THE EFFECT OF SOIL MOISTURE TENSION ON THE TRANSPIRATION RATE OF A YOUNG SUNFLOWER WHEN IRRIGATED BY A CONDENSATION METHOD

by

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STATEMENT OF THE PROBLEM

The relation of soil moisture tension and plant transpiration has long been discussed among scientists concerned with this problem. It is known that the availability of the soil moisture to plant growth is affected by its chemical and physical properties. The ability of the soil to grow plants is dependent not only upon the proper supply of the nutrients but also upon the physical conditions which will make possible the most efficient usage of available nutrients by plants.

Soil moisture tension is one of the important soil characteristics which directly affects the moisture extraction pattern of the plants. Kramer (15, p. 1-29) defined the soil moisture tension as the negative pressure of the soil water including gravitational, hydrostatic, and surface forces but not osmotic forces.

It is commonly known that a plant transpires a considerable amount of water from soil during the growing period. The availability of the moisture to the plant depends on the force with which the water is held by the soil. The gravitational water is little available to the plant and seldom present long enough to contribute to plant growth. For most plants, the water readily available for plant growth is so-called capillary water in the range between the field capacity and the permanent wilting percentage. The field capacity is defined in this paper as the moisture content after the gravitational water has drained away and capillary water movement has become very slow. The permanent wilting percentage is taken to be the moisture content when the plant first becomes permanently wilted, and will not recover when placed in an atmosphere with 100 percent relative humidity. Soils show great variation in this respect.

Some discussion has occurred as to whether water is equally available over the entire range from field capacity to wilting percentage. Veihmeyer and Hendrickson (35, p. 425-448) have stated that the water is equally available over the entire range from field capacity down to the wilting point. Many other workers reported data which included both supporting and opposing opinions on the statement. There are several apparent contradictions in these data. There are even some different interpretations of the theoretical analysis.

How moisture tension affects plant transpiration, and whether there is a certain range of moisture tension in which plant transpiration is not affected are the problems to be studied here. The present investigation was undertaken with purpose of obtaining further information concerning these problems.

Many investigations have been made of the effect of soil moisture on the plant growth by surface watering method. But it was not until 1925 that Shantz (30, p. 705-711) and Veihmeyer (34, p. 125-284) called attention to the uniformity of the moisture distribution after surface watering. Difficulty in maintaining a constant soil moisture tension has been one of the main reasons why the inconsistency of data exists. In this investigation a new method (39) is employed to avoid the defective moisture distribution.

LITERATURE REVIEW

Transpiration and Soil Moisture

Shull (31, p. 1-31) made one of the earlier attempts to measure the force with which water is held by the soil. Richards (25, p. 115-121) developed a pressure membrane apparatus by which any pressure up to more than 25 atmospheres tension can be measured directly.

Briggs and Shantz (4, p. 20-21) and (5, p. 229-235), in their study of wilting coefficient, stated that only slight differences exist among the various crops in their ability to reduce the soil moisture before the wilting occurs, and that the loss of water from the soil to the air goes on through the plant tissues even after the death of the plant and appears to be limited only by the establishment of a state of equilibrium between the soil and the air. The final result is the same as if the soil and air were in direct contact. This process becomes slower and slower as the water content is reduced and reaches its final limit in a condition of equilibrium between soil and air.

Veihmeyer and Hendrickson have done a considerable amount of work along this line. They stated (35, p. 425-448) that transpiration is not reduced until the soil moisture reaches the permanent wilting point.

According to Maximov (24), the growth of various herbaceous species was found to be largely independent of water content until the soil moisture reached a very low level. Magness, Degman, and Furr (21) reported that the growth rate of apples was not reduced by decreasing soil moisture until at least the driest part of the root zone reached the wilting percentage.

Whitfield (38, p. 83-96) conducted an experiment to check the relation of different soil moisture to transpiration. He reached the conclusion that water loss apparently increases with increase of the water content until the optimum conditions are reached. Excess water content gave a water loss below that of the optimum moisture content owing to poor aeration.

Daubenmire and Charter (7, p. 762-770) reported that growth of seedings of several species of desert legumes continued unchecked until the moisture content of the soil reached the permanent wilting percentage, and then ceased abruptly.

According to the theory of Schofield (27, p. 757-762) and the work of Thornthwaite (32, p. 55-94), consumptive use will be nearly independent of crop so long as the crop covers the land surface and so long as sufficient moisture is present.

Edlefsen (10, p. 917-940) has applied the free energy equation to compute the energy involved in the displacement of water in the soil-water-plant system. The result implies that the energy increase in extracting the soil moisture as the moisture content changes from field capacity to wilting percentage is negligible compared with energy available near the leaf surface.

Aldrich and Work (1, p. 115-123), and Lewis, Work and Aldrich (16, p. 309-323) reported that in very heavy soils in Oregon the rate of growth of pears is closely related to the moisture content of the upper three feet of soil. Schopmeyer (29, p. 447-462) found that the transpiration rate of loblolly and shortleaf pine seedings grown in containers decreased with decreasing moisture content while the soil was still above its permanent wilting percentage. Uneven distribution of roots was observed in these cases.

Furr and Reeve (12, p. 149-170) reported that a decrease in soil moisture from field capacity to the permanent wilting percentage caused the osmotic pressure in plants in dry air to increase about 5 atmospheres and that in plants in moist air to increase 2.5 atmospheres. They concluded that the plants are subjected to an increasing water deficit from halfway between the moisture equivalent and the permanent wilting percentage.

Davis (8, p. 791-805) reported that the growth of young maize plants was slowed by decreasing soil moisture and that it ceased before the soil moisture content fell to the wilting percentage. Haynes (13, p. 385-395) reported that the growth of corn plants increased with increasing soil moisture almost to saturation.

Long (19, p. 594-601) reported that adding 100 milliequivalents of sodium chloride per liter, which results in a solution with an osmotic pressure of about 4 atmospheres, caused severe wilting of tomato plants. He suggested that if water is equally available to plants from field capacity to permanent wilting percentage, a range of about 15 atmospheres, surrounding their roots by 4 atmospheres should not have seriously interfered with absorption.

Ayers, Wadleigh and Magisted (3, p. 796-810), and Wadleigh and Ayers (36, p. 106-132) found the growth and yield of kidney beans to be reduced if the soil was allowed to dry part way down to the permanent wilting percentage. Scofield (28) reported that larger yields of alfalfa are produced when the plants were continuously supplied with water by subirrigation than when they were watered intermittently, although never allowed to wilt.

Kramer (15) based on Edlefsen's free energy analysis, interprets the situation by assuming that because of the drop of free energy near the leaf there is not more than

10 atmospheres available between the root and soil. Van Bavel and Kramer (15) both refer to work done on transpiration rates of tomatoes in sucrose solution having osmotic pressure of only 1 or 2 atmospheres. Rates were reduced in higher concentration.

Taylor (2, p. 171-174) reported that the water removed by alfalfa, sugar beets, and potatoes was 10 to 20 percent more on the lower tension plots than on the higher plots. Marsh (22) obtained similar results on sweet corn. The data indicate a definite increase in consumptive use but evaporation from the soil surface was not reported.

