal of results was attributed to the experimental procedure of watering each pot to a selected soil moisture level each day. The constant wetting of the soil surface allowed some water to remain in a more available position for water loss by evapotranspiration as evaporation could take place directly from the soil surface as the tree seedlings removed water from the deeper portions of the soil. Under the conditions imposed by the depletion study a dry soil surface was allowed to restrict evaporative losses and may have depressed transpiration by drying out the soil around the seedling roots in the top portion of the soil. Transpirational water losses were the lowest in both studies.

DISCUSSION

Water Loss Under Different Soil Moisture and Solar Radiation Levels

The results of the soil moisture depletion study and the soil moisture-solar radiation study indicate that soil moisture exerts a definite influence on water loss but that the influence of solar radiation is obscure.

Loss by transpiration decreased with decreasing soil moisture over the entire depletion curve. This would indicate that the rates of transpiration are influenced by the availability of soil moisture to the plant roots.

Evapotranspiration and evaporation were also related to soil moisture. While soil moisture was abundant and soil moisture tension was increasing slowly, the rate of water loss was strongly influenced by moisture levels. At lower moisture levels water losses did not decrease as rapidly but a downward trend was still present.

The failure of solar radiation to be clearly a major factor in controlling the rate of water loss may be due to the uncontrolled temperature and relative humidity conditions in the experiment. A linear relationship has been observed by some workers between water loss and incident light intensity (Kuiper and Bierhuizen, 1958). However, these workers used controlled temperature and relative humidity conditions. In this experiment the combination of high soil moisture and high solar radiation levels did produce significantly higher mean daily water losses.

A comparison of the rates of water loss by transpiration, evapotranspiration, and evaporation revealed that transpiration depleted soil moisture most slowly. In all cases it was significantly slower than evapotranspiration or evaporation. The apparent reversal of the rates of evaporation and evapotranspiration in the two studies dealing with the average daily water loss has been attributed to the experimental procedure. It is probably safe to assume that evaporation from a bare soil surface would be greater than evapotranspiration from a similar soil with cover when both soils are at or above field capacity in the surface layer (Rowe, 1948). Direct evaporation from a bare soil surface would not require an expenditure of energy to move water through the plant. Under field conditions in arid areas where the soil surface is rapidly dried evapotranspiration would soon assume a leading role in soil moisture depletion. This would be especially true on deep soils during extended periods without precipitation.

Wilting Point

The results of the wilting point study showed that water loss by evapotranspiration was significantly greater than water loss by transpiration alone. The differences were probably due to evaporation from the upper layers of the soil decreasing the average soil moisture percentage in the pot below the wilting point of the seedlings.

The results also indicate that statistically significant differences in wilting percentages may be obtained under different levels of solar radiation. This effect may have been influenced by several outside factors. One is that plants under low solar radiation and high temperatures may not produce enough photosynthate to sustain the plant, root growth may be restricted, and water absorption lowered. The eventual depletion of food supplies within the plant may hasten permanent wilting.

However, with only one exception, higher incident solar radiation levels did induce permanent wilting at lower soil moisture percentages than did low solar radiation levels. These differences are reasonable even though errors may have been made in judging permanent wilting. The one exception occurs in the transpiration experiment where trees under six percent solar radiation wilted at a lower soil moisture value than those under 49 percent.

It is possible to conclude from this study that tree seedlings grown under high incident solar radiation levels will survive under lower soil moisture conditions than tree seedlings grown under restricted solar radiation. Moisture tolerances within a species do vary according to the amount of solar radiation received. This has important implications in silviculture.

SUMMARY

A study was made of the rates of water loss by transpiration, evapotranspiration, and evaporation from soil in 10-inch plastic pots. Transpiration and evapotranspiration were studied using Aleppo pine (<u>Pinus halepensis</u> Mill.) in sealed and non-sealed pots. The effects of different levels of soil moisture and solar radiation were measured.

In a soil moisture depletion study the water loss from the tree seedlings under covered and exposed soil conditions was related to incident solar radiation and soil moisture. Moisture loss decreased both with decreasing soil moisture and decreasing solar radiation. Evaporation from a bare soil surface was not clearly related to incident solar radiation. Evaporation was related to soil moisture and decreased with decreasing soil moisture.

When the soil was at or near field capacity evaporation was the greatest source of water loss. As soil moisture became less available evapotranspiration assumed the leading role in rate of water loss.

The soil moisture at the permanent wilting points of the tree seedlings were significantly higher under covered soil conditions than under exposed soil conditions. Also, statistically significant differences existed supporting the conclusion that tree seedlings which received greater incident solar radiation wilted at lower soil moisture percentages.

A second study related transpiration, evapotranspiration, and evaporation to four fixed levels of soil moisture and solar radiation. Statistically significant differences existed which supported the conclusion that greater soil moisture allowed greater rates of water loss. The effects of incident solar radiation were obscure but an effect may have been present between full solar radiation and reduced levels of solar radiation.

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A P P E N D I X

Table 1. Soil moisture retention at different atmospheric pressures for soil used in moisture depletion study.

