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The Influence of Soil Moisture Suction and Evaporative Demand on Actual Evapotranspiration and Yield of Alfalfa

Bozorg Bahrani

Utah State University

THE INFLUENCE OF SOIL MOISTURE SUCTION AND EVAPORATIVE DEMAND ON ACTUAL EVAPOTRANSPIRATION AND YIELD OF ALFALFA

by

Bozorg Bahrani

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Bozorg Bahrani

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INTRODUCTION

Evapotranspiration has been defined as the combination of evaporation of water from the soil surface and transpiration of water by vegetation. If the ground is well covered by plants, most of the water is lost by transpiration of water directly from the plant tissue, rather than by evaporation of water directly from the soil surface. The term consumptive use is synonymous with evapotranspiration.

For many years scientists in various parts of the world have been studying the problem of estimating in advance how much irrigation water would be required for crops grown under different conditions of climate, soils, and water supply. It is not easy to obtain an exact figure of consumptive use for each crop under different field conditions since the rate of use of water in evapotranspiration is a function of many variables. Van Wijk and his associates (45) consider the actual evapotranspiration, E, of a tract of vegetation of a given shape to be a product of two factors:

$$E = (A)\ (B) \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (1)$$

The factor B is the evaporation from a body with a wet surface, and of a shape similar to that of the evaporating part of the plant cover receiving the same energy. This factor can be considered a constant under a given set of atmospheric conditions under consideration.

The factor A is a reduction coefficient, the value of which is determined by plant and soil factors. Van Wijk et al (45) consider these factors to be plant physiological condition, soil moisture suction, cultural treatment given the plant such as cutting of leaves. Whenever all of these factors are in favorable condition to the plant and water is readily available, the value of A will be a maximum corresponding to a maximum value of E. This is the so-called potential evapotranspiration for a vegetation cover of the shape under consideration.

In the present investigation the effect of soil moisture suction on the rate of water use and growth of an alfalfa field is studied. The rate of moisture depletion in the root zone as determined by the neutron scattering method is taken as the actual rate of evapotranspiration.

REVIEW OF LITERATURE

Measuring Evapotranspiration

Actual evapotranspiration

Among the many ways of measuring the actual rate of evapotranspiration, the most common is by taking the difference in water content of the soil profile determined by direct soil moisture sampling at different times. Veihmeyer (46, 47) has used this method for measuring actual evapotranspiration in many experiments. This method, however, is laborious, time consuming, and is not always sufficiently accurate (30).

Tensiometers and gypsum resistance blocks have been used by some workers to estimate the amount of water in the soil (1). The results are not very reliable because the relation between soil-water suction and soil-water content are subject to temperature and hysteresis effects and changes in soil structure (30).

Lysimeters have been widely used in research dealing with evapotranspiration measurements. These instruments are not absolute devices for field work and are only good for research (30).

The neutron scattering method for measuring the amount of water in the soil has received much attention during the last decade. Nixon and Lawless (24) compared this method with moisture sampling and reported that it is less time consuming and more accurate and reproducible, especially as the depth of sampling increases. Stone and others (37) have reported the same results. Stewart and Taylor (36) were among the first who published the field use of this method and reported that if calibrated carefully this method appears to be more accurate in determining moisture content than resistance methods and only slightly less accurate than gravimetric method. However, Stone et al (37) have encountered some disadvantages of the method as follows: The result is not accurate at shallow depths (0 - 20 inches) and when there is an abrupt change in water content of the soil (wet-dry front). Nixon and Lawless have also reported other errors for this method due to random emission from the neutron source and mechanical and electrical limitations of the measuring device.

Potential evapotranspiration

The rate of water use in evapotranspiration is dependent only on weather and climatological factors if the crop completely covers the soil and never lacks a readily available supply of water. This makes it possible to estimate the consumptive use of water for a large area by using only climatological data regardless of the type of crop and soil. In the past 20 years, much research has been done in various parts of the world to establish the relationship between evapotranspiration and the weather. These methods have the advantages of application to a rather broad area and of being able to predict the consumptive use of water in the area with some success.

Different methods have been presented by different scientists for calculation of evapotranspiration from weather data (see Appendix A), and they can be grouped into three categories:

1. The aerodynamic method based on the vapor transfer process; very accurate, difficult, measurements of transport of water vapor are required.

2. The energy balance method which is based on the law of conservation of energy; measurements of the disposition of the heat flux at the earth's surface are required.

3. Empirical relationships between experimental data and various climatic and water supply data. These methods consist of simple empirical equations relating consumptive use of water with some function of air temperature or measured evaporation.

The Penman method (25, 26, 27, 28, 29) which is a combination of aerodynamic and energy balance methods appear to be one of the most promising methods to estimate potential evapotranspiration (30). Pelton (30) has calculated the evapotranspiration by use of Penman equation on monthly, daily, and even hourly bases and has obtained high correlation with measured evapotranspiration. The main difficulty he found for the Penman equation was that although it has a high correlation with potential evapotranspiration, it underestimates the actual evapotranspiration.

The heat budget method described by Suomi and Tanner (38) has also been found to be one of the best approaches for relating potential evapotranspiration to weather factors. In this method net radiation is considered to be the only source of energy for evaporation of water from the plant and soil surface. Lemon and his associates (20) have found a high correlation between evapotranspiration and daily net radiation. Halstead and Covey (11) and Tanner (40) have found high correlation between the evapotranspiration calculated by the heat budget method and the actual value measured by Lysimeter. Pelton (30) has reported high correlation with daily and hourly bases.

The Thornthwaite (43) method is an empirical equation relating the potential evapotranspiration (PE) with only one factor: mean monthly air temperature. This method was found to give satisfactory results in calculation of potential evapotranspiration on a seasonal basis (31, 30, 44). But it has been reported that as the period of estimation decreases the discrepancy between calculated PE and actual value of evapotranspiration increases. Pelton (30) found a very low correlation between the actual evapotranspiration and PE on a daily basis. Other empirical methods, Blaney-Criddle (4), Hargreaves (12), Lowry-Johnson (21) again relate the consumptive use of water mainly with mean or maximum monthly air temperature, except that the daylight hours and latitude of each location is also taken into account in some cases (see Appendix A). The Blaney-Criddle method has been used widely by many workers, especially irrigation engineers, at places all over the United States because of the simplicity of the equation. It has given satisfactory results on the yearly and seasonal bases. On the monthly and daily bases, as in Thornthwaite method, the errors increase (30).

Van Wijk and De Vries (45) have expressed some objections to the methods in which air temperature is used as the only climatic factor:

> The mean monthly temperature is a function of time which lags behind the average net radiation, and this can make errors in calculation of potential evapotranspiration even on a seasonal basis.

Another objection is the effect of advective heat (oasis effect). When there is advective heat coming into an area, the evapotranspiration does not increase in proportion to the temperature, causing the calculated potential evapotranspiration to be higher than the actual amount.

Another empirical method is to relate evaporation of water from a free water surface to evapotranspiration. The pan evaporation for calculation of consumptive use of water by crops has been used for a long time by some investigators (1, 3), and different coefficients for crops and seasons have been introduced. The difference between the evaporation of black and white atmometer was introduced by Halkais _et al_ (10) to give a high correlation with evapotranspiration. These two methods are very simple to use for a small area in which they have been adopted, but they cannot be generalized for different climates and large areas where the effect of advective heat will cause a large error in this estimation.

On comparing the methods of estimation of potential evapotranspiration, it can be seen that the theoretical methods give reliable results, but they consist of complicated equations the solution of which requires many measurements. This makes the theoretical methods too difficult to be practically used in agriculture. On the other hand, the empirical methods are very simple and easy to use but have the disadvantage of not giving a reliable result. Generally speaking, any method for estimating potential evapotranspiration which must be modified seriously for local conditions, seasons, type of crops, and soils is not a method with sufficient generality to be useful in irrigation practices (30).

Factors Affecting Evapotranspiration

The methods which have been discussed estimate the potential rate of evapotranspiration, assuming a homogeneous soil moisture regime and other factors in favorable condition throughout for plant growth. These conditions are continually fluctuating in the field by significant amounts.

Therefore, it is difficult and sometimes impossible to apply these equations to irrigation under field conditions. This means that to obtain the actual value of water use in evapotranspiration there are factors other than climatological ones which must be taken into account.

Halkias et al (10) have considered transpiration to be like evaporation from a wet surface dependent on the weather factors, but, unlike evaporation, being also controlled to a certain extent by conditions within the plant. They considered radiation, temperature, humidity, wind, and soil moisture as the external factors, and the type of epidermis distribution of roots, stomata opening, and relative coverage of the ground by the plant as the internal factors for evapotranspiration. Lemon et al (20) reported that evapotranspiration is controlled by soil moisture, plant physiological conditions, and meteorological factors. They considered soil moisture suction to be the most important soil factor. For the meteorological factors, they believe that net radiation, wind, air temperature, humidity, and also the "oasis" effect are the most important ones. Tanner (40) introduced the three factors that affect evapotranspiration from crops planted in a large field in order of their importance as follows: (a) The amount of heat available from solar radiation as a climatic factor, (b) the moisture availability including capillary conductivity of the soil, soil moisture stress and soil moisture content, and (c) the physiological reaction of the plant to the moisture availability and evaporation demand. Many other authors writing about evapotranspiration have named the same three groups of factors as controlling evapotranspiration. It should be emphasized that the soil, the plant, and the atmosphere are parts of a single system for the transfer of water from the plant root-soil interface to the atmosphere, although it has been indicated that the effect of soil, plant, and meteorological factors are distinct and could be discussed in individual topics (16). Therefore, there is a great need to look at the whole soil-plant-atmosphere continuum. During the past 10 years much attention has been given to the various parts of this system. Micrometeorologists, plant physiologists, soil physicists and others have provided a great deal of information through investigation in their own particular fields. Many contradictory results have been obtained by different investigators for the effect of soil, plant, and atmospheric factors on evapotranspiration. One of the possible explanations for this is that those factors have been mostly studied separately rather than being considered as a whole system (16).

It is believed that a study of the energy balance or heat budget at a crop surface would permit one to learn much about the interaction of soils, plants, and meteorological factors in the evapotranspiration process.

The energy relation of evapotranspiration

Evaporation of water requires a large amount of energy as the heat of vaporization which at 25° C tmperature is 580 Cal. per gram of water. Every acre-inch of water that evaporates consumes 6.05×10^{10} calories of heat. In evapotranspiration this energy is obtained from the solar radiation. The loss of water from the soil either through direct evaporation or through plant transpiration is dependent upon two closely related groups of factors: (a) those that affect the availability of heat at the surface, and (b) those that affect the water availability at the evaporating surface (16, 18). The availability of heat at the surface is governed by the manner in which the energy of solar radiation is dissipated. The net radiation which is the difference between the incoming and outgoing radiation is considered to be the total absorbed energy from the sun at the earth surface. Suomi and Tanner (38) considered the net radiation (R_n) to be used in three different ways at the earth surface: heating the air by convection (sensible heat flux, A), heating the soil by conduction (soil heat flux S), and evaporating the water (latent heat of water, E). In equation form these relationships are:

$$R_n = S + A + E \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

Halstead and Covey (11) have used the symbol of "$q_{convection}$" instead of A for the sensible heat flux.

$$R_n = S + E + q_{conv.} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$

Soil heat flux is usually a small part of net radiation and sometimes it can be neglected (11, 40). Rearranging equation 3 , another equation is obtained:

$$E = R_{n-s} - q_{conv.} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (4)$$

Where R_{n-s} is used for R_n-S, this equation shows that the rate of evapotranspiration is directly related to the net radiation. But sometimes the sensible heat ($q_{conv.}$) has also an important role in determining the rate of evapotranspiration. It is believed that in a well-irrigated and cultivated agricultural area where there is no stress in the soil moisture around the absorbing roots that are well distributed in the soil, more than 80 percent of net radiation is used for evapotranspiration and only a small part goes into the air and the soil (11). Lemon and his associates (20) have found a very high correlation between the net radiation and the amount of heat used for evapotranspiration in a well-irrigated cotton crop at College Station, Texas. Tanner (40) has shown that there are some cases in which the heat used in evapotranspiration exceeds the net radiation. For instance, when the soil is very moist it may be cooler than the air so that the heat is transferred from the air to the surface for evaporation of water. An extreme case of this kind of heat exchange is explained by the wet bulb thermometer which derives all the heat for evaporation from the air. During the night when the net radiation has a negative direction, the heat for evapotranspiration, estimated by Tanner (40) to be 5 to 10 percent of the daytime evapotranspiration, is obtained from the air and soil. In all these instances the heat used in evapotranspiration exceeds the net radiation. Another important case for this is when there is an "oasis" effect (which will be discussed later) wherein the advective heat increases evaporation from a moist area that is surrounded by a dry region.

It was shown (16) that the partition of the net radiation into three parts depends directly upon the soil and plant ability to offer up water for evapotranspiration. If the soil moisture is not readily available for evapotranspiration, then a large share of net radiation goes toward heating the air and soil and a small part to evaporate water. In this kind of area the air temperature is very high and the evapotranspiration rate is very low, indicating a negative correlation between air temperature and evapotranspiration. Consequently, the air temperature will rise (18) as the available soil moisture decreases. Tanner (40) showed the effect of ground coverage of the crop on the partition of the net radiation. Days when the hay was cut he found that a small percentage of the net radiation was used for evaporation of water while a large part was converted to sensible heat causing a rise in air temperature. The reason for this, he explained, is that less water is available at the surface for evaporation because of the absence of the plant tops.

The effect of the size of area and the "oasis" effect

If a small irrigated area with vegetative cover is surrounded by a dry region, there will be lateral movements of warm air from the dry region over the vegetation in irrigated areas. This large advective heat over a field or plot was first described by Halstead and Covey (11) as the "oasis" effect. If equation 4 of the energy relation of evapotranspiration is considered, it can be seen that in the surrounding area $E = 0$ results in $R_{n-s} = q_{conv.}$, meaning that all of the net radiation is used to heat the air, causing a very high temperature. This heat flux will move to the moist area where the temperature is much lower and reverses the sign of $q_{conv.}$ in equation 4 with the result that E exceeds net radiation.

Experiments in Wisconsin (38) showed that over an irrigated pasture a maximum of 25 percent of the total evapotranspiration came from the heat derived from the air passing over the crop. According to King (16) Rider in England found that over a field of peas the evapotranspiration was twice that of the incoming solar radiation because of the advective heat effect.

The "oasis" effect suggests that extreme caution should be taken before the results from atmometers, small tanks, small evaporimeter, and small plots which are well supplied with water are used to estimate evapotranspiration from the large fields.

Soil factors

It has already been shown that as long as the water is readily available in the root zone, the only factor which controls the rate of evapotranspiration is the amount of available heat at the earth surface, and this is the condition for potential evapotranspiration. As soon as a moisture stress develops in the soil, the moisture and plant factors also begin to check the evapotranspiration rate. The manner in which these two factors affect evapotranspiration has been investigated for a long time in various parts of the world and many different results have been obtained.

Veihmeyer (46) in 1927 reported that transpiration rate per unit of leaf area of small peach tree grown in tanks was constant from field capacity to permanent wilting point. This conclusion was accepted by some other workers (26) for the soil type, plant type, and root distribution in his tanks. In 1955 Veihmeyer and Hendrickson (47) tried to generalize these conclusions for all plants and soil types based on experiments with other plants. On the other hand, there have been a large number of investigators who have found different results. Some workers presented evidence or assumed that evapotranspiration is decreased linearly with a decrease in the amount of water in the root zone between field capacity and the permanent wilting point. This group is represented by Thornthwaite (44). Some others hold the view that the decrease is not linear. (This group is represented by Penman, 26.) With soils sufficiently deep for the rooting habit of plants to be unchecked, Penman (26) considered that the evapotranspiration continues at the potential rate from field capacity until the readily available water around the roots is used. Thereafter, the actual evapotranspiration decreases fairly sharply.