An explanation of these apparently contradictory results has been suggested by Magness (20, p. 651-661) and by Lewis, Work and Aldrich (16, p. 309-323). They suggested that in the cases in which trees have suffered from water-shortage when the soil moisture was well above the wilting percentage, the trees were growing on heavy soils with slow capillary movement of water and poorly distributed root systems. As a result, the soil in immediate contact with the absorbing roots may be at or near the wilting percentage while the other part of the soil may be well above this point. On the other hand, experiments which show that soil moisture is equally available from the field capacity to about the wilting percentage have been with trees growing on moderate to light textured soils in which the root distribution is usually much more complete and capillary movement more rapid than in heavy soils. Some other factors which may serve to explain the contradictory results are included in the discussion.

Transpiration and Soil Temperature

Clements and Martin (6, p. 619-630) found that the transpiration varies very little with soil temperature between 55° and 100° F., but drops rapidly below 55° F., was reduced to half at 38° F., and approached zero at 32° F.

Martin (23, p. 15-35) has investigated the effects of air temperature, relative humidity, leaf-temperature, nighttime and daytime, wind, and radiation on the transpiration of Ambrosia trifida and the Russian mammoth variety of Helianthus annuus. He found certain correlations of transpiration with each of these factors.

Delf's (9, p. 283-310) investigation showed that the permeability of protoplasm for water, as measured by the rate of tissue shrinkage in a dilute sugar solution is increased continuously by temperature up to the highest investigated, 42° C.

Kramer (14, p. 371-372) stated in his study of the effects of soil temperature on the absorption of water by plants that it cannot safely be assumed that exactly the same relation holds between soil and soil-point cone as between soil and roots, yet it seems very likely that increasing soil temperature produces an equally marked effect on the movement of water from soil to root. If this is true, then lowering of the temperature of the soil directly decreases the absorption of water in two ways; first, by its physical effects (chiefly increased viscosity and decreased vapor pressure) which result in a slower movement of water from soil to root, and second, by its physiological effects on the permeability of the root cells. Soil temperature also effects root growth and hence the size of the absorbing system, and thus indirectly the amount of absorption.

Auto-irrigator

Transeau (33, p. 54-60) suggested an auto-irrigator installation used to measure absorption of water by transpiring plants. Livingston (17, p. 39-40) suggested the use of porous porcelain cones buried in the soil and connected to a reservoir as a means of controlling the supply of the moisture. The tendency for the soil to dry out at a distance from the irrigator, and the root to become massed around the irrigator absorbing directly from the surface of the irrigator were the problems of this type of device.

Wilson (37, p. 139-154), Richards and Blood (25, p. 115-121) improved the device by the use of double-walled pots. Later Richards and Loomis (26, p. 223-235) found that the double-walled pot maintained a constant soil-moisture content for small plants with low tensions but not for a large plant removing water rapidly.

Emmert and Ball (11, p. 295-306) separated the soil in the container into several layers with coarse sand layers and watered with tubes leading to each layer of sand.

Recently Wolfe (39) has proposed a method by which the moisture content can be maintained at any point less than the field capacity. This was thought impossible by any other method. If it is feasible, the investigation on the relationship between soil moisture tension and plant transpiration could be approached experimentally on a more sound basis.

METHOD OF ATTACK

To obtain a close approach to the true relationship between the soil moisture tension and the plant transpiration rate, attention has been paid to control the conditions under which the experiment was carried out. A constant temperature room which has a humidity control facility was selected as the experimental space. The temperature and relative humidity were kept constant, 75° F. and 58 percent, respectively. Artificial light was used to maintain light and radiation constant.

A sunflower was used in the study. Before it reached the two-leaf stage, it was transplanted into a plastic box. The box was sealed and then the sunflower was grown in the greenhouse until the experiment began. In the experiment a condensation method (39) was used in keeping the moisture tension as steady and uniform as possible. The plastic box with all attachments was located on a balance and a temperature gradient in the soil was controlled by passing a dry cool air through the grills in the soil column. The moisture was supplied by condensation from saturated air forced through under pressure. A plastic cylinder and a pressure indicating instrument were located on another balance. The change of weight read from this balance gives the amount of water supplied with pressure indicated.

The residual moisture was absorbed in a drier. The change in the weights of the plastic box, moisture supplying cylinder, the drier and the plant determined the rate of the plant transpiration.

EQUIPMENT

A plastic box with inside dimensions 3 inches wide, 3 inches long, and 4 inches high, constructed of 1/2-inch thick plexiglas was used to contain the soil. It has three 3/8-inch openings, one at the bottom and two at the top plate of the plastic box. The top plate was removable to facilitate placing and sampling of the soil.

The box contained five temperature controlling grills constructed of 3/8-inch and 5/16-inch copper tubing. Six 5/16-inch tubes in each of the grills were placed 1/2 inch from center to center, and the grills were placed 0.656 inch from center to center in the soil column. Two pieces of 40-mesh brass screens, 3 x 3 inches, were placed 1/2 inch above the bottom and 1/2 inch below the top of the box, respectively. The bottom of the 3/8-inch tube in the bottom grill and the top of the 3/8-inch tube in the top grill coincided with the screens, respectively. The soil column was placed between the screens and had a depth of 3 inches. The air dry weight of soil was 640 grams.

Each grill was connected with two openings in the box so that the cooling air from outside of the box could be passed through the grill. These openings were tapped and fitted with brass fittings. The grills were easily loosened and removed after each run to facilitate sampling soil.

The dry cool air was used to cool the soil to the respective temperatures. The air was conducted through 1/2-inch copper coils cooled by flowing tap water and refrigerating tank. The refrigerating tank had a small propeller to stir the water and a thermostat to control the temperature of the water in the tank. The amount of cooling air flowing through the temperature controlling grills was regulated by manually controlled valves. The direction of the flow of the cooling air was alternated about 10 times per minute as it passed a cylinder with rotating vanes in it. Thus the soil was cooled uniformly in the horizontal plane. The temperature of the refrigerating tank was held at 2° C.

A plastic cylinder, 3 inches in diameter, 4.5 feet high and 1/8 inch thick, was built to supply saturated air to the soil column. The saturation of the air was obtained by bubbling air through the water column in the plastic cylinder. The saturated air was passed through the soil column under 5 pounds per square inch pressure. A heat lamp was used to warm the water when its temperature was lowered due to the heat requirement of the evaporating water. The temperature of the water in the cylinder was kept at room temperature, 75° F. Except for the copper coil and manifold, the air circuits were conducted through 1/2-inch and 3/8-inch Tygon plastic tubing.

Two balances were used to weigh the plastic box and moisture supplying cylinder. The sensitivity of the balances was checked at the beginning of the experiment. The balance used to weigh the plastic box had 0.05 gram sensitivity and the other one had 0.25 gram sensitivity.