Tension atmospheres	Soil Moisture percent
15.00	9.30
5.00	13.35
3.40	14.88
0.33	26.31

Table 2. Particle size distribution of soil used in soil moisture depletion study.

Particle size		Composition percent
sand		48
silt		47
clay		5
	Total	100

68	73	63		101	102	95		90	85	86		119	112	114
69	62	65		105	103	97		89	88	84		109	120	118
70	66	74		104	91	92		83	87	82		110	108	115
72	61	75		99	93	96		77	79	80		111	117	116
71	67	64		98	94	100		81	78	76		106	107	113

Figure 1. Diagram of design of soil moisture depletion study showing the position of each pot by code number.

Table 3. Data on temperature, relative humidity, and solar radiation from May 15 to August 22, 1961.

Date 1961		Temperature °F Max.	Min.	Relative Humidity (percent) Max.	Min.	Solar Radiation cal./cm.^{2}/day
May	15	102	57	32	5	802
	16	105	62	48	8	768
	17	106	57	46	9	723
	18	109	59	40	7	813
	19	109	60	44	7	770
	20	102	56	49	9	825
	21	96	57	52	15	678
	22	104	57	45	12	808
	23	106	58	42	9	812
	24	106	60	48	9	815
	25	102	64	46	12	720
	26	108	61	46	12	681
	27	109	60	43	12	813
	28	106	63	45	11	761
	29	102	57	56	15	625
	30	110	59	50	13	812
	31	106	61	46	14	804
June						
	1	107	56	40	11	821
	2	109	56	44	10	828
	3	100	57	47	15	815
	4	104	62	45	14	810
	5	101	57	56	15	807
	6	110	62	42	13	712
	7	110	61	40	10	816
	8	110	65	46	12	819
	9	110	67	48	13	798
	10	110	68	47	16	774
	11	109	69	47	18	782
	12	106	69	49	20	714
	13	110	70	49	15	777
	14	110	70	39	12	788
	15	110	81	46	14	781
	16	110	80	49	25	747
	17	110	72	74	23	626
	18	108	78	63	21	754
	19	110	80	59	20	772
	20	110	81	48	18	771
	21	110	80	68	22	756

Continued

Continued
Table 3.

Date 1961		Temperature °F. Max.	Min.	Relative Humidity (percent) Max.	Min.	Solar Radiation cal./cm.²/day
June	22	110	70	58	22	751
	23	110	84	48	18	754
	24	110	83	56	20	754
	25	110	81	54	20	637
	26	109	77	63	22	760
	27	110	82	51	21	744
	28	105	81	61	29	727
	29	106	77	75	31	683
	30	108	77	76	20	732
July	1	109	79	64	26	679
	2	106	76	97	27	481
	3	102	67	93	26	578
	4	104	71	54	14	780
	5	108	73	38	15	772
	6	107	83	53	15	745
	7	110	77	65	20	746
	8	110	80	56	22	775
	9	110	80	81	22	775
	10	110	82	58	17	747
	11	110	85	68	17	740
	12	110	85	51	21	755
	13	109	82	50	26	730
	14	110	78	72	21	753
	15	110	80	60	22	742
	16	109	79	84	26	726
	17	110	81	69	25	751
	18	110	80	69	24	741
	19	110	78	70	20	741
	20	110	80	76	22	726
	21	110	75	99	23	715
	22	110	72	95	33	449
	23	110	75	92	24	719
	24	107	75	96	27	641
	25	107	76	95	20	748
	26	109	78	88	16	667
	27	106	74	97	22	636
	28	100	76	74	26	570
	29	97	76	80	33	498
	30	99	80	87	33	570
	31	102	76	92	28	690

Continued

Continued
Table 3.

Date 1961	Temperature °F. Max.	Min.	Relative Humidity (percent) Max.	Min.	Solar Radiation cal./cm.^{2}/day
August					
1	106	75	82	20	544
2	102	74	83	26	576
3	109	75	100	19	605
4	96	72	100	25	519
5	106	77	75	19	729
6	109	78	85	15	694
7	110	78	73	18	706
8	110	76	90	20	706
9	105	79	100	22	690
10	104	76	94	27	480
11	107	76	70	23	571
12	110	76	99	20	665
13	102	80	70	22	573
14	101	74	100	24	573
15	96	74	100	42	573
16	98	73	97	24	573
17	103	74	100	21	621
18	105	76	100	24	589
19	110	76	100	20	651
20	106	84	49	20	672
21	109	80	80	22	672

Table 4. Soil moisture retention at different atmospheric pressures in soil moisture and solar radiation study.

Tension atmospheres	Soil Moisture percent
15.00	9.20
5.00	11.47
3.40	13.69
0.33	22.00

Table 5. Particle size distribution of soil used in soil moisture and solar radiation study.

Particle size		Composition percent
sand		50
silt		46
clay		4
	Total	100

20	30	6	26	19	34	32	37	43	44	47	23
39	2	56	42	25	49	40	22	10	5	24	15
9	27	4	33	12	51	52	13	53	54	8	48
57	46	7	31	41	17	11	14	35	55	45	59
60	29	28	36	21	58	38	16	18	50	3	1

Figure 2. Diagram of design of soil moisture and solar radiation study showing the position of each pot by code number.