There are some evidences that suggest that plant growth and transpiration is negatively correlated with the soil moisture potential or water activity in the root zone. Taylor (41) reported that the crop yield is directly related to the mean integrated soil moisture suction.

Haynes (13) related the average soil moisture suction in the root zone to the yield, transpiration ratio (water use per unit of dry matter) and total water use. His result is shown in Table 1.

Table 1. The relationship among soil moisture suction, vegetative growth (expressed as dry weight of the tops), and water use in corn*

Approx. range of soil moisture suction (atmos.)	Mean oven dry weight per plant (grams)	Water use	
		Per plant (grams)	Per gram of dry weight (grams)
0 to 12	11.8	1970 ± 23	167 ± 2
0 to 0.7	24.0	4060 ± 24	169 ± 1
0 to 0.01	33.9	5550 ± 100	168 ± 3

*After Haynes (13).

This table shows that the growth and water use of the plant increased with decreasing soil moisture suction almost to zero. The transpiration ratio seemed to have no significant relation with plant growth and soil moisture stress.

Eldefsen (9) has applied the free energy equation to compute the energy involved in displacement of water in the soil-water-plant system. He reported from his result that most of the free energy change of water in the soil-water-plant-air interface occurs at the leaf surface, and that the energy increase in extracting the soil moisture as the soil moisture content changes from field capacity to wilting point is negligible compared with the energy available near the leaf surface. Lassen et al (17) have opposed Eldefsen's idea, based on the work of Richards and Wadleigh. They concluded that the range of soil moisture stress observed in the soils is of the same order of magnitude as that found in the plant.

Kramer (15) used a term of diffusion pressure deficit (DPD) for the soil moisture stress and free energy and reported that:

> The availability of soil moisture depends primarily on the existence of a sufficiently steep DPD gradient from soil to roots to cause the intake of adequate water. As the soil moisture content decreases the gradient of DPD from soil to root decreases, and this results in slower movement of water from soil to roots. The DPD in roots of cultivated plants usually is less than 10 atms. and seldom exceeds 25 atms. Theoretically, water cannot be equally available over the range from field capacity to permanent wilting point because this covers a DPD range from 0 to 15 atms. in the soil, and it has been adequately demonstrated that water uptake and plant growth is often reduced by DPD of from one to four atms.

Schofield (32), studying the effect of the height of water table both on evaporation and growth rate, reported that with water table at

1.60 meter (3.40 meter is equivalent to field capacity) both transpiration and growth were reduced.

West and Perkman (48) reported that the rate of absorption of water by the roots can be limited by the rate of movement of water through the soil to the roots and that this depends on the suction gradients and the capillary conductance. The latter is negatively related to the moisture tension.

Slatyer (33) studied the effect of total soil moisture stress on transpiration, growth, and turgidity of three different plants. He reported that transpiration rate was rapidly reduced as the total moisture stress increased. At a high level of stress, transpiration remained constant at a very low rate. Stem elongation and plant cell relative turgidity, he found, was also closely related to the total soil moisture stress.

In discussing the results of his experiment, Slatyer pointed out that:

> Increase in total soil moisture stress results in an associated increase in diffusion pressure deficit (DPD) in the plant, with consequent loss of turgor. It is this progressive decrease in turgor pressure, in the cells of the active tissues, which has direct and indirect effects on most plant processes.

By this he meant that water stress in the soil has a marked effect on plant processes through the reduction on turgescense. The reduction in transpiration, he explained, is attributed to the effect of turgescense on stomatal closure and the slower rate of soil water movement to the absorbing surface of the roots.

Chem (8) has studied the effect of soil moisture tension in the range of 0 to 30 atms. on the transpiration rate of a young sunflower irrigated by a condensation method. He found that transpiration rate decreased rapidly with increase in moisture tension up to a point of 15 atms. tension; at higher tensions transpiration remained fairly stable.

In a recent review of Russian literature, Lemon presents several moisture evaporation curves (19). They are divided into three portions in which evaporation (a) proceeds in accordance with the atmospheric demand, (b) declines rapidly in rate as the moisture films become discontinuous and transfer of moisture to the soil surface decreases, and (c) is extremely slow and moisture movement is dominated by absorbtive forces at the soil-water-interface. Lemon (18) explained that in the third stage the influence of simple liquid by capillarity gradually gives way to vapor flow in the empty pores as a mechanism of transport, and that vapor flow is much slower than liquid flow.

According to Holmes and Robertson (14), Marlatt investigated the change in the evapotranspiration as the soil dried out. By regular soil sampling under a corn crop throughout the season, he obtained curves similar to those of Lemon. He found that the actual rate of evapotranspiration proceeded at the potential rate (the first flat portion of the curves) up to a point depending chiefly on rooting depth, then fell off sharply. Figure 1 shows the shape of the curves obtained by Marlatt. Except for the initial flat part they are characteristic of many soil moisture retention curves (14).

Several investigators have studied the effect of soil moisture on the relation between the actual and potential evapotranspiration rate. Penman (27) has plotted the actual evapotranspiration (Et) as a function

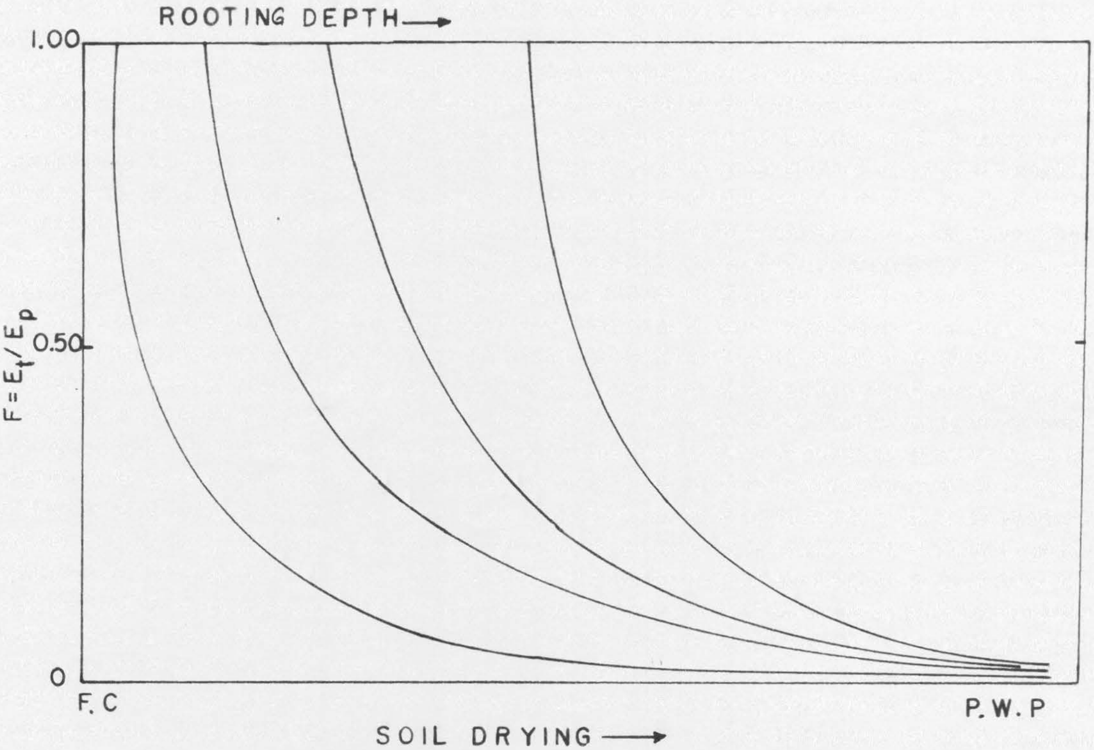


Figure 1. The F factor as a function of soil moisture and crop rooting depth according to Marlatt (redrawn from Holmes and Robertson, 14)

of potential evapotranspiration (Ep). He has stated that:

> As the soil dried Et remains equal to Ep (the slope of the curve remains 1:1) up to a point where the root reservoir has been transpired and slightly beyond that point the actual transpiration rate decreases rapidly, and the slope of the curve will become close to zero.

Makkink and Van Heemst (22), have considered this problem in a slightly different manner. They considered Et to be a function of Ep and soil moisture suction (S). Et was plotted against Ep at five different soil moisture suctions (S = 0,1,3,5,7m of water) (see Figure 2). When S = 0, Et equals Ep up to rate of Ep = 4mm/24hr. The drier the soil becomes, the sooner Et falls below Ep. According to these curves, when S = 7m of water and with Ep = 4mm/24 hr., the reduction in Et is 30 percent; but for Ep = 2mm/24 hr., there is no reduction in Et. This figure shows that the more the evaporative demand (Ep), the more severe the effect of soil moisture becomes in reducing evapotranspiration rate.

In Figure 3 they have plotted the maximum non-reduced Et as a function of S. Taylor[1] has interpreted this curve in a proper manner:

> As long as the soil moisture suction is below a certain value, the actual and potential evapotranspiration rates are equal which depends also upon the magnitude of the potential evapotranspiration itself.

Butler and Prescott (3) have considered Et to be equal to:

$$Et = I\,(Ew)^{0.75} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (5)$$

Ew is evaporation from standard 3-foot diameter tank evaporimeter, and I is coefficient which depends on soil moisture and crops. They tried to relate I ($I = Et/(Ew)^{0.75}$) with the amount of available water (w) in

[1]S. A. Taylor. Personal communication in the subject of evapotranspiration in a soil physics course at Utah State University.

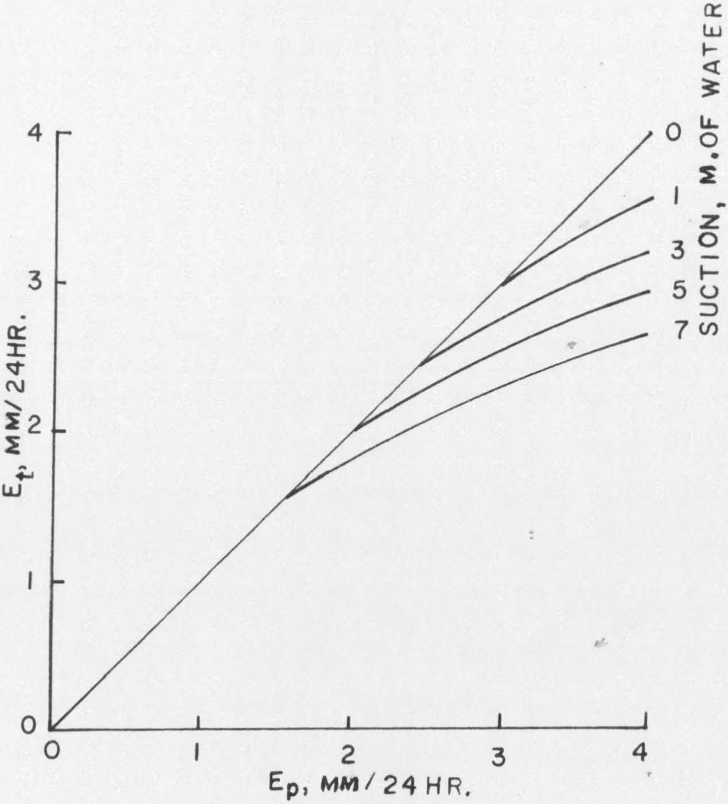


Figure 2. Actual evapotranspiration (E_t) as a function of the potential evapotranspiration (E_p) and soil moisture suction in a clay soil (redrawn from Makkink and Van Heemst, 22)

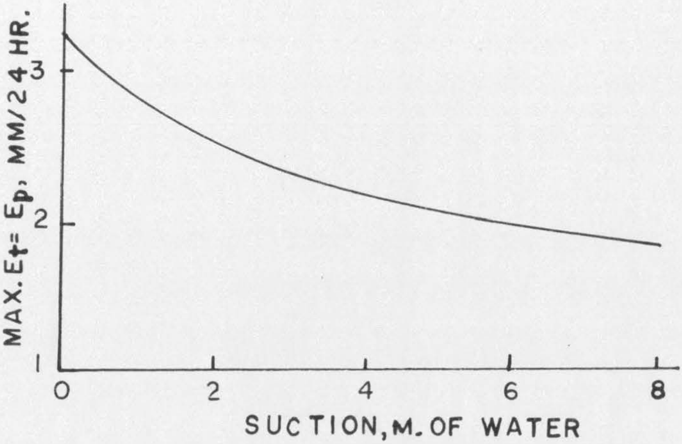


Figure 3. The maximum non-reduced evapotranspiration as a function of soil moisture suction (redrawn from Makkink and Van Heemst, 22)

the root zone. Knowing the fact that there was an upper limit for I as W decreased, they introduced a general equation in differential form:

$$dI/dw = C\ (2.4-I), \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

which indicates a linear function of I vs. W on semi-log paper. The value of C is constant for different crops; for wheat it was calculated to be 0.119.

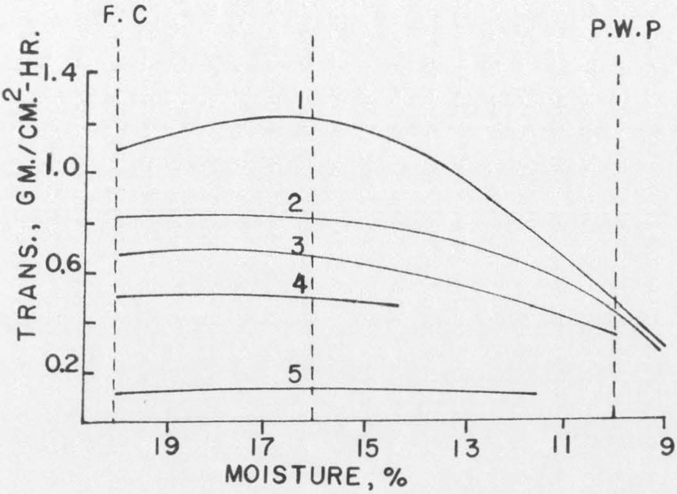
Slatyer (34) has reported the relationship between the ratio of I and the amount of available soil moisture from field capacity to permanent wilting point in fields of cotton, peanut, and grain sorghum crops. He found linear curves for cotton and peanut, but for the grain sorghum there was a flat portion at the beginning of the curve as a result of a more extensive root system and a greater ability to withstand atmospheric desiccation.

Smith (35) has made an attempt to answer the question: "Which method of potential evapotranspiration estimation, combined with which theory of the variation of actual evapotranspiration with soil moisture (Veihmeyer, Penman, or Thornthwaite), gives results which are closest to those obtained by observations?" His experiment was conducted in an area with a permanent Savanna grass cover and auger sampling method was used for determination of the actual evapotranspiration.

He reported that no matter which method is used for potential evapotranspiration estimation, the Thornthwaite theory (linear relationship between the ratio of actual to potential evapotranspiration and the amount of available moisture) gave the most reliable results, whereas the Veihmeyer theory gave the poorest reliability.