All temperatures were measured with laboratory grade mercury thermometers graduated to 0.1° C. Temperature was read approximately to 0.01° C. Calibration of the thermometers showed that the maximum deviation from the mean of the thermometers was 0.1° C. Five thermometers were held in T-shaped plastic inserts in the cold air tubes at one side of the box.

The soil used in the experiment was a sandy soil with considerable permeability and a low field capacity. The moisture-tension curve is plotted in Figure 3. The moisture content when air dried was 0.8 percent.

The artificial light consisted of eight 20-watt standard warm-white General Electric Fluorescent Lamps and one 60-watt Sylvania Lumiline Lamp. These lamps were fixed on a square plywood of 24 inches wide and 25 inches long. The distance from the lamp to the top of the sunflower was 11 inches, and the intensity of the light was 715 foot-candles.

Temperature and relative humidity of the room, 11 feet wide, 14 feet long and 15 feet high, were controlled by two refrigeration units, a set of automatically controlled heaters, and a steam jet. The relative humidity was also under automatic control. The temperature was kept at 75° F., ± 1° and the relative humidity at 58 percent, ± 2 percent.

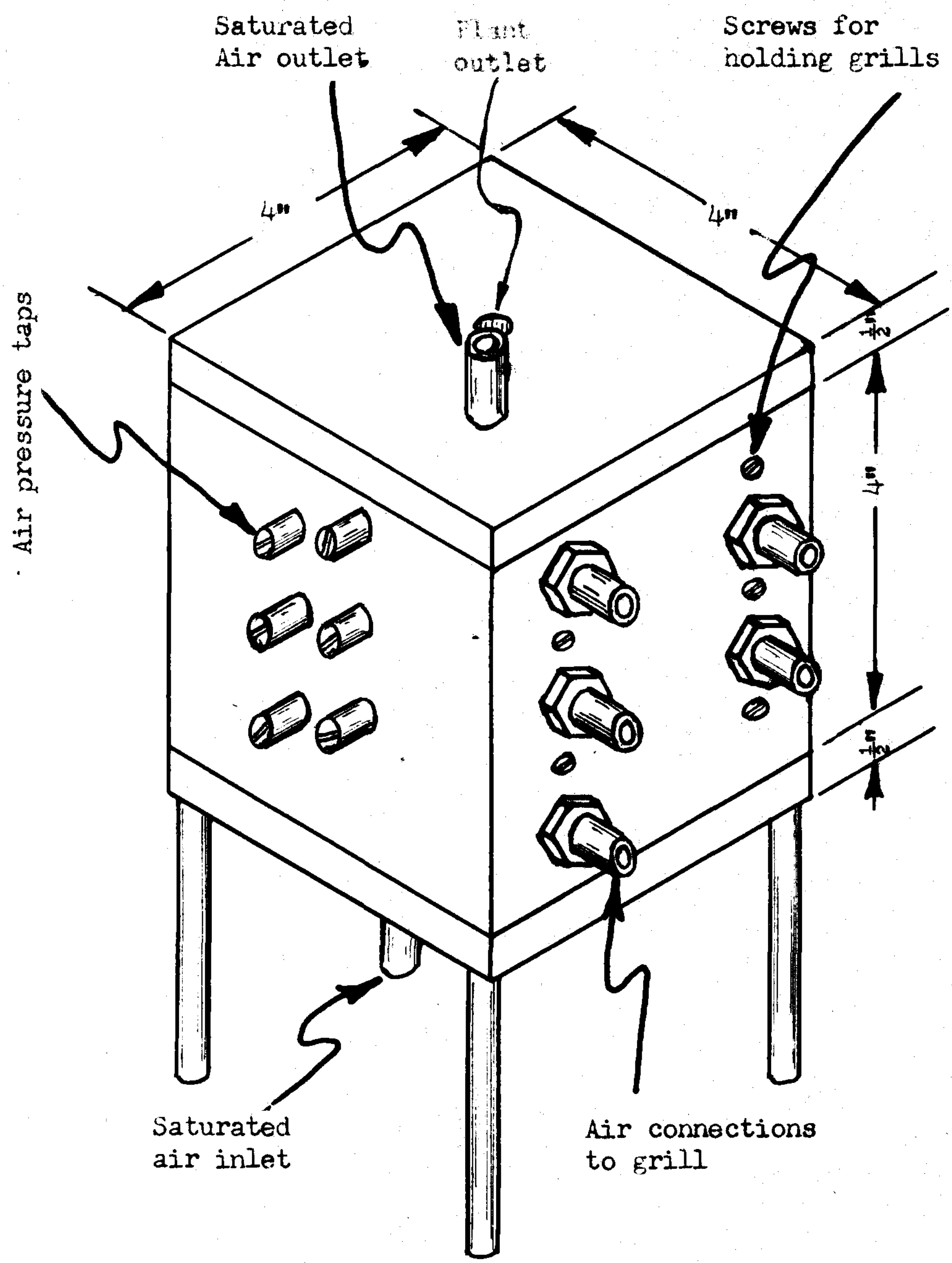


Plate 1. Plastic soil box

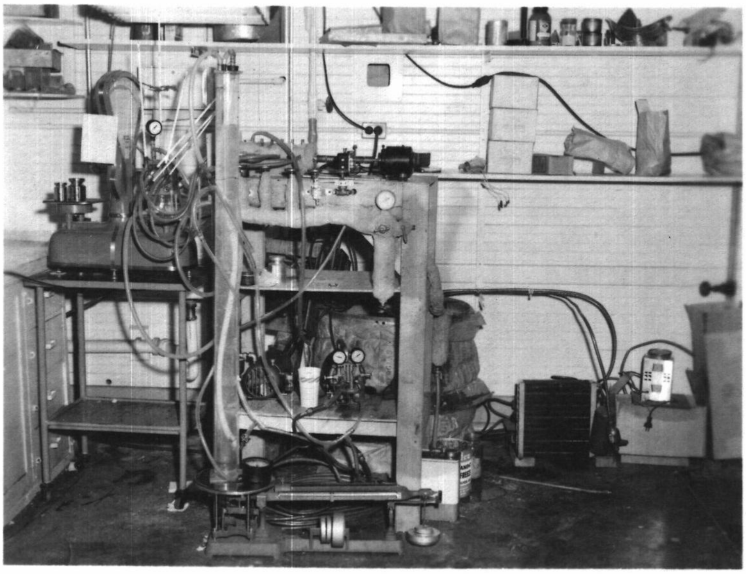


Plate 2. General arrangement of the experiment, showing moisture supply system, cooling air circuit, weighing device, and plastic box with plant.

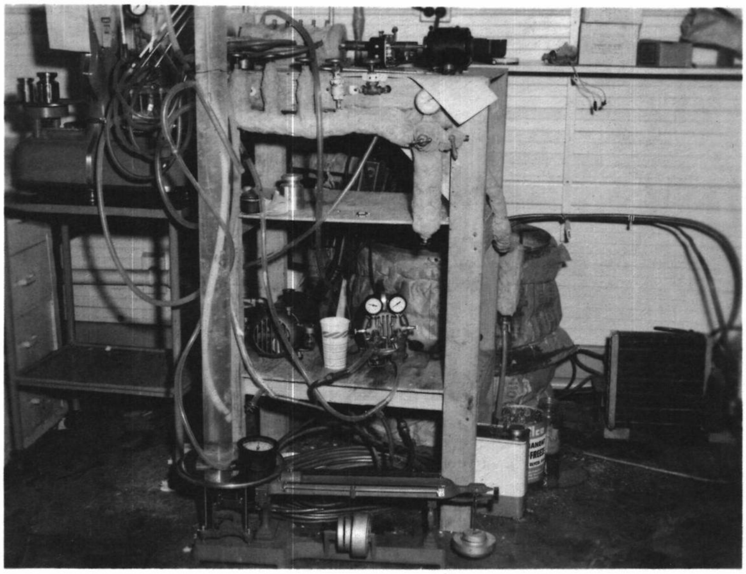


Plate 3. Cooling air circuit, includes refrigerator and tank, moisture trap, valves, and oscillatory cylinder.

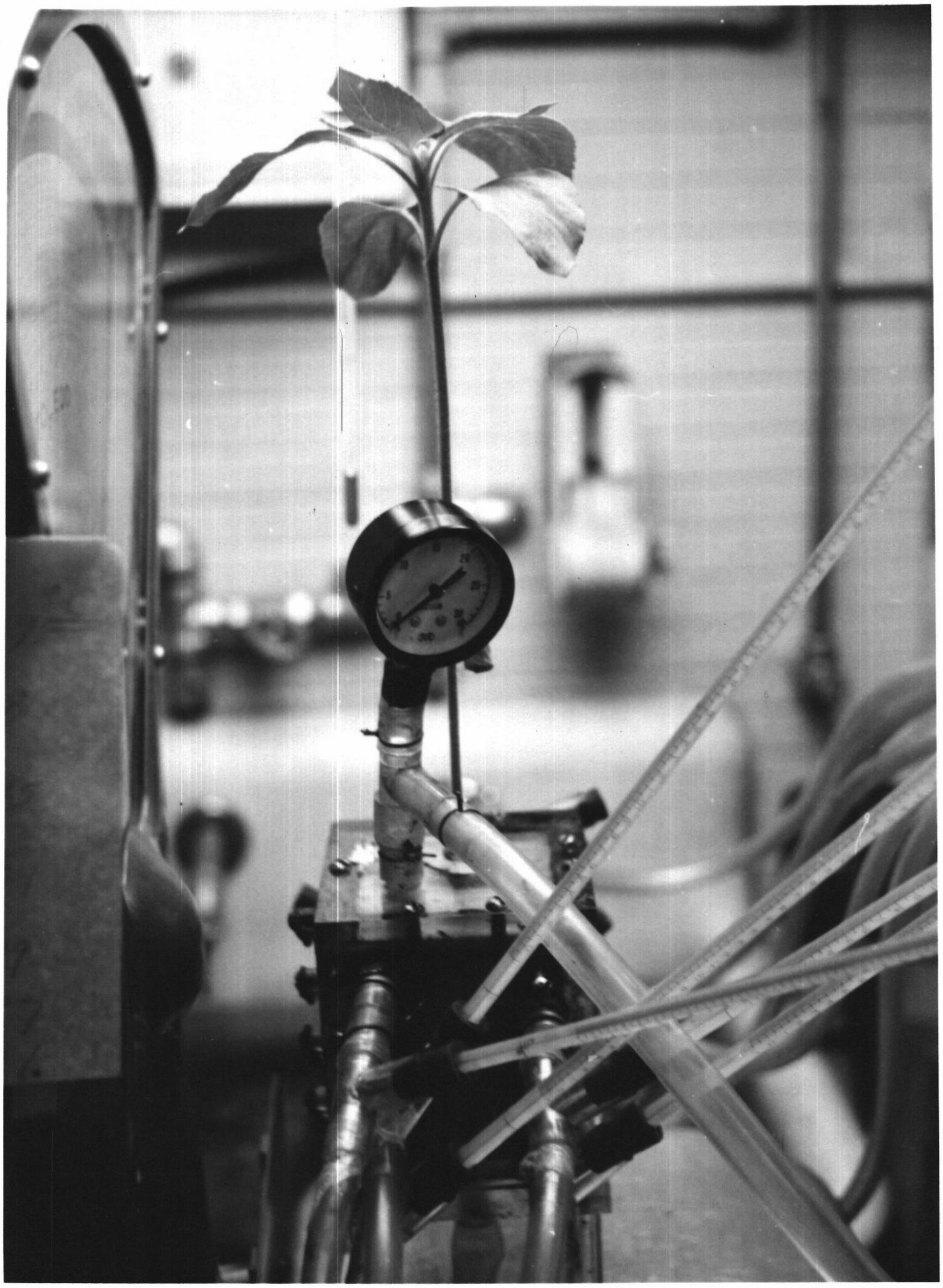


Plate 4. Experiment at the end of high moisture tension, 12 atmospheres, on June 28