Neal (23) has measured the daily and hourly evapotranspiration rate and related it to variation of soil moisture in different soils for tomato plants. In this study he found from the hourly measurement that transpiration reduction was much higher in the afternoon than in the morning because of higher evaporation demand in the afternoon. This indicates that in those cases where transpiration was measured for only a short period of time during each day the choice of period would influence the amount of reduction in transpiration. He also reported the effect of type of soil in this respect. Transpiration of tomato plants in compost soil was reduced with the first reduction in available soil moisture, while those in sand showed no reduction until over 80 percent of available water had been removed. Clay soils were intermediate and showed a gradual reduction starting when 40 percent of available water was exhausted.

Bierhuizen (2) has studied the interaction effect of light intensity on transpiration-soil moisture relationship on kidney beans. He reported from the result of his experiment that transpiration showed a remarkable change with variation in the amount of moisture. It increased with the amount of water from the wilting point and then became nearly constant at higher levels of moisture. But at the highest light intensity, transpiration rate showed a maximum point at high moisture levels near field capacity beyond which it slightly decreased. This may be, he explained, caused by a deficiency of oxygen at higher moisture levels. The amplitude of the change in transpiration rate with soil moisture content became less pronounced at the lower light intensity. With the same moisture content, it was found that transpiration rate has a positive relation with light intensity. These results are summarized in Figure 4, in which transpiration



1. Light intensity = 4.5×10^4 ergs
2. Light intensity = 2.4×10^4 ergs
3. Light intensity = 1.4×10^4 ergs
4. Light intensity = 0.66×10^4 ergs
5. Result from Veihmeyer and Hendrickson

Figure 4. Transpiration rate of kidney beans as a function of moisture percentage and light intensity (redrawn from Bierhuizen, 2)

rate is plotted vs. moisture percentage for four different light intensities. The result from Veihmeyer and Hendrickson for the same crop is also shown in this figure. It is a straight line. Beirhuizen (2) stated that:

> The lack of the relation between transpiration rate and availability of soil moisture in Veihmeyer and Hendrickson's result may be due to the fact that they carried their experiments under a limiting potential evapotranspiration. It is shown in Figure 4* that their experiments cannot serve as general proof that soil moisture is equally available from field capacity to permanent wilting point, since transpiration is only only one-tenth of that normally occurring in the field for the same crop.

Comparing Bierhuizen's results with those of Neal (23), it is probable that the higher rate of reduction in transpiration rate with the change of soil moisture in the afternoon is due to higher light intensity.

Plant factors

Some of the plant factors related to transpiration rate have been discussed with combination to weather and soil factors. Generally, plant factors might be divided into two groups: (a) those which affect the amount of available heat at the surface, (b) those which affect the availability of water at the transpiring surface. For the first group King (16) has named some of the plant factors as the albedo of plants and the ground coverage and spacing of the plants. A dark green crop like a lush pasture reflects less radiation than does a ripening grain field. The ground coverage affects the partition of net radiation; the more dense the ground coverage, the greater the portion of net radiation that is used for evaporation of water. Pelton (30) reported a negative correlation between the height of the crop and the Bowen ratio ($\beta = A/E$). .(5)

*Figure number has been changed to correspond with Figure 4 herein.

which is the ratio of sensible heat to evaporation heat. When the crop was cut, the Bowen ratio was maximum, indicating that the larger part of net radiation went to warm the air. Bushinger (7) reported that crops' surface roughness affect the amount of available heat for potential evapotranspiration, and he suggested the use of some correction factor for the crop roughness effect in the Penman equation.

For the second group of plant factors which affect the availability of water, rooting depth and concentration have been considered to be the most important ones (14, 18, 20, 20). The effect of rooting depth is most easily visualized when available soil moisture starts to be under stress (20). Tanner (40) reported that the impedence to water movement within the plants from the root surface to the leaf cell affects the rate of transpiration, and this is mostly dependent upon the physiological condition and the type of plant.

Lemon (20) showed that the stage of maturity of the cotton plant can influence the rate of transpiration even at a relatively high soil moisture content. He also reported that the total area of the leaves significantly affects the rate of transpiration.

King (16) has reported that the opening of the stomata influences transpiration differently in different species. This is true because the control which plants exert on stomatal movement is not the same for all plants.

Summary of Literature Review

1. Evapotranspiration is controlled by two major factors: (a) the supply of water to be evaporated, (b) the supply of energy to provide the heat of vaporization of the water.

2. As soon as the soil moisture starts to be under stress in the plant root zone, the third group of factors which are related to the plant become important in controlling the rate of evapotranspiration.

3. When moisture is readily available, there is an upper limit to the rate of evapotranspiration from an extended area of crop, a limit which appears to be independent of plant and soil moisture factors and is only controlled by weather factors. Under these conditions this maximum rate is called potential evapotranspiration.

4. There are alternative ways to obtain quantitative values of potential evapotranspiration. All make use of meteorological data. The most satisfactory incorporate both energy and aerodynamic aspects of the evaporation process.

5. The theoretical method of potential evapotranspiration estimation consists of complicated equations the solution of which requires many measurements. This makes them too difficult to be practically used in agriculture.

6. The empirical methods are simple to use, but give satisfactory results only for the area and soil type in which they have been "calibrated."

7. The methods in which evaporation rate of a small free water surface is used for estimation of potential evapotranspiration are subject to large errors resulting from the "oasis" effect.

8. To study the manner in which different factors affect the rate of evapotranspiration, it is desirable to take the soil, the plant, and the atmosphere as a single system and to study the system as a whole.

9. The heat budget of evapotranspiration os one of the basic

approaches for the study of the factors affecting evapotranspiration.

10. The contradiction of the results obtained by different investigators for the effect of soil moisture on evapotranspiration might be due to: (a) difference in experimental conditions in various places, especially differences in evaporative demand, (b) studying the soil, the plant, and the weather factors separately rather than considering them as a whole system.

11. From the review of literature it can be concluded that the rate of water use cannot be constant between field capacity and permanent wilting point. Therefore, there has to be a reduction in transpiration rate as the soil dries out. The rate of this reduction seems to be dependent upon soil types, plant species, and evaporative demand of different seasons and areas.

METHODS AND PROCEDURES

The experiment was carried out in a third year alfalfa field at the Greenville experimental farm in North Logan. The soil under the field was Millville silt loam. The experimental field was 130 x 130 feet which was the most uniform part of a 6½-acre alfalfa field.

Layout of Experiment

The field experiment was a completely randomized type design with three moisture treatments and three replications. In Figure 5 the experimental layout is shown which consists of nine plots of 43 feet by 43 feet.

Three different moisture treatments were as follows:

W_0 - Irrigated when the suction in the active root zone was at or around 0.6 bars.

W_1 - Irrigated when the suction in the active root zone was at or around 3.5 bars.

W_2 - Irrigated when the suction in the active root zone was at or around 10 bars.

The whole 6½-acre field of alfalfa was cut on June 15, 1959. No irrigation was applied to the field before that time. The experimental field was separated from the large field after the cut by a border strip 6 feet on each side.

The observations on all of the experimental instruments in the field were taken on the following days which were called "observation days" during the experimental period of July 1st to August 21st: July 2nd, 6th, 9th, 13th, 16th, 21st, 28th, 30th, August 1st, 3rd, 11th, 13th, 19th, 21st.

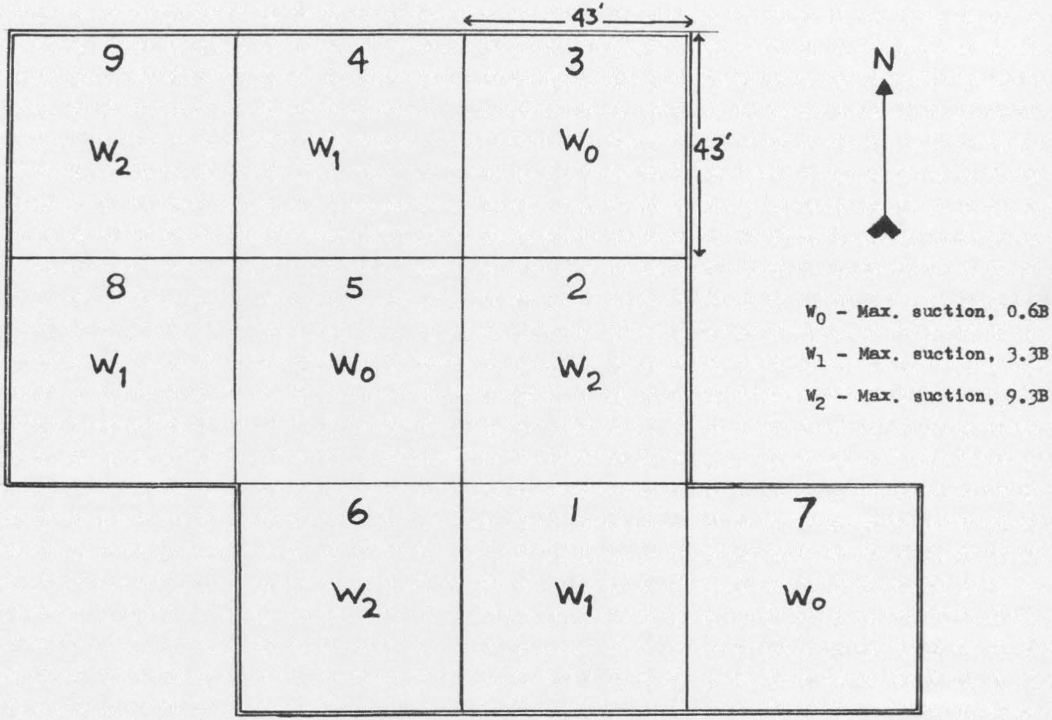


Figure 5. Field plot layout for evapotranspiration experiment consisting of three moisture levels and three replications in alfalfa

Irrigation

A sprinkler irrigation system with perforated pipes was used. The distribution pattern and the application rate of each perforated pipe for a given pressure was known. Table 2 gives the dates, the amount of irrigation application, and rainfall.

Table 2. Date and amounts of irrigation application and rainfall during the experimental period

Date	Inches of irrigation water or rainfall		
	W_0	W_1	W_2
July 1	2.4	-	-
July 3	1.7	-	-
July 8	1.6	-	-
July 14 (rain)	0.1	0.1	0.1
July 15	2.4	-	-
July 19	2.4	-	-
July 24	-	2.6	-
July 31	1.2	1.1	-
Aug. 1 (rain)	0.54	0.54	0.54
Aug. 14	Flood irrigation - - - - - - - - -		
Aug. 18 (rain)	1.13	1.13	1.13
Aug. 20 (rain)	0.40	0.40	0.40

Moisture Measurements

The moisture suction was measured with tensiometers in W_0 plots and with the gypsum resistance blocks in W_1 and W_2 plots. The amount of water stored in the soil was measured with the neutron moisture meter.

Tensiometers were of the Irrometer type with a gauge showing the suction in fraction of one bar. They were installed at 6, 18, 30, and 42 inch depths in the three W_0 plots.

Gypsum blocks were of the screen electrode type which were installed at 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6, 7, 8, 9, and 10-foot depths in the W_1 and W_2 plots. The Bouyoucos moisture meter was used to take block readings. The meter was calibrated to read directly the suction in atmospheres. The blocks used in the experiment were selected by taking readings with a Bouyoucos bridge when the blocks were saturated with water. The reading on all of the selected blocks was 125 ohms. Tensiometer readings were taken at 6:00 a.m. (before sunrise) and block readings were taken at 10:00 a.m. on the "observations days."

Neutron moisture meter

The neutron moisture meter used was from Nuclear-Chicago and consisted of two parts—the p-19 moisture probe with a neutron source of radium 266 and beryllium, and the model 2800 portable scaler.

The neutron moisture meter was calibrated by taking soil samples for the determination of the percent moisture in dry weight basis and the bulk density at the same location where neutron moisture readings were taken. The determinations for calibration were made in three different soil types (Millville loam, Trenton clay, and Francis loamy sand), each in two or three different locations. In each location soil samples were taken with 6-inch intervals to a depth of 60 inches, then an aluminum access pipe (6 feet long and 2 inches in diameter) was installed in the same hole made for soil sampling. The probe was lowered into the tube and the counts per minute (CPM) were recorded for the neutron source at 2-inch depth intervals from the surface to 60 inches. The counts per minute were also recorded for the neutron source in the shield at the beginning and the end of each trail in each location. The counts per minute in the shield was constant within 2 percent in all cases. The ratio of CPM in the soil to that in the shield was used for estimating the soil water content.

Three aluminum pipes 6 feet long and 2 inches in diameter were installed in the center of the three plots of W_0, and 6 pipes 9 feet long with the same diameter were installed in the six plots of W_1 and W_2. The upper and lower end of each pipe was sealed with a rubber stopper to prevent water from entering and condensing in the pipes. The readings were taken from 2:00 p.m. to 6:00 p.m. on the "observation days" (at the same time for each plot on each day) in the following manner: from 0.50 down to 4 feet at 6-inch intervals, and from 4 to 9-foot depth in 12-inch intervals. Counts per minute in the shield were also recorded as standard at the beginning and end of each trial on each plot.

Meteorological Measurements

The mean daily air temperature, daily pan evaporation, rain, daily wind veolocity (miles per day), and data for daily relative humidity from dry and wet thermometers were taken from the weather station located 300 feet southwest of the experimental field. Because of the fact that there was a building between the weather station and the experimental field, it was felt that the wind velocity measured by cup anemometer in the station may not be the same as that over the experimental field. A propeller type anemometer faced in the direction of wind automatically was set in the experimental field at 4 feet above the ground, and the observations from this anemometer were compared with those in the station.

Radiation

The economical net radiometer described by Suomi and Kuhn (39) equipped with dial thermometer, was used to measure the net radiation over the field on the observation days during the experimental period. The instrument was set on the proper stand parallel and 4 feet above the ground in the center of the experiment. Theory: The net radiation normal to the earth's surface which is the difference between the total upward radiation flux and the total downward radiation flux is determined by measuring the temperature at the two faces. One face was exposed to the downward radiation currents, and one face was exposed to upward radiation currents. An evaluation of net radiation from these two temperature observations requires a table of σT^4 vs. $t^\circ c$, where t° c is the temperature measured at the top and bottom faces of the instrument, σ is the Boltzman radiation constant and T is the absolute temperature. The short expression which was used for calculation of net radiation in Langleys per minute with 3 to 5 percent accuracy is:

$$R_n = 1.25\ \sigma(T_t^4 - T_b^4) + 0.0025\ (T_t - T_b) \qquad (7)$$

where T_t and T_b are absolute temperatures at the top and bottom faces of the instruments, respectively.

Readings on the net radiometer were taken from sunrise in the morning to sunset in the evening at 30-minute intervals on the observation days. Extra readings were made during the time in which clouds made interruptions in incident radiation.

Soil temperature

Soil temperature at the 4-inch depth was measured by the use of calibrated thermistors installed in 6 plots (2 plots from each moisture treatment. The thermistors were Western Electric model 17A and were insulated with tygon paint. A resistance bridge made by the Berkeley Division of Beckman Instrument Company model 300 which reads microamperes was used to take readings from thermistors in the field. Calibration was made by having thermistors in a calorimeter and taking readings at different temperatures ranging from 5° to 50° C. The readings on thermistors were taken seven times per day on the observation days as follows: 0600, 0800, 1000, 1200, 1400, 1600, 1800 hours.

The hay was cut on August 5th. The yield was measured by taking three randomized samples, each one square yard, from each plot. The dry weights of the samples were determined after drying them in an oven at 70° C. The height of the hay was also measured at the time of taking the hay samples from the plots.