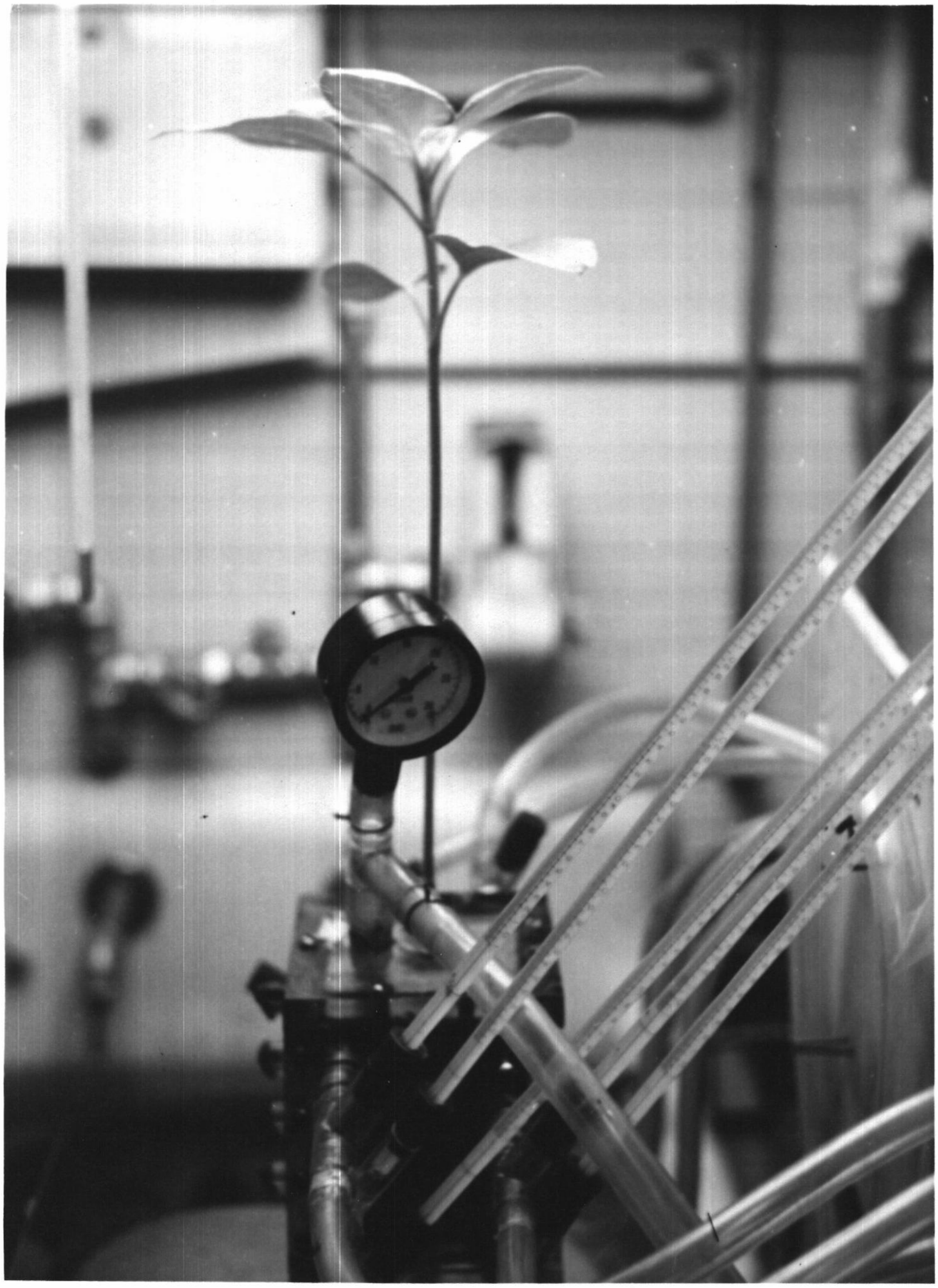


Plate 5. Experiment at low moisture tension, 6 atmospheres, on June 29.

EXPERIMENTAL PROCEDURE AND RESULT

A dwarfed sunflower, 10 inches high, was used in this experiment. Five seeds were soaked in a small can with a fertilized soil on May 14. Nitrogen, potassium, and phosphorous were added to the soil, on the basis of 100 pounds per acre for nitrogen, 200 pounds per acre for potassium, and 50 pounds per acre for phosphorous. The fertilizer was dissolved into water and then applied to the dry soil as the moisture content was first raised to 10 percent in the plastic box.

Three days later the most healthy sprout was transplanted to the plastic box. The brass screen was placed on the surface of the soil column and the sprout came out through the hole at the center of the screen. When the sprout grew long enough to reach the hole in the top plate of the box and the hull still remained on the top, it was helped through the hole with great care. The top plate of the box was fixed with screws and the box was sealed. It was left in the greenhouse to grow for 37 days until the experiment started.

The greenhouse was controlled at 75° F. in the daytime and 55° F. at night. The relative humidity and light were not under control. The box was weighed twice a day and the average daily transpiration rate during the growth was recorded.

During this period of time in the greenhouse, the moisture content was kept near the field capacity, most of the time at 10 percent. Water was applied through the hole on the top of the box.

Since 64 grams, 10 percent of the dry weight, had been applied there was little water added until on May 29 when the plant had three pairs of leaves and showed slight wilting for the first time at 6.4 percent moisture content, based on the moisture content determination at the end of the experiment. Thereafter the water was applied once a day to twice a day as the plant grew larger.

Several times the plant was allowed to reach the slight wilting condition. On June 9, the moisture content when the plant showed slight wilting was 7.2 percent. The plant was 5 1/2 inches high and had 5 pairs of leaves. The average consumptive use on May 29 was 0.4 grams per hour and on June 9 was 1.1 grams per hour.

The dimensions of the sunflower when the experiment started was as following:

(1) Height---10 inches

(2) Stem diameter at top of plastic box---0.22 inches

(3) Leaves

		No. of leaves
1st pair	Dropped off	
2nd pair	1 3/4" long and 1 1/4" wide	2
3rd pair	1 3/4" long and 1 7/8" wide	2
4th pair	1 7/8" long and 1 1/4" wide	2
5th set	1 1/2" long and 2 3/8" wide	3
6th pair	Just started at 1/4" long	2
	Total number of leaves:	11

(4) Total area of the leaves at the end of the experiment was 165 square centimeters. The leaf area was determined by taking the shape of each leaf on cross section paper and counting the number of squares. One square unit equals 1.56 square centimeters.

Before the experiment started the transpiration in the greenhouse and that in the constant temperature room under the artificial light was observed. The result is shown in Figures 1 and 2. The light and radiation showed considerable effect in accelerating and decelerating the transpiration. Temperature and relative humidity also affected the transpiration rate.

Figures 1 and 2 are comparisons of the transpiration in the greenhouse and constant temperature room. On June 13, the average temperature in the greenhouse was 70° F., the deviation from the average temperature during the daytime was ± 4° F. Average relative humidity was 53 percent, and changed from 44 to 56 percent. On June 14, in the "constant temperature" room when the air conditioning was not operated, the average temperature was 80° F., and deviation from the average temperature during the daytime was ± 5° F. Average relative humidity was 43 percent, and changed from 40 to 48 percent. On June 15, in the constant temperature room when the conditioning was not operated, the average temperature was 86° F., deviation from the average

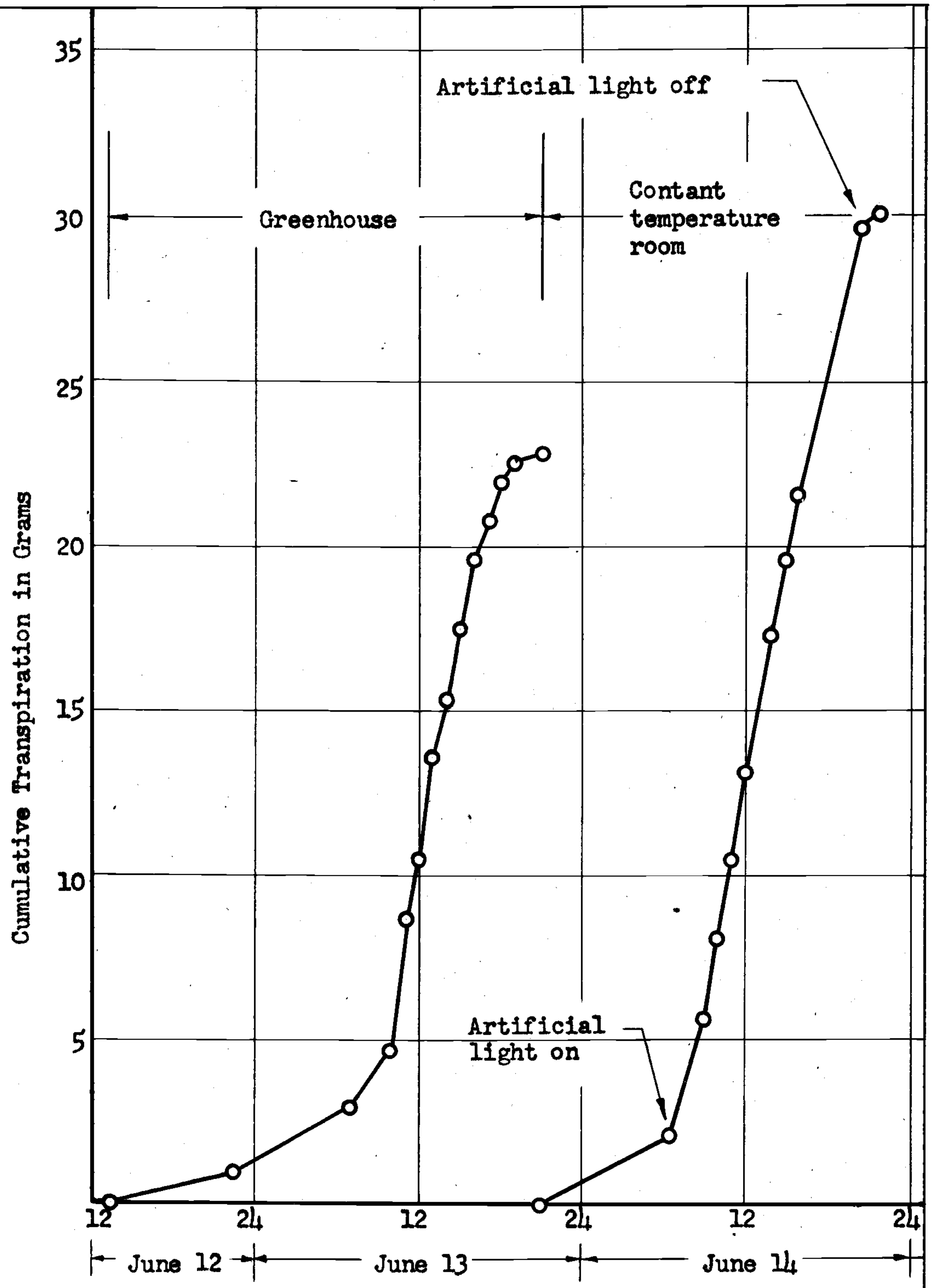


Figure 1. Comparison of transpiration in greenhouse and constant temperature room.

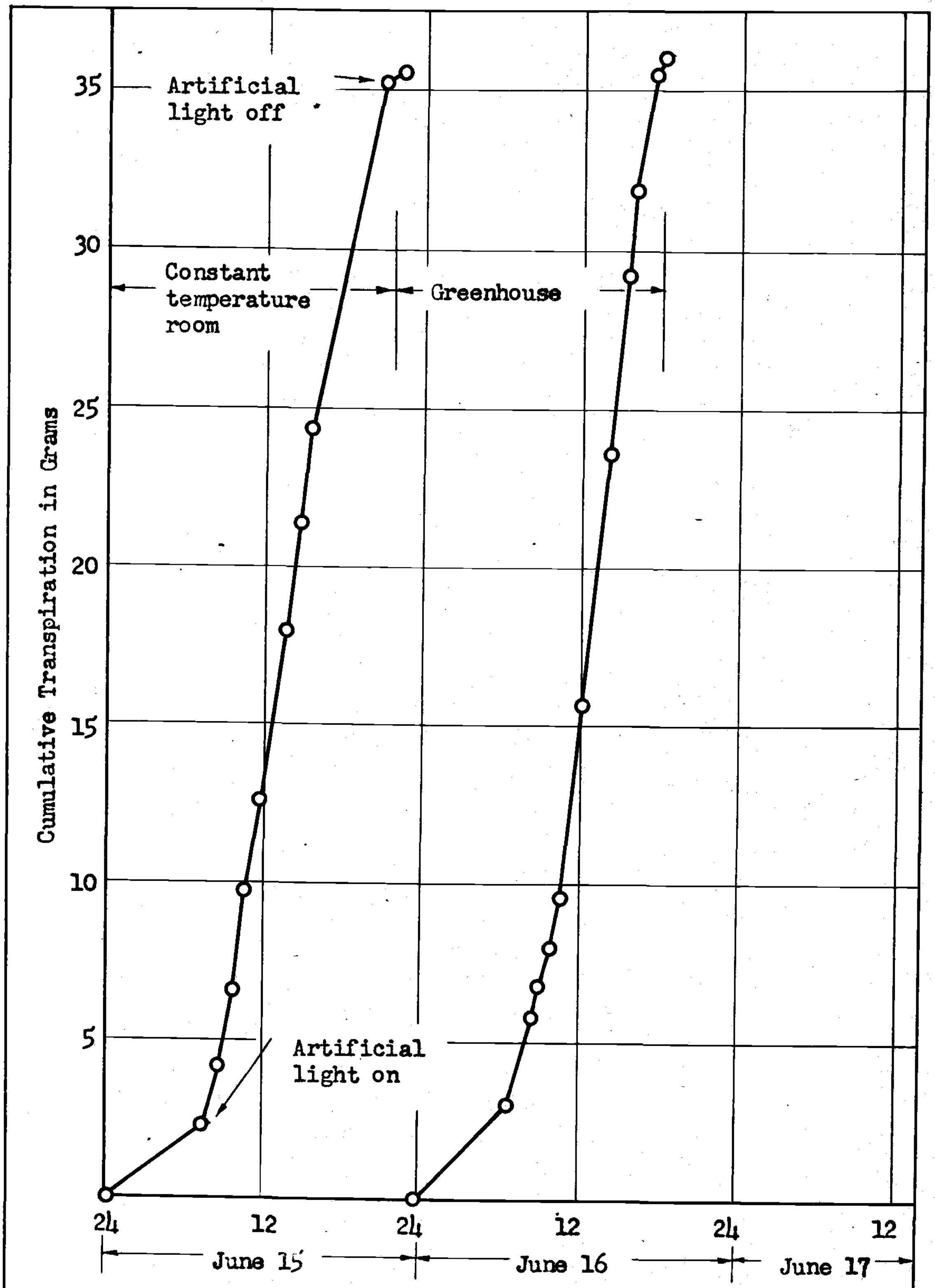


Figure 2. Continuation of Figure 1.

temperature during the daytime was $\pm$ 1° F. Average relative humidity was 41 percent, changed from 38 to 44 percent. On June 16, in the greenhouse, the average temperature was 86.5° F., deviation from the average temperature during the daytime was $\pm$ 7.5° F. Average relative humidity was 55 percent, changed from 53.5 to 60 percent. The average moisture content was kept, by surface watering, at 9 percent for the first two days and at 5 percent for the remaining two days. For a short period of time in the morning of June 16, the moisture content was lowered to 3 percent. Decrease in the transpiration rate was observed from the plotting.