RESULTS

Average Suction

The change in suction with time is shown for three different treatments in Figure 6. The suction values are averages from plots with the same moisture treatments and represent the average suction in the root zone. The maximum average suction in the root zone during the experimental period was 0.65, 3.3, and 9.35 bars in W_0, W_1, and W_2, respectively.

The change in suction with respect to depth for the day of July 6th, July 28th, August 1st, and 13th, is shown for W_1 and W_2 plots in Figure 7. The suction values are averages of three replications in each moisture treatment. The maximum suction for all days for W_1 plot was shown to be at 0.5 and 4-foot depth and for W_2 at 0.5 and 3-foot depth. The suction gradient in all curves would cause water to move upward from all depths below four feet.

Neutron Moisture Calibration

The neutron moisture calibration curve is shown in Figure 8 in which the CPM ratio (counts per minute in soil/counts per minute in shield) is plotted against P_v (soil moisture content - volume basis, percent). The linearity of the curve was statistically significant with regression coefficient (r) or 0.95. According to the manufacturer, the calibration curve should pass through the origin, but the data in the range of 7 to 40 percent moisture did not indicate any curve in the relationship. It was assumed that the bend occurs below the point where P_v is 7 percent, and a curve which passes through the origin was drawn

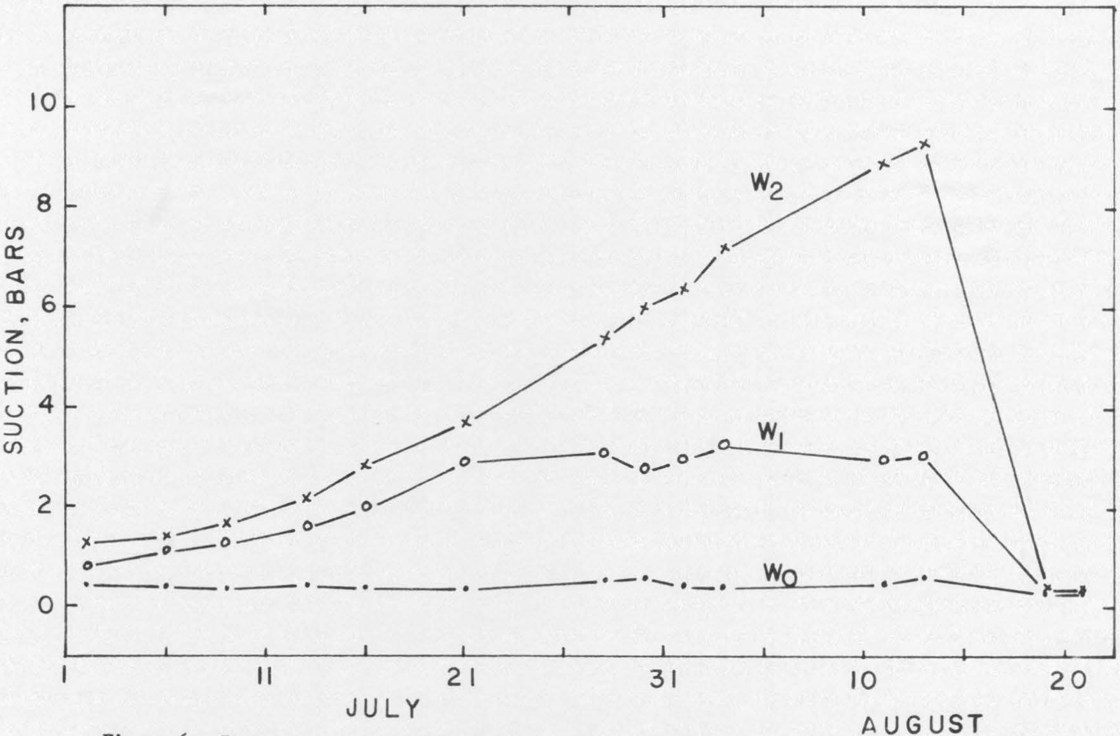


Figure 6. Time changes in average moisture suction in the wet zones of three replications of each of the moisture treatments W_0, W_1, and W_2 for alfalfa

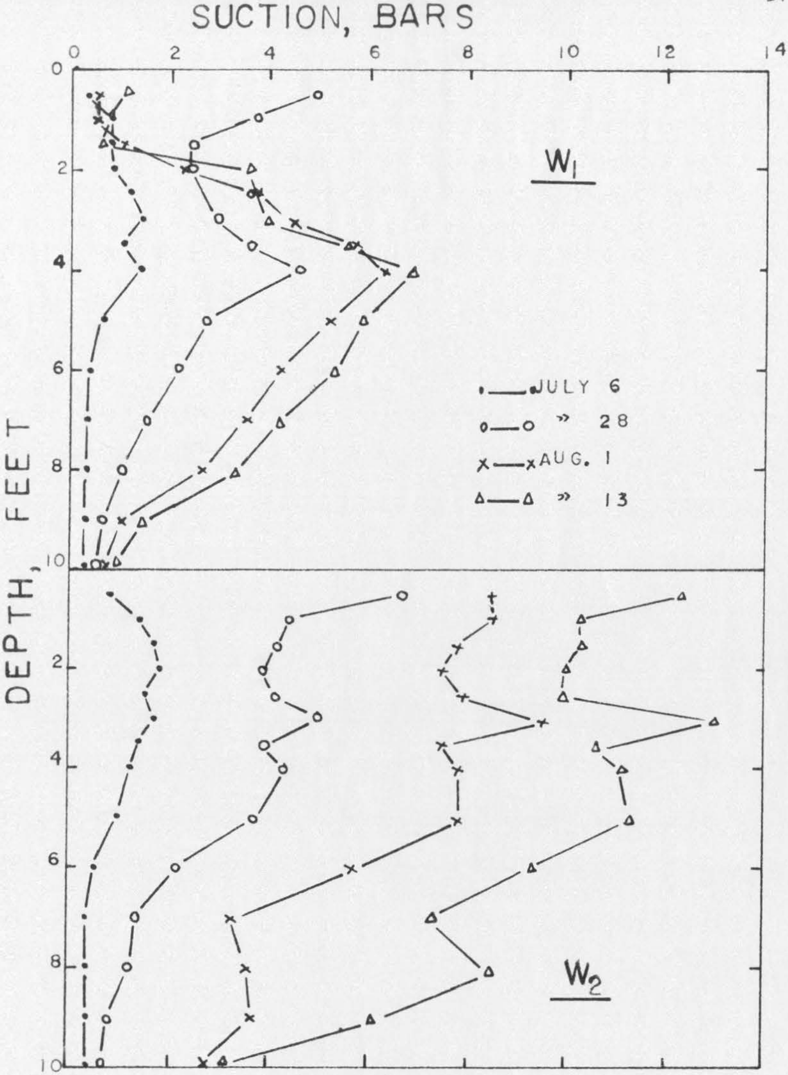


Figure 7. Depth distribution of the average moisture suction for W_1 and W_2 plots

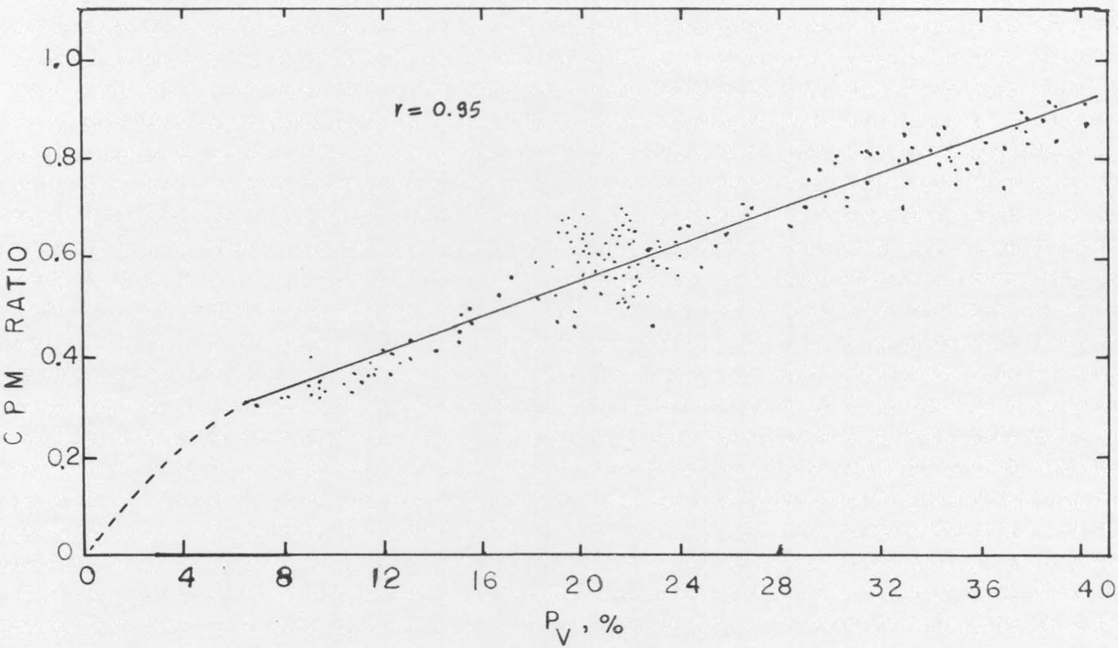


Figure 8. Calibration curve for neutron moisture meter, ratio of counts per minute (CPM) in the shield to that in the soil vs. volume moisture percent (P_V)

with dotted lines in the lower moisture content range where no data were available.

Water Removal

The amount of water in the soil profile was determined by the use of equation

$$I = \sum_{k=1}^{m} (P_v)_k (h_k - h_{k-1})/100 \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where I is the inches of water stored in k = 1 to m depth intervals in the profile, P_v is percent moisture on a volume basis obtained from neutron calibration curve by the use of CPM ratio for each depth, k is the number of 6-inch depth intervals in the profile, and h is the depth of profile in inches.

The variation of the amount of water in the soil with respect to depth for the W_0 plots is plotted in Figure 9 in which the water distribution pattern for the day of July 2nd and 6th, and August 3rd and 13th is shown. Those days represent 1, 3, 9, and 13 days, respectively, after a complete irrigation. This figure shows that the moisture gradient in the profile is downward in all cases, and the amount of water for the depths deeper than 5 feet remained fairly constant with respect to time throughout the experimental period.

In Table 3 the number of inches of water stored in the upper 9 feet of soil profile determined from equation 8, is shown for eight different days during the experimental period for all plots. The data for W_0 plots was available only for 6 feet. But according to Figure 9 it was assumed that the amount of water stored in the profile deeper than 6 feet remained constant for W_0 plots during the experimental period, and did not change significantly with respect to time. Based on this assumption, the average

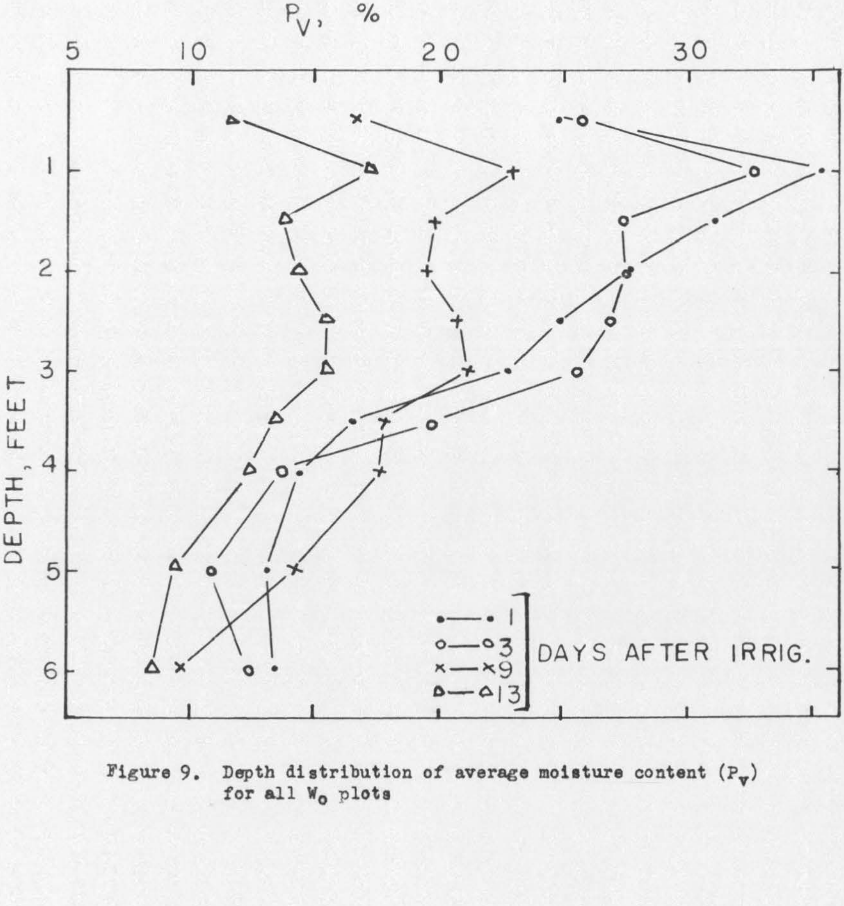


Figure 9. Depth distribution of average moisture content (P_v) for all W_0 plots

Table 3. Amount of water stored in soil from neutron readings

	W_0 in 6-ft. depth			W_1 in 9-ft. depth			W_2 in 9-ft. depth		
Date	Plot 7	Plot 3	Plot 5	Plot 1	Plot 4	Plot 8	Plot 2	Plot 6	Plot 9
July 2	20.10	17.89	22.63	13.31	13.12	15.74	10.1	11.44	10.2
" 6	20.69	18.89	20.91	12.0	11.84	13.89	9.63	11.05	11.2
" 13	20.02	16.26	17.50	10.43	10.24	11.9	10.1	9.47	8.25
" 28	18.54	15.65	16.77	9.27	12.30	12.22	9.11	9.07	6.30
" 30	18.37	15.49	16.69	8.25	10.38	12.70	5.5	8.30	5.63
Aug. 4	17.02	14.73	16.32	8.30	9.14	11.43	5.57	6.87	6.00
" 11	14.91	14.04	14.91	7.16	8.24	11.37	5.29	6.61	6.06
" 13	14.68	13.31	14.00	6.93	7.63	10.0	5.19	6.22	5.44

inches of water stored in the depth interval of 6 to 9 feet of W_1 and W_2 plots, determined at the beginning of the experiment when all plots had uniform water distribution patterns, was added to all the figures of W_o plots to obtain the number of inches of water in 9-foot depth.

The data of Table 3 was statistically analyzed and the analysis of variance is shown in Appendix B. According to the analysis of variance table, the effect of three moisture treatments and the days were highly significant, but the interaction effect between days and moisture treatment was not significant. This indicates that the amount of water in the soil profile of W_o plots did not remain constant, although from Figure 6 it is clear that the average moisture suction in the root zone remained fairly constant. This is not surprising, because by looking at the moisture retention curve of Millville loam (see Figure 23 in Appendix C), it can be seen that when the moisture suction is less than 0.60 bars the change of moisture content does not cause a significant change in moisture suction, and to a certain extent moisture suction remains constant.

The amount of water removed from the soil which is the rate of evapotranspiration was determined by the use of equation:

$$E_t = (I_2 - I_1) + I_a \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (9)$$

where I_1 and I_2 are the inches of water stored in the upper 9-foot depth of soil profile at two different days, and I_a is the water application in irrigation or rain in inches.