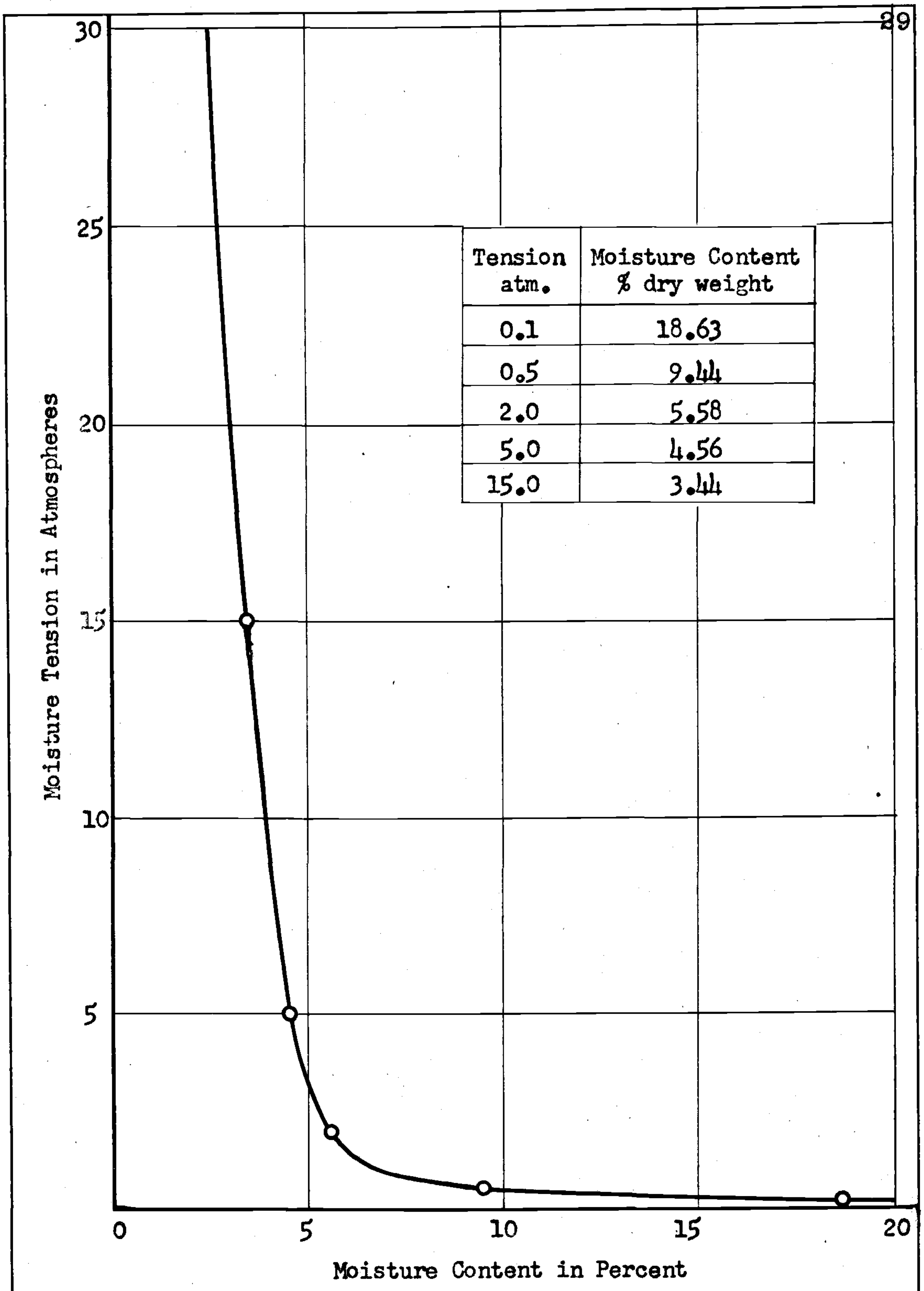
The purpose of this procedure was to compare the effect of the change in the growing environment when the plant was to be moved to the constant temperature room. In the constant temperature room, even though the temperature and humidity control were not operated, the transpiration rate showed its steadiness as can be observed from the slope of the lines. The total amounts transpired on June 14 and June 15 also showed consistent trends. These facts tended to assure the degree of consistency of the environment control after the temperature and humidity controlling units were operated in the experiment. The effect of the moisture tension was isolated and investigated.

The moisture-tension curve for the soil used in this experiment was constructed to show the relationship of moisture-tension and moisture content. At high moisture content the pressure membrane apparatus was used. At low moisture content the porous plate apparatus was used. The curve is shown as Figure 3. From the shape of the curve, the sandy nature of the soil can be observed.

The experiment under controlled conditions started from the lower tension toward the higher tension and then duplicated once from higher to lower tension. The average tension of the runs and the corresponding date are shown in Figure 4.

The room conditioning was started on June 19 and continued to the end of the experiment on July 1. The average room temperature was 74.9° F. The average relative humidity was 58 percent. The windows were blackened and the plant was exposed to the artificial light 14 hours every day. The light was turned on from 6:30 to 7:30 in the morning and turned off at 20:30 to 21:30 in the evening.

Each run was started from cooling the different layers of the soil column to respective temperatures shown in Table 1. Then the saturated air was supplied under 5 pounds per square inch gauge pressure. The



Tension atm.	Moisture Content % dry weight
0.1	18.63
0.5	9.44
2.0	5.58
5.0	4.56
15.0	3.44

Figure 3. Moisture tension curve.