This method of calculating evapotranspiration or water use is based on the assumption that the deep percolation of water from the 9 feet of soil profile was negligible. An examination of Figure 7 showed that deep percolation of water could possibly be neglected in W_1 and W_2 plots, because the suction gradient in all cases would cause water to move upward for all depths below 4 feet. On the other hand, it was shown in Figure 10 that in W_0 plots there was a downward moisture gradient in the soil profile which might have caused downward movement of water during some periods as well as upward movement throughout the profile during other periods. Therefore, there was some possibility of deep percolation in W_0 plots the rate of which was not known for the present investigation.

In Figure 10 the variation of average moisture suction in the root zone and the amount of water in the upper 9-foot depth of W_2 plots with respect to time is shown. From this figure it can be seen that the slope of the water storage curve, which is the rate of evapotranspiration decreased as the tension went up; at 9 bars suction the slope of the curve became close to zero. In Figure 11 the amount of water in the upper 9-foot depth of W_2 plots is plotted against average moisture suction. This curve is actually a type of moisture retention curve and has the typical shape.

Water Use and Moisture Suction

The mean integrated moisture suction in the root zone was calculated for the month of July by the method of Taylor (41, 42), and the results are shown in Table 4. The total water use for the month of July obtained from neutron moisture meter measurement is also shown in Table 4.

The linear correlation between mean integrated moisture suction and the monthly water use was statistically significant with the regression coefficient of 0.95. In Figure 12 the monthly water use is plotted against mean integrated moisture suction. The variation of amount of water used

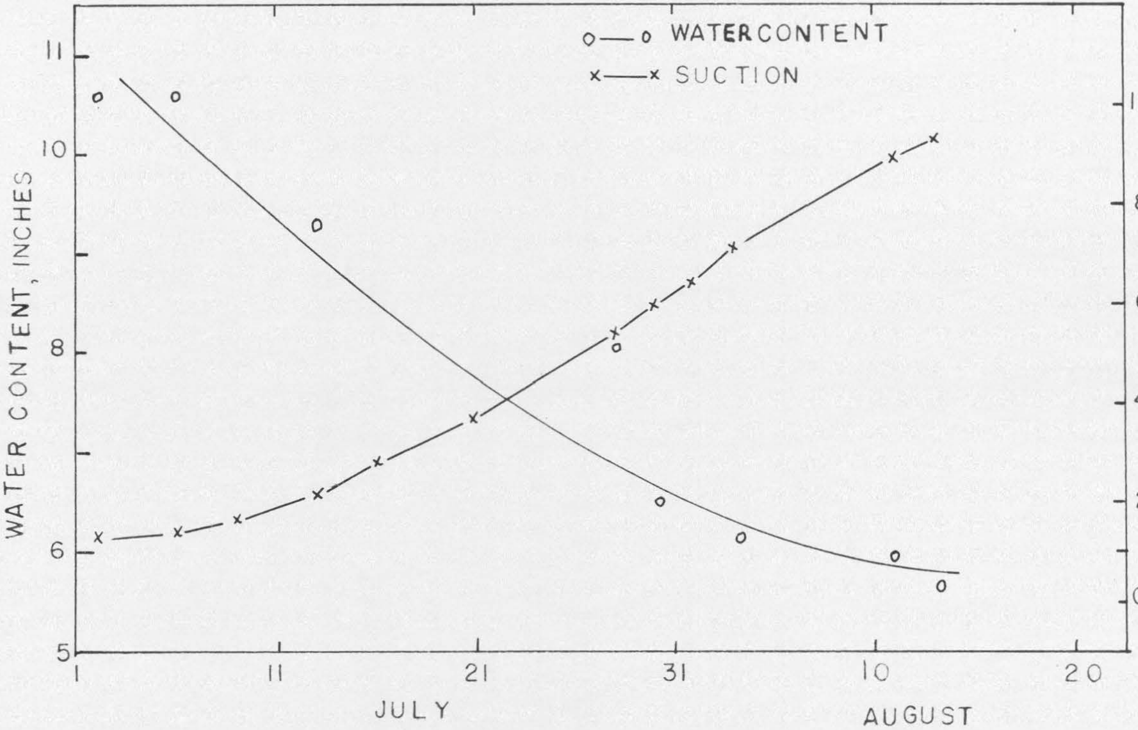


Figure 10. Time variation in average moisture content and suction for all W_2 plots

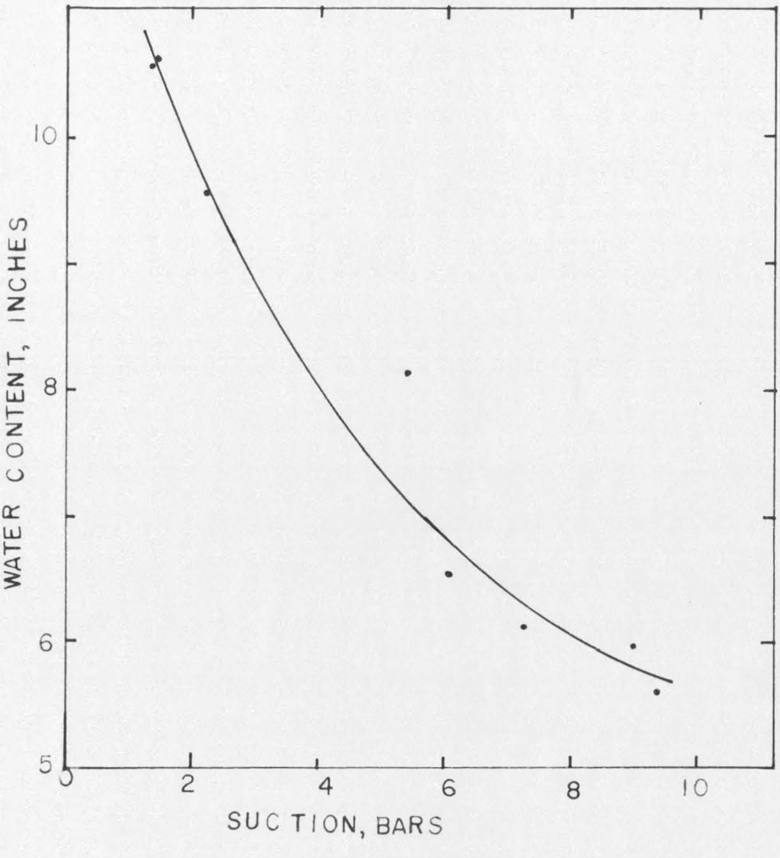


Figure 11. Soil moisture retention curve; water content obtained from neutron moisture meter and suction from gypsum blocks averaged for all W_2 plots

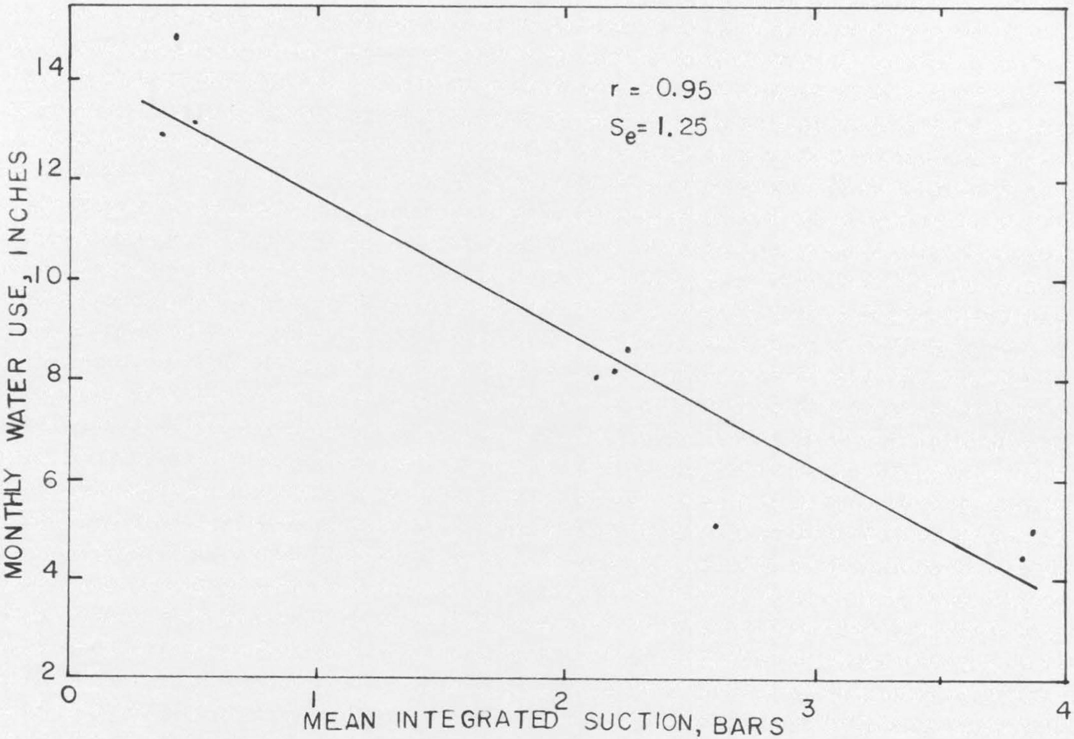


Figure 12. Water use for the month of July vs. mean integrated moisture suction

Table 4. Total water used, mean integrated moisture suction, mean maximum suction for the month of July, and the yield of alfalfa

	W_0			W_1			W_2		
Plots	3	5	7	1	4	8	2	6	9
Total water use (inches)	13.11	14.86	12.83	8.69	8.26	8.02	5.01	5.05	4.60
Mean integrated moisture suction (bars)	0.50	0.43	0.38	2.24	2.19	2.13	3.86	2.60	3.83
Mean maximum suction (bars)	0.68	0.54	0.58	3.44	3.09	2.89	6.16	4.29	7.90
Yield, gram dry weight/yard^2	489	453	454	321	284	321	279	284	253

among the W_0 plots was much greater than that of W_1 and W_2 plots. This can be explained from the fact that there might have been some water deep percolation at different rate in W_0 plots.

The monthly water use was also correlated with the mean maximum moisture suction (see Table 4) and again a linear correlation was found with r of 0.91 (see Figure 13). The variation among the mean maximum moisture suction of W_2 plots is much greater than that of W_0 and W_1 plots; this caused the r and standard error to be less than that of Figure 12. A curvelinear function with a flat portion at the higher suctions, as is shown in Figure 13 with dotted line, seemed to fit the data better than a straight line. A comparison of these two figures shows that the monthly water use is more closely correlated with mean integrated moisture suction than mean maximum suction.

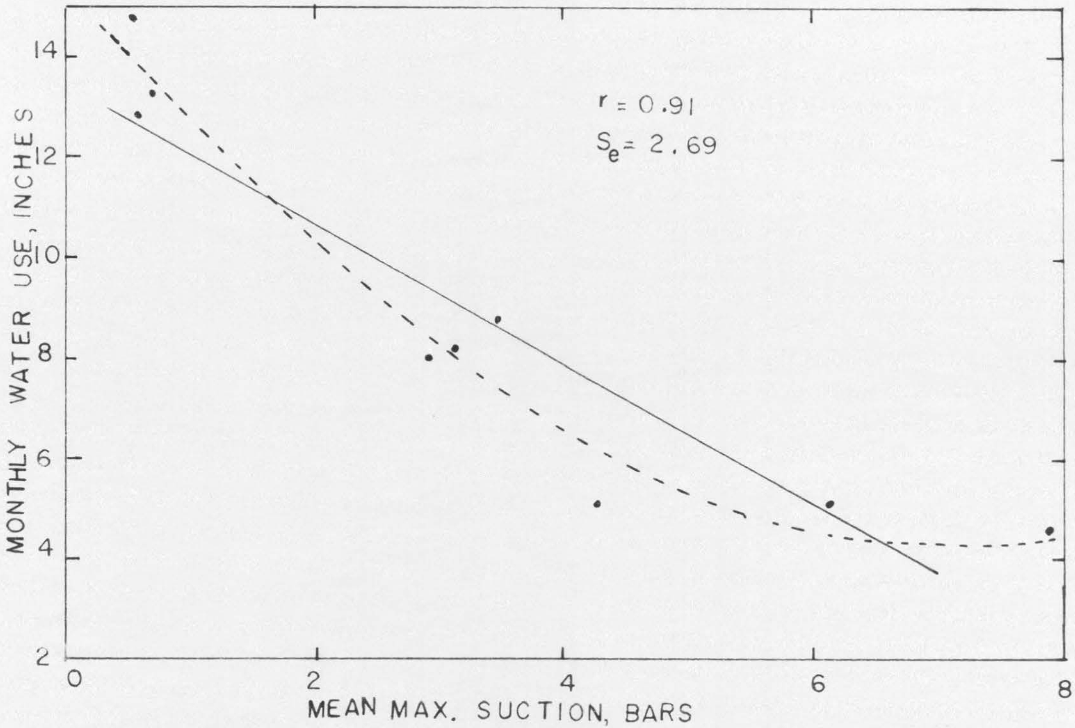


Figure 13. Water use for the month of July vs. mean maximum moisture suction

The average daily evapotranspiration is correlated with average moisture suction at different time intervals throughout the experimental period as shown in Figure 14. The best fit curve to the data had a curvelinear shape. An examination of the data shows that the four points which are far above the curve are those which were obtained from the data of July 30th and August 13th. On these days water condensation was observed in the aluminum pipes. This might have influenced the neutron moisture meter readings. Therefore, those points have been ignored. The data of this figure represent the average of three plots in each moisture treatment.

Weather

The net radiation per day over the field was determined by plotting the net radiation per minute against the time of day, and taking the area under the curve. In Figure 15 the variation of the net radiation during the day of July 2nd is shown, and the area under the curve which represents the total daily net radiation has been calculated to be 351.37 cal. cm^{-2} day^{-1}.

The analysis of variance of soil temperature at 4 inches depth shows that the effect of moisture treatment, different days, and time of day is highly significant. The interaction effect of days-moisture treatment and time of day-moisture treatment is also significant. In Figure 16 the variation of soil temperature in three different moisture treatments during the day is shown. The data of this figure represent the average of 10 days and 3 replications. This figure indicates that soil temperature near the surface was significantly lower in the wet plots than in the dry plots during the day. This can be explained by either the cooling effect

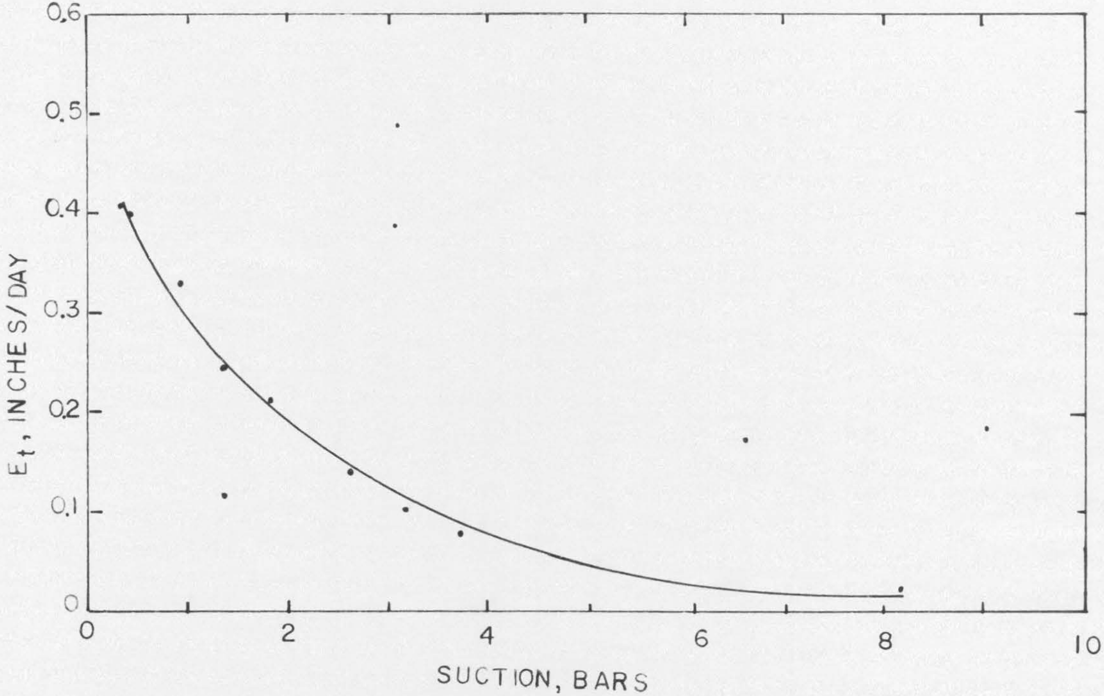


Figure 14. Daily evapotranspiration (E_t) as a function of average moisture suction

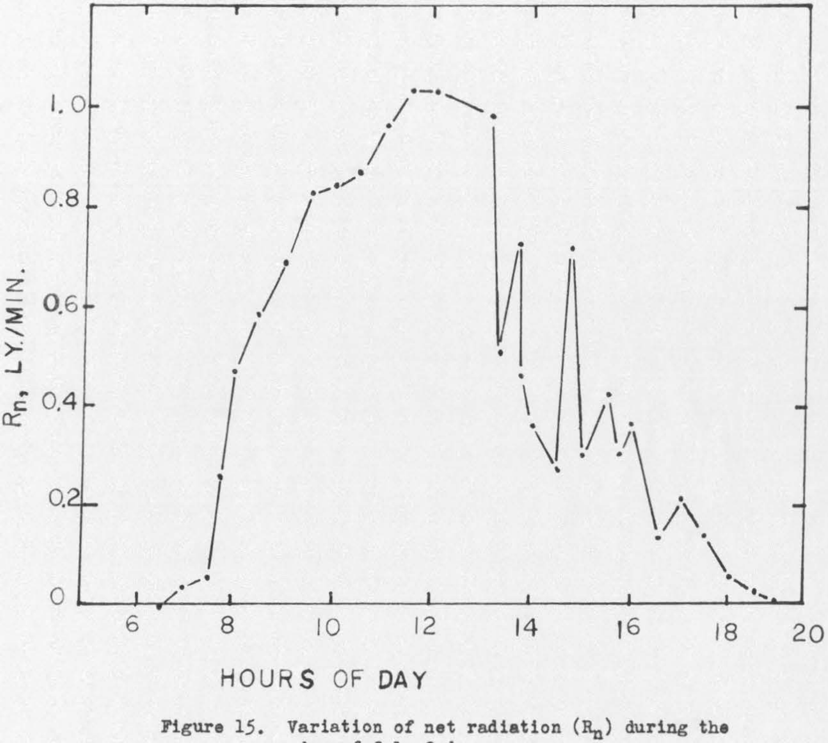


Figure 15. Variation of net radiation (R_n) during the day of July 2nd

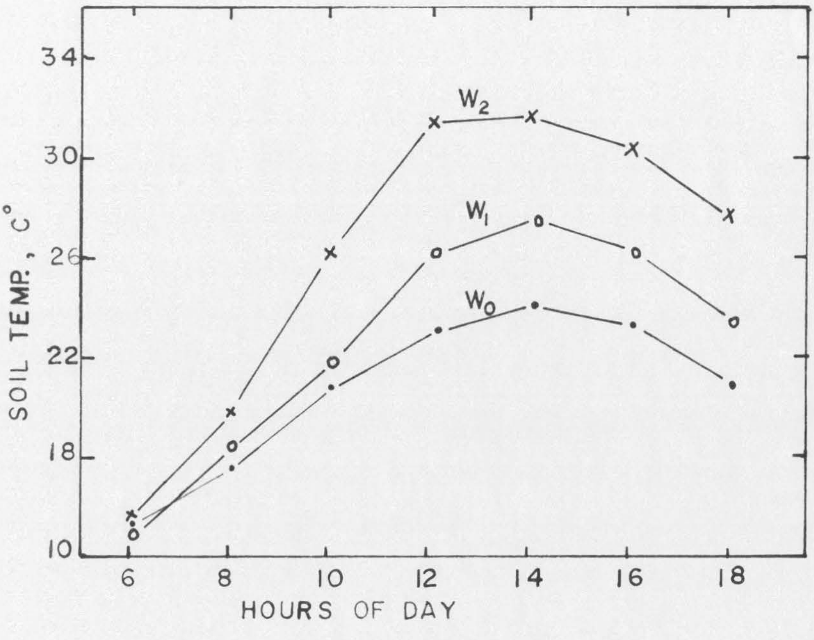


Figure 16. Variation of average soil temperature at 4-inch depth for three replications and 10 days of observation for three moisture treatments

of evaporation being higher or to a greater heat capacity of the wet plot.

In Figure 17 the variation of daily net radiation, mean daily soil temperature at 4 inches depth, and the rate of evapotranspiration in the W_0 plots (where moisture was never limiting) is shown during the experimental period. In order to describe this figure it is desirable to divide the experimental period into three parts: (a) from July 2nd to August 5th when the hay was cut; (b) from August 5th to August 14th when the plots were irrigated with a heavy flood irrigation; and (c) from August 14th to August 21st. During the first period the soil temperature near the surface seemed to follow the daily net radiation. In other words, there was a positive correlation between the net radiation and soil temperature when there was a vegetative cover on the ground. The data on the rate of evapotranspiration when the moisture was not controlling seemed to show no significant change during the first period. This indicates that the change in net radiation was not great enough to cause a significant change in the rate of evapotranspiration.

After the hay was cut there was a sharp decrease in the rate of daily net radiation and a sharp increase in the mean daily soil temperature. The decrease in the net radiation could be attributed to the higher reflection coefficient of the bare ground after the hay was cut which caused a greater outgoing radiation. The increase in the temperature might be caused by either the direct exposure of the bare soil to the sunshine or to lower soil evaporation rate (see equation 2). After the hay was removed, the rate of water used was also decreased which is not surprising because when the hay was cut the water use was limited to the surface

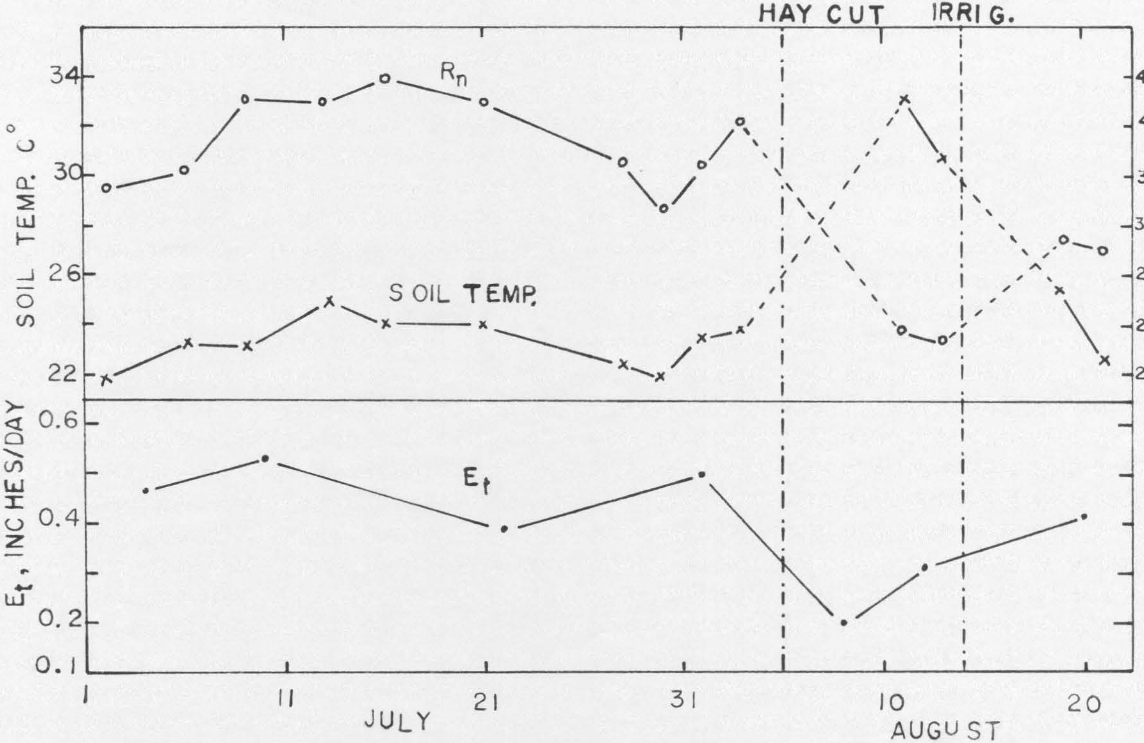


Figure 17. Average changes in daily net radiation (R_n), soil temperature and daily evapotranspiration (E_t) for W_o plots with time

evaporation which was expected to be lower than evapotranspiration. In the third period after a heavy irrigation had been applied, the net radiation was increased but it did not reach the value of the first period. This rise in net radiation over the alfalfa stubble could be caused by the darker color of the ground when it is moist. The decrease in soil temperature in this period can be attributed to higher heat capacity and greater evaporation rate of the wet soil. The rate of water use was also increased after the irrigation which is due to the increase in the net radiation, and the amount of the water in the soil. In Figure 18 the ratio of evapotranspiration to the average net radiation both in inches is plotted against the average moisture suction. The best fit curve had a curvelinear shape similar to that in Figure 14.

Growth and Yield

A pronounced difference was observed in the height of alfalfa and color of the leaves, particularly during the last period of growth. The dry plots showed darker green color than the moist plots. The difference in the height of alfalfa on the three different moisture treatments was noticeable, particularly at the time when the hay was cut. The dry plots started to blossom earlier than the wet plots. No wilting was observed on any plot during the experiment.

The difference in the yield of the alfalfa in terms of dry weight of hay for the three moisture treatments was statistically significant (see Table 4 and Figure 19). There was a decrease in the yield from W_0 to W_2 moisture treatment. In Figure 21 the yield is plotted against the mean integrated moisture suction for the period of growth. The difference

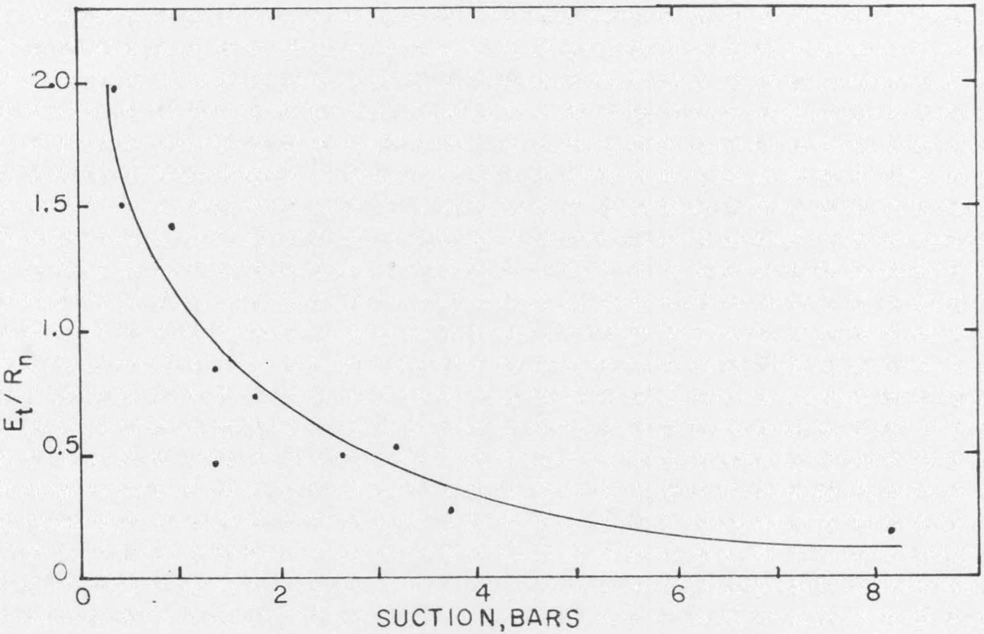


Figure 18. Ratio of evapotranspiration to net radiation ($\frac{E_t}{R_n}$) as influenced by average moisture suction

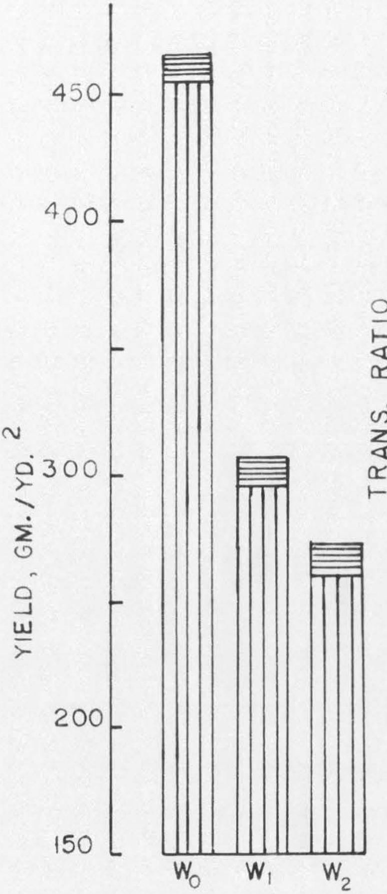


Figure 19. Yield of alfalfa for different moisture treatments

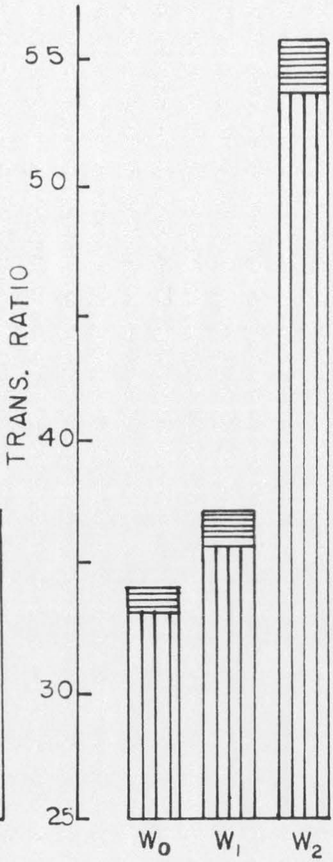


Figure 20. Transpiration ratio of alfalfa for different treatments

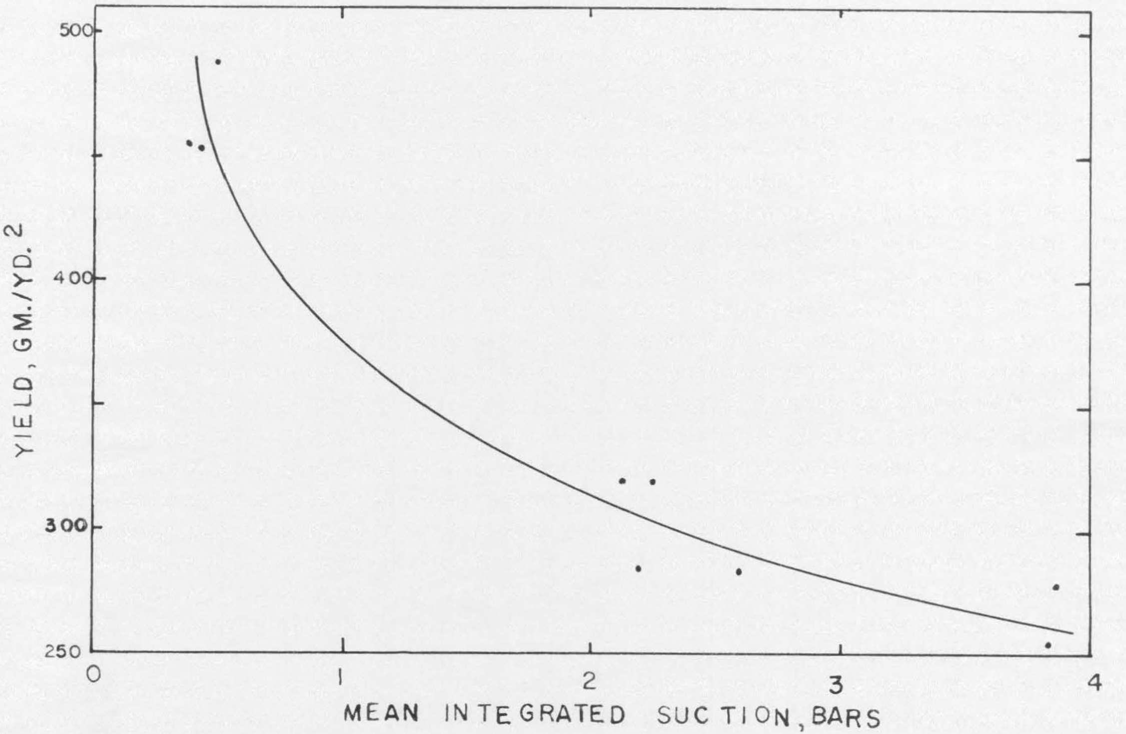


Figure 21. Yield of alfalfa vs. mean integrated moisture suction

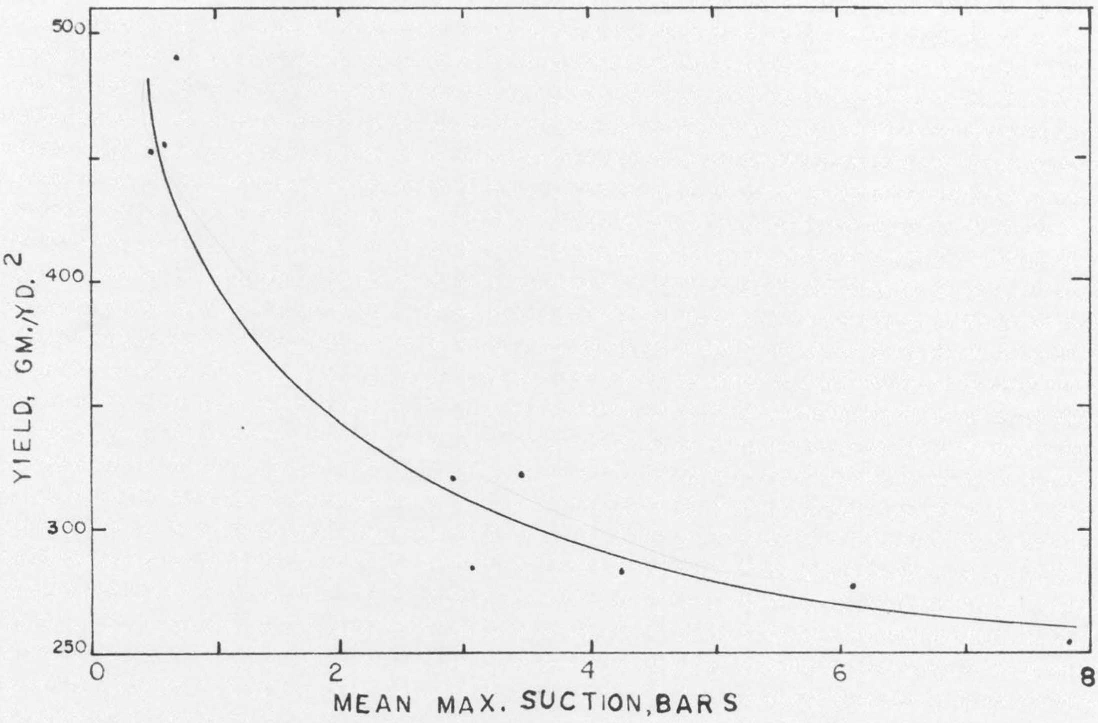


Figure 22. Moisture retention curve for the Millville loam

between the yield of W_0 and W_1 plots was much greater than that between W_1 and W_2 plots. In Figure 22 the yield is plotted against the mean maximum moisture suction in the root zone. It is seen from the curve that there was a sharp decrease in the yield from 0.50 to 3 bars suction, and from there on the yield decreased slowly.

The effect of moisture treatment on the transpiration ratio (yield/amount of water use) is shown in Figure 20. The transpiration ratio increased from W_0 to W_2 plots, and the difference between the transpiration ratio of W_1 and W_2 plots was much greater than that between W_0 and W_1 plots. From this figure it is clear that the yield per unit of water use would be greater if the soil is kept dry.

Potential Evapotranspiration

The potential evapotranspiration was calculated for the growing season of the alfalfa (months of May, June, July, August, and September) by the methods of Blaney-Criddle, Thornthwaite, Penman, and pan evaporation and the result is shown in Table 5. The measured evapotranspiration averaged for all plots for the month of July is also shown in Table 5. The coefficient of 0.75 proposed by Ashcroft and Taylor (1) was used to convert pan evaporation to consumptive use of alfalfa crop. In Table 6 the measured net radiation over the field is compared with the calculated net radiation by Penman formula for different days of July. As is shown in this table, the values of net radiation were about two times higher than calculated values for all days. From this table a correction coefficient of 1.93 was obtained for the calculated net radiation from Penman formula. By using this correction factor for net radiation, the values of Table 5 for the Penman method were corrected and the result is shown in the right column of the same table.

The data of this table show that the values of potential evapotranspiration obtained by the methods of Thornthwaite and Penman seemed to underestimate the actual value (comparing with measured value for July). On the other hand, Blaney-Criddle and pan evaporation agreed more closely to the measured value in July. The corrected Penman method for net radiation also seemed to agree fairly well with Blaney-Criddle and pan evaporation methods.

Table 5. Estimation of potential evapotranspiration by different methods (inches per month)

Date	Blaney-Criddle	Thornthwaite	Penman	Pan evaporation	Measured evaporation	Penman corrected for R_n
May	3.55	2.27	3.48	4.41	-	5.11
June	6.11	4.76	4.41	5.83	-	6.61
July	7.36	5.38	4.58	6.52	8.94	6.89
August	6.22	4.64	4.36	5.92	-	6.10
September	3.38	2.81	2.42	3.10	-	3.00

Table 6. Measured net radiation compared with net radiation calculation with Penman equation

Date	R_n mm. water measured	R_n mm. water Penman
July 2	6.06	3.46
July 6	6.29	3.28
July 9	7.35	3.20
July 13	7.24	4.19
July 16	7.57	3.87
July 21	7.22	3.66
July 30	5.80	3.60

DISCUSSION AND CONCLUSIONS

It is apparent from the result of this investigation that soil moisture suction had a significant effect on alfalfa plant processes. There was a serious reduction in the yield of alfalfa from W_0 to W_1 plots where the mean integrated moisture suction was 0.40 and 2.19 bars, respectively. The reduction in yield from W_1 to W_2 plots where the mean integrated moisture suction was 3.44 bars, was more than four times less than that from W_0 to W_1 plots. This indicates that most of the reduced effect of moisture suction took place in the range of 0.40 to 2.19 bars.

Observations in the field showed that the physical appearance of the plants was also different in different moisture treatments, that is, plants on drier plots were darker in color, shorter in height, and started to blossom earlier than plants on the wet plots.

It should be noticed here that all the experimental plots were under uniform conditions except for the moisture suction which was different for the moisture treatments. The plant ground coverage was mostly uniform at all times in all plots and was close to 100 percent in the middle of the experimental period. Therefore, any difference observed in the growth processes of the plants was expected to be caused by differences in the moisture status of the plots. An interesting result has been obtained for the effect of moisture treatment on the transpiration ratio. There was an increase in transpiration ratio from W_0 to W_2 plots. The difference between transpiration ratio of W_1 and W_2 plots was more than four times as much as that between W_0 and W_1 plots. This is not surprising because data obtained in the water use of crops showed that water use was decreased from W_0 to W_2 plots; therefore, the ratio of yield to amount of water used which is the transpiration ratio turned out to increase from W_0 to W_2 plots. This relationship shows that it is more economical to keep the soil drier to obtain greater dry matter per inch of water use.

The result on the rate of water use of alfalfa showed that there was a linear correlation between a monthly water use and the mean integrated moisture suction. A linear relationship was also found between the monthly water use and the mean maximum moisture suction, but with a greater standard error and smaller regression coefficient, indicating that the water use was more closely correlated with mean integrated than mean maximum moisture suction in the root zone. There is some doubt on the validity of the data obtained for the water use on W_0 plots because the examination of the data (see Figure 9) showed that there might have been some deep percolation losses, the rate of which was not measured. Therefore, a fraction of the water used in the W_0 plots might have been lost to deep percolation rather than evapotranspiration.

The close relation of crop growth and plant processes to mean integrated moisture suction rather than average suction has been reported by many other authors particularly during the past 10 years (41). A simple explanation for this is that in calculation of mean integrated moisture suction the time and duration of suction in the root zone is taken into account, and that duration of a developed moisture stress has a very important effect in reducing plant turgidity which is the actual cause for reduction in plant growth processes.

The daily evapotranspiration was correlated with the average moisture suction and a curvelinear function was obtained (see Figure 14). As is shown in the figure, evapotranspiration was reduced rapidly as the soil suction increased from 0.40 up to 4 bars. Above 4 bars suction, evapotranspiration continued at a fairly constant, but considerably lower rate. The same type of curve was obtained for the ratio of evapotranspiration to net radiation (see Figure 18). From this figure it is seen that evapotranspiration exceeded net radiation (almost up to two times as much) for the days the average moisture suction was less than 1 bar. For the higher moisture suction the ratio was less than 1 at all times and decreased sharply with increase in soil moisture suction up to the point of 5 bars and then leveled off. The only possible explanation for evapotranspiration to exceed net radiation that has been suggested (11, 16, 38) is the existence of advective heat coming from a desert area and passing through the experimental field. In the case of this experiment the existence of such an advective heat from Salt Lake desert or from dry mountainous areas is possible.

Particular attention should be given to Figure 18 because it actually shows the net effect of soil moisture suction on the rate of evapotranspiration. This is explained by the fact that net radiation is an estimation of potential evapotranspiration and evaporating demand; when the actual rate of evapotranspiration is divided by net radiation most of the effect of weather factors is canceled out. Therefore, variations in that ratio is expected to be caused only by moisture suction variation.

The relationships between evapotranspiration and soil moisture suction obtained from the present investigation agree fairly well with those reported by Chem (8), Lemon (18), Holmes and Robertson (14), and Slatyer (33). For the range of soil moisture suction under which the experiments have been conducted, the shape of the curve obtained from this experiment checked fairly closely with the results of others.

The results of weather measurements showed that there was a significant increase in the soil temperature near the surface from wet to drier plots at all times. This could be caused by either a cooling effect of surface evaporation at higher rates or greater heat capacity of the wet plots; both cause the temperature to be lower. There was a positive correlation between the soil temperature near the surface and the net radiation during the time there was a vegetation cover on the ground.

Evapotranspiration decreased after the hay was cut by a significant amount. This was expected because after the hay was cut the only possible way of water loss from the soil was surface evaporation, the rate of which is much smaller than transpiration from vegetative cover. There was a reduction in net radiation intensity after the hay was cut which could be attributed to greater reflection coefficient of bare ground. The soil temperature near the surface was increased (more than 1.5 times) after the hay was cut which was due to reduction in evaporation rate as is indicated in the heat budget equation (equation 2) at the surface. After the bare ground was irrigated, net radiation and evaporation rate increased; as a consequence soil temperature decreased (see equation 2).

The increase in net radiation and evapotranspiration with a decrease in soil temperature after irrigation has also been reported by Budyko and Pogosian (6) in a recent publication in USSR. They explained that the increase in radiation balance at the surface after irrigation is caused by the increase in absorption of short wave (solar) radiation the cause of lower albedo of moist surface, and decrease in the heat loss due to short wave radiation (reflection) because of the decrease in the temperature of the underlying surface and the increase in the humidity of the lower layer of the atmosphere.

A comparison of the methods for estimating potential evapotranspiration of the alfalfa crop showed that Thornthwaite and Penman methods under-estimated the actual value. The Blaney-Criddle, pan evaporation, and corrected Penman methods agreed fairly closely with each other and seemed to give results which were more close to the actual value. There are some explanations for this, as follows: The Blaney-Criddle method has been developed for arid and semi-arid regions (4) and because the Logan area is a semi-arid region, this method should give a good result in estimation of potential evapotranspiration. The coefficient for the conversion of pan evaporation to evapotranspiration of alfalfa has been obtained by Ashcroft and Taylor (1) in an experiment conducted in the same place where this present experiment was carried out; therefore, this method is also expected to give a reliable result in estimation of consumptive use. In corrected Penman method, actually, the measured net radiation is used, and because of the close correlation between net radiation and evapotranspiration reported by many workers (11, 18, 40), this method also should give a close estimation of evapotranspiration. For these reasons the Blaney-Creiddle, pan evaporation, and corrected Penman methods were the best in estimating the consumptive use of the alfalfa crop.

SUMMARY

1. The purpose of this investigation was to determine the effect of soil moisture suction on the consumptive use and growth processes of an alfalfa crop under field conditions.
2. The field experiment was a completely randomized type design with three moisture treatments each with three replications. The sprinkler irrigation system with perforated pipes was used.
3. A neutron moisture meter was calibrated and used for determination of the amount of water stored in the upper 9 feet of the soil profile.
4. Tensiometers and calibrated gypsum blocks were used to measure the moisture suction in the soil profile.
5. An economic net radiometer was used to measure net radiation over the field, and calibrated thermistors were used to measure the soil temperature at 4-inch depth.
6. The result of this experiment showed that there was a significant decrease in the dry matter production of alfalfa from wet to dry plots; and a curevelinear relation was found between the yield and mean integrated moisture suction in the root zone.
7. There was a significant decrease in the amount of water use for the month of July from wet to dry plots; and a significant linear correlation was found between the average consumptive use and the mean integrated soil moisture suction.
8. Transpiration ratio increased from wet to dry plots, indicating that the dry matter of alfalfa obtained per inch of water use increased as the soil was kept drier.

9. Daily evapotranspiration and its ratio to net radiation showed a curvelinear relation with the average moisture suction in the root zone. At the lower suctions evapotranspiration decreased rapidly with increasing suction and then leveled off at higher suctions up to 8 bars.

10. Evapotranspiration exceeded net radiation during the time moisture suction was less than 1 bar. This indicates the possibility of advective heat passing over the field.

11. The soil temperature near the surface followed net radiation during the time that there was a vegetative cover on the ground. After the hay was cut net radiation and evapotranspiration decreased and soil temperature increased by amounts.

12. There was a significant difference in the soil temperature near the surface among the soil moisture treatments; soil temperature increased from wet to dry plots.

13. The Penman formula for calculation of net radiation seemed to under-estimate the actual net radiation by a significant amount. A correction factor was obtained to correct the Penman formula for estimating net radiation.

14. The Planey-Criddle, pan evaporation methods and corrected Penman method for net radiation were found to give the best results for estimation of consumptive use of alfalfa crop for the condition of the present experiment.

LIST OF REFERENCES

(1) Ashcroft, G. and S. A. Taylor. Moisture tension as a measure of water removal rate from soil and its relation to weather factors. Soil Science Society of America Proceedings 17:171-174. 1953.

(2) Bierhuizen, J. F. Some observations on the relation between transpiration and soil moisture. Netherland Journal of Agricultural Science 6: #2. May 1958.

(3) Butler, P. E. and J. A. Prescott. Evapotranspiration from wheat and pasture in relation to available soil moisture. Australian Journal of Agricultural Research 6:52. 1955.

(4) Blaney, H. F. and W. D. Criddle. Determining water requirements in irrigation areas from climatological and irrigation data. Soil Conservation Service TP-96. 1950.

(5) Bowen, I. S. The ratio of heat velocity by conduction and by evaporation from any water surface. Physics Review 27:779-87. 1926.

(6) Budyko, M. I. and K. P. Pogosian. Modification of climate in the surface layer of the atmosphere with the amelioration of drought areas. Weekly Weather and Crop Bulletin, p. 7. Nov. 30, 1959.

(7) Bushinger, J. A. Some remarks on Penman's equations for the evapotranspiration. Netherland Journal of Agricultural Science 4:77-80. 1956.

(8) Chem, T. F. The effect of soil moisture tension on the transpiration rate of a young sunflower when irrigated by a condensation method. (M.S. Thesis.) Oregon State College, June 1959.

(9) Eldefsen, N. E. Some thermodynamic aspects of the use of soil moisture by plants. Transactions of American Geophysical Union 21:619. 1941.

(10) Halkias, N. A., F. J. Veihmeyer, and A. H. Hendrickson. Determination of water needs for crops from climatic data. Hilgardia 24:207. 1949.

(11) Halstead, M. H. and W. Covey. Some meteorological aspects of evapotranspiration. Soil Science Society of America Proceedings 21:461. 1957.

(12) Hargreaves, G. H. Irrigation requirement habsed on climatic data. Proceedings of American Society of Civil Engineering. November 1956.

(13) Haynes, J. L. The effect of availability of soil moisture upon vegetative growth and water use in corn. Journal of American Society of Agronomy 40:385-395. 1958.

(14) Holmes, R. M. and G. W. Robertson. Evaporation, climate and soil moisture control. Monthly Weather Review, pp. 101-106. March 1959.

(15) Kramer, P. J. Discussion on: Does transpiration decrease as the soil moisture decreases? Transaction of American Geophysical Union 36:438. 1955.

(16) King, K. M. Effect of soil, plant and meteorological factors on evapotranspiration. Royal Meteorological Society, Canadian Branch. Vol. 8, No. 4. 1957.

(17) Lassen et al. Discussion on Veihmeyer and Hendrickson's article: Does transpiration decrease as the soil moisture decreases? Transactions of American Geophysical Union 36:436. 1958.

(18) Lemon, E. R. Evapotranspiration. A report from Irrigation Department of University of California, Davis. December 1956.

(19) ________ The potentialities for decreasing soil moisture evaporation loss. Soil Science Society of America Proceedings 20:120. 1956.

X (20) Lemon, E. R. et al. Some aspects of the relationship of soils, plants and some meteorological factors to evapotranspiration. Soil Science Society of America Proceedings 21:464-468. 1957.

(21) Lowry, R. L. Jr. and Johnson, A. F. Consumptive use of water for agriculture. Transactions of American Soceity of Civil Engineering 107:1243. 1942.

(22) Makkink, G. F. and H. D. J. Van Heemst. The actual evapotranspiration as a function of potential evapotranspiration and the soil moisture tension. Netherland Journal of Agricultural Science 4:67-72. 1956.

(23) Neal, O. M. Jr. The effect of soil moisture and a transpiration reducing spray on transpiration and growth. (Ph.D. Thesis) Michigan State University, 1956.

(24) Nixon, P. R. and G. P. Lawless. Determining deeply penetrating rain water with a neutron scattering moisture meter. A presentation of the Annual Meeting of American Society of Agricultural Engineers, New York. 1959.

(25) Penman, H. L. Natural evaporation from open water, bare soils and grass. Proceedings of Royal Society of London. A. 193:120-145. 1948.

(26) ________ Evaporation: An introductory survey. Netherland Journal of Agricultural Science 4:9-28. 1956.

(27) ________ The dependence of transpiration on weather and soil conditions. Journal of Soil Science 1:74-89. 1949.

(28) ________ Estimating evapotranspiration. Transactions of American Geophysical Union 37:43-50. 1956.

(29) ________ and R. K. Schofield. Some physiological aspects of assimilation and transpiration. Society of Experimental Biology Symposium 5:115-129. 1951.

(30) Pelton, W. L. Potential evapotranspiration estimated by the Penman and Thornthwaite methods. (Ph.D. Thesis.) University of Wisconsin, June 1958.

(31) Pierce, L. T. Estimating seasonal and short term fluctuation in evapotranspiration from meadow crops. Bulletin of American Meteorlogical Society 39:78-93. 1958.

(32) Schofield, C. S. The water requirement of alfalfa. Washington: U.S. Govt. Printing Office, U.S. Dept. of Agric. Cir. No. 735. 1945.

(33) Slatyer, R. O. The influence of progressive increase in total soil moisture stress on transpiration, growth, and internal water relationships of plants. Australian Journal of Biological Science 10:320. 1957.

(34) ________ Evapotranspiration relation to soil moisture. Netherland Journal of Agricultural Science 4:73. 1956.

(35) Smith, G. W. The determination of soil moisture under a permanent grass cover. Journal of Geophysical Research 64:477. 1959.

(36) Stewart, G. L. and S. A. Taylor. Field experiment using neutron scattering method to measure soil moisture. Soil Science 83:151. 1957.

(37) Stone, J. F. Soil moisture determining by a portable neutron scattering moisture meter. Soil Science Society of America Proceedings 19:419. 1955.

(38) Suomi, V. E. and C. B. Tanner. Evapotranspiration estimated from heat budget measurement over field crop. Transactions of American Geophysical Union 39:298. 1958.

(39) Suomi, V. E. and Kuhn, P. M. An economical net radiometer. Tellus 23:1-6. Nov. 1957.

(40) Tanner, C. B. Factors affecting evapotranspiration from plants and soils. Journal of Soil and Water Conservation 12:221-227. 1957.

(41) Taylor, S. A. The use of soil moisture tension to evaluate the effect of soil moisture on crop yields. Soil Science 74:217-226. 1952.

(42) _________ Estimating the integrated soil moisture tension in the root zone of growing crops. Soil Science 73:331. 1952.

(43) Thornthwaite, C. W. An approach toward a rational classification of climate. Geography Review 38:55-95. 1948.

(44) _________ and J. R. Mather. The water budget and its use in irrigation. Year Book of Agriculture, U.S. Dept. of Agriculture, pp. 346-357. 1955.

(45) Van Wijk, R. and D. A. De Vries. Evapotranspiration. Netherland Journal of Agricultural Science 2:105. 1954.

(46) Veihmeyer, F. J. Some factors affecting the irrigation requirements of deciduous orchards. Hilgardia 2:125-291. 1927.

(47) Veihmeyer, F. J. and A. H. Hendrickson. Does transpiration decrease as soil moisture decreases? Transactions of American Geophysical Union 36:425-448. 1955.

(48) West, E. S. and O. Perkman. Effect of soil moisture on transpiration. Australian Journal of Agricultural Research 4:326. 1953.

APPENDIX A

Formulas for Estimation of Potential Evapotranspiration

Blaney-Criddle (4)

$$U = KF$$

$$F = \sum^{m} f$$

$$f = \frac{t \times p}{100}$$

Where: U is the consumptive use of water by the crop in inches for growing season.

K is the empirical seasonal consumptive use coefficient for a given crop

f is the monthly consumptive use factor

t = mean monthly air temperature F^{o}

p = mean monthly percentage of day-time hours for a given latitude

m = number of months of the growing season

Hargreaves (12)

$$U = \sum^{m} ke$$

$$e = cd\ (t - 32)$$

$$c = (0.38 - 0.0038\ h)$$

Where: U is the consumptive use of water by the crop in inches for growing season

k is impirical coefficient for a given crop, location and season.

e is the monthly consumptive use factor

t is mean monthly air temperature F°

d is monthly daytime coefficient for a given latitude

h is mean monthly relative humidity at noon

Lowry and Johnson (21)

$$U = 0.8 + 0.156\ F$$

Where: U is the valley consumptive use in acre-foot per acre

F is the sum of days time maximum monthly air temperature. The days on which maximum air temperature is less than 32°F are neglected.

Thornthwaite (43)

$$PE = \left(\frac{N}{30}\right)\left(\frac{H}{12}\right) PE^*$$

$$PE^* = 1.6 \left(\frac{10\,\bar{T}}{I}\right)^a$$

$$I = \sum_{k=1}^{12} i$$

$$i = \left(\frac{\bar{T}}{5}\right)^{1.514}$$

$$a = f(I^3)$$

Where:

PE is the potential evapotranspiration in cm. per month

N is the number of days per month

H is the mean monthly daytime hours for a given latitude

PE* is the unadjusted potential evapotranspiration

$\bar{T}$ is the mean monthly air temperature in C°

I is the heat index for a given station which is the sum of heat indexes of 12 months of year (i)

a is a function of I^3

Penman (25)

$$E_t = f\,E_o$$

$$E = \frac{\Delta H_o + \gamma E_a}{\Delta + \gamma}$$

$$H_o = R_a(1-r)(0.18 + 0.55\ n/N) - \sigma T_a^4 (0.56 - 0.09\sqrt{Pa})(0.10 + 0.90\ n/N)$$

$$Ea = 0.35(p_d - p_a)(0.5 + 0.0098\ u_2)$$

Where: E_t = the daily evapotranspiration in mm. of water

= an empirical reduction factor for a given location and season

E = evaporation from a free water surface in mm. of water per day

γ = psychrometer constant = 0.27

Δ = slope of saturated vapor pressure curve of air at absolute temperature T_a in F^o in mm. of mercury per degree F^o

H_o = daily net radiation in mm. of water per day

E_a = evaporation in mm of water per day

R_a = mean monthly extra terrestrial radiation in mm. of water per day

r = reflection coefficient of a given crop

n = actual duration of sunshine

N = maximum possible duration of sunshine

σ = Boltzman radiation constant = 2.01×10^{-9} mm. of water per day

T_a = mean daily air temperature

p_a = actual vapor pressure in the air in mm. of mercury

p_d = saturation vapor pressure at mean air temperature in mm. of mercury

u_2 = mean wind speed at 2 meters above the ground in miles per day

APPENDIX B

Analysis of Variance Tables

Table 7. Analysis of variance of the yield of alfalfa in gm. per square yard

Source of variations	Degrees of freedom	Sums of squares	Mean sums of squares	F
Total	26	202799.63	-	-
Moisture treatments	2	189260.51	94630.25	81.84**
Plots within treatment (error)	6	6933.79	1155.56	
Samples	18	6605.41		

**Significant at 1 percent level

Table 8. Analysis of variance of soil temperature at 10 cm. depth in °C

Source of variations	Degrees of freedom	Sums of squares	Mean sums of squares	F
Total	419	13483.96		
Treatments	209	12193.19	58.34	9.50**
D	9	424.73	47.19	7.68**
W	2	1762.91	881.45	143.5 **
T	6	8058.92	1343.1	218.7 **
DxW	18	126.6	7.03	1.14
DxT	54	930.83	17.23	2.80 **
WxT	12	496.65	41.38	6.73 **
DxWxT	108	392.55	3.63	.59
Error	210	1290.77	6.14	

*Significant at 1 percent level

D = Days

W = Moisture treatment

T = Hours of day

Table 9. Analysis of variance of the amount of water stored in the upper 9 feet of soil in inches

Source of variations	Degrees of freedom	Sums of squares	Mean sums of squares	F
Total	71	1446.28		
Treatments	23	1351.30	58.75	29.70**
W	2	1072.19	536.09	271.03**
D	7	267.87	38.27	19.35**
WxD	14	11.34	0.810	0.409
Error	48	94.98	1.978	

**Significant at 1 percent level

W = moisture treatments
D = days

APPENDIX C

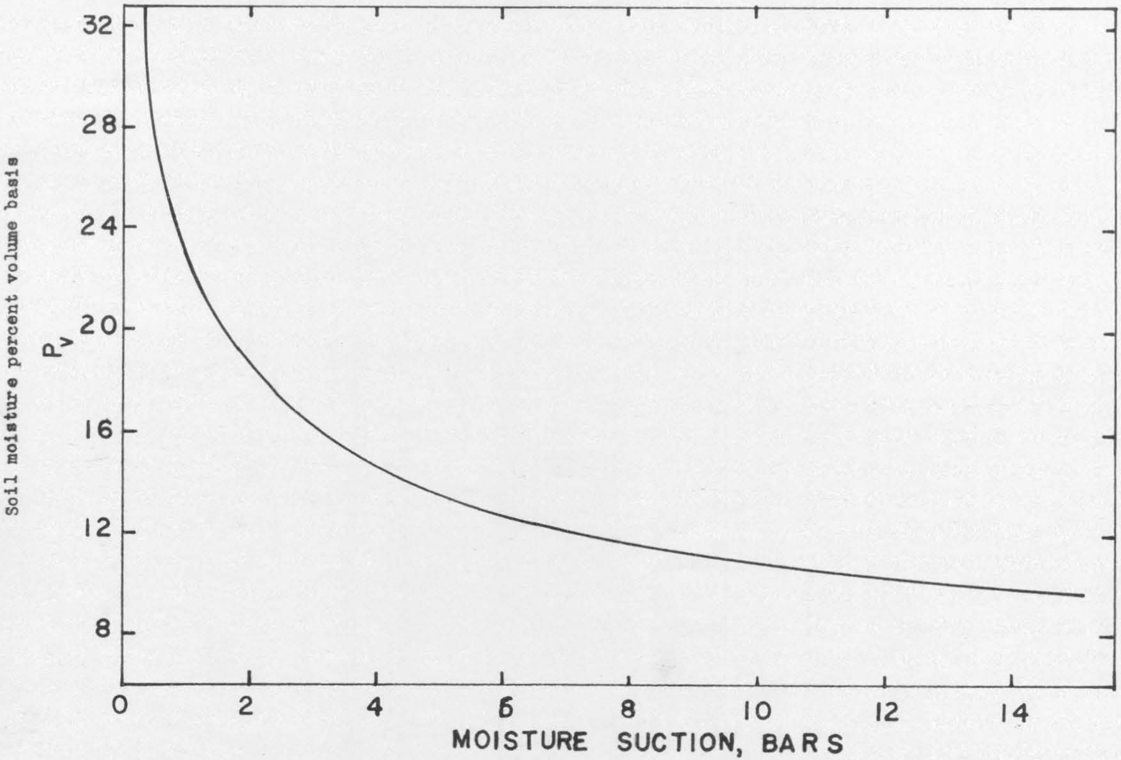


Figure 23. Soil moisture retention curve for the Millville loam