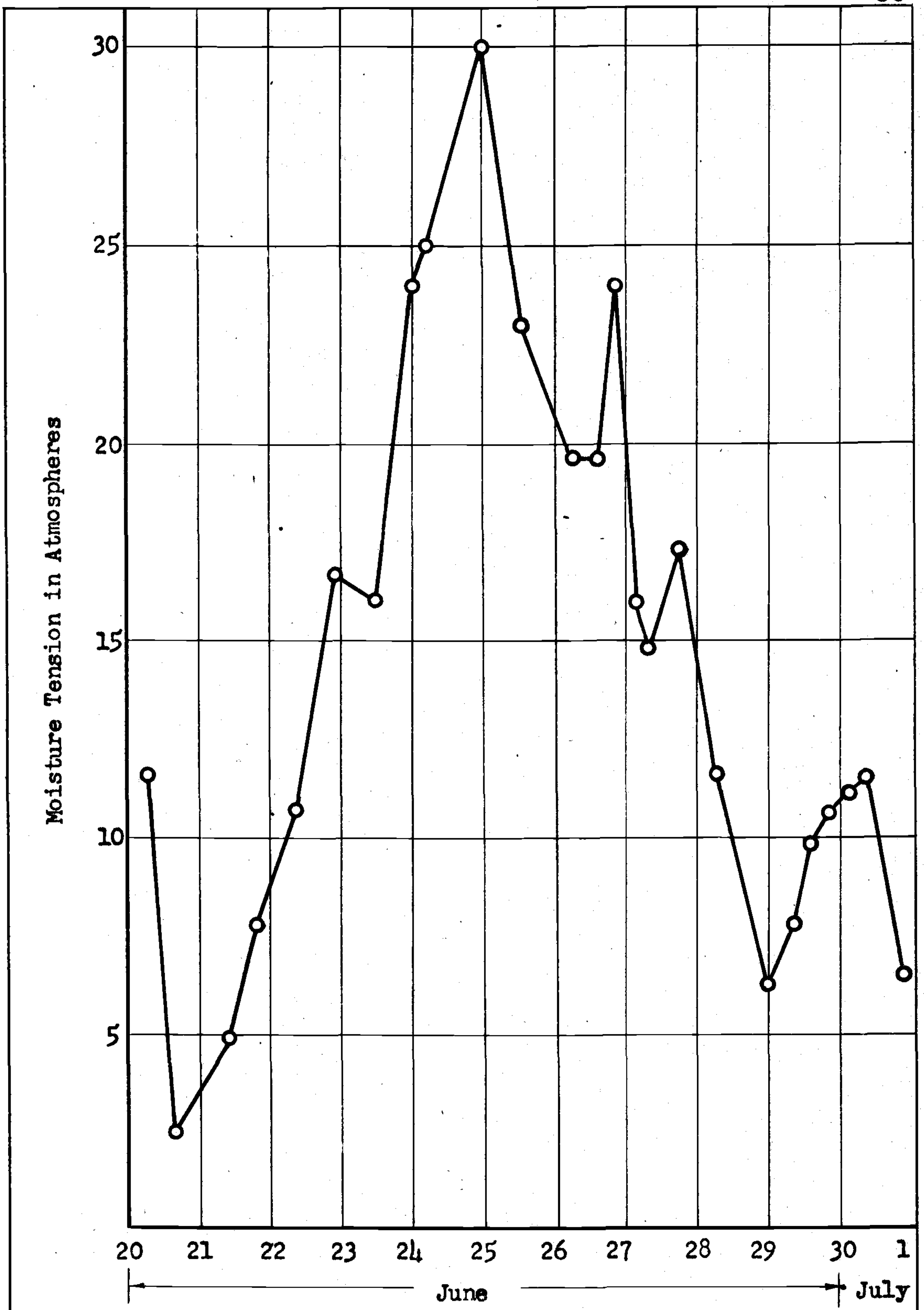


Figure 4. The average tension of the run and the corresponding date.

temperatures were regulated closely by adjusting the opening of the cooling air valves.

Table 1. Calculated temperatures required to produce equal condensation between uniformly spaced grills for 10-inch mercury initial pressure. Cited from Wolfe (39).

Grill 1 °C	Grill 2 °C	Grill 3 °C	Grill 4 °C	Grill 5 °C
23.89	21.72	19.44	17.02	14.44

Table 2. Observed temperatures, average of the thermometer readings of the five grills through the experiment.

Grill 1 °C	Grill 2 °C	Grill 3 °C	Grill 4 °C	Grill 5 °C
23.92	21.69	19.46	17.11	14.55

The length of the runs ranged from 1.5 to 4 hours depending on the moisture tension to be maintained. After each individual run the weight of the plastic box, moisture supplying cylinder, and the drier were determined. The transpiration rate was computed.

Following the weighing, the box was left under the same condition but without the moisture supply. Thus two series of transpiration rates were obtained, one with moisture being supplied and one without. The measurements were continued only for a short period of time due to the fact that the moisture tension around the root would be increased after a certain period of time without supplying moisture. In other words, the uniformity of the moisture distribution in the soil will not be the same as that during the run. The moisture content will, also, be slightly lower than that during the run. The length of most of the observations was 0.5 hour, with some exception. For instance, during the first half of the experiment the period of observation was longer than 0.5 hour in order to build higher tension.

The moisture supplied to the plastic box was not condensed completely in the soil. The air was still saturated at the temperature and pressure of the top grill theoretically. The sodium calcium hydrate drier was used to retain the moisture which came out from the plastic box. Between the runs this drier was renewed.

The result of the runs is shown in Table 3. The result of the observations between two runs is summarized in Table 4. Figure 4 is plotted based on these two tables. The result of the successive runs is shown in the following table.

Table 3. Transpiration rate while irrigator is operated.

Date & time	Moisture content % of dry weight	Moisture tension atmospheres	Transpiration rate grams/hour
June 24 13:30-17:40	2.85	25	0.58
June 25 13:30-15:30	2.50	30	0.60
June 26 08:10-11:30	2.75	30	0.42
June 26 15:15-16:45	2.60	20.4	0.60
June 27 12:10-16:40	3.05	17.3	0.69
June 27 17:20-20:20	3.25	15.4	0.69
June 28 08:00-10:00	3.40	16.7	0.50
June 29 16:00-20:00	4.35	6.7	0.96
June 30 17:30-19:00	3.80	11.1	0.83
June 30 19:45-20:30	3.70	12.0	0.86
July 1 11:35-14:35	3.98	9.4	1.05

After each run of the experiment the transpiration rate was observed. The conditions were exactly the same except for not cooling the different layers of the soil and for not supplying moisture under pressure. The result is shown in the following table.

Table 4. Transpiration rate while irrigator is not operated.

Date & time	Moisture content % of dry weight	Moisture tension atmospheres	Transpiration rate grams/hour
June 20 19:00-20:50	3.75	11.6	0.90
June 21 07:35-09:50	5.30	2.5	1.80
June 21 19:15-21:20	4.60	4.9	1.16
June 22 07:00-09:15	4.20	7.8	0.98
June 22 17:55-19:35	3.85	10.7	0.96
June 23 07:20-10:45	3.30	16.7	0.54
June 23 16:35-20:45	3.35	16.0	0.50
June 24 07:25-13:30	2.90	24.0	0.32
June 24 17:40-21:10	2.85	25.0	0.30
June 25 07:20-11:40	2.45	30.0	0.23
June 26 11:30-12:00	2.95	23.0	0.40
June 26 16:45-17:15	3.10	19.6	0.60
June 27 11:30-12:00	3.10	19.6	0.60
June 27 16:40-17:10	3.35	16.0	0.70

(continued)

Table 4. (continued)

Date & time	Moisture content % of dry weight	Moisture tension atmospheres	Transpiration rate grams/hour
June 27 20:20-20:50	3.45	14.8	0.50
June 28 10:00-10:30	3.25	17.3	0.60
June 28 19:30-20:00	3.75	11.6	1.00
June 29 15:15-15:45	4.40	6.3	0.90
June 30 11:10-11:40	4.20	7.8	1.10
June 30 13:30-14:45	3.95	9.8	1.04
June 30 16:45-17:15	3.85	10.7	1.00
June 30 19:00-19:30	3.80	11.1	0.80
June 30 20:30-21:00	3.75	11.5	0.80
July 1 08:15-10:30	4.37	6.5	1.18

On July 1, the plant was cut from the top of the plastic box. The plant weighed 8.60 grams right after it was cut off. The weight of the root was not obtained directly from the plant in order to keep the soil column undisturbed. The weight of the root was estimated as 50 percent of the weight of the stem and leaves. Thus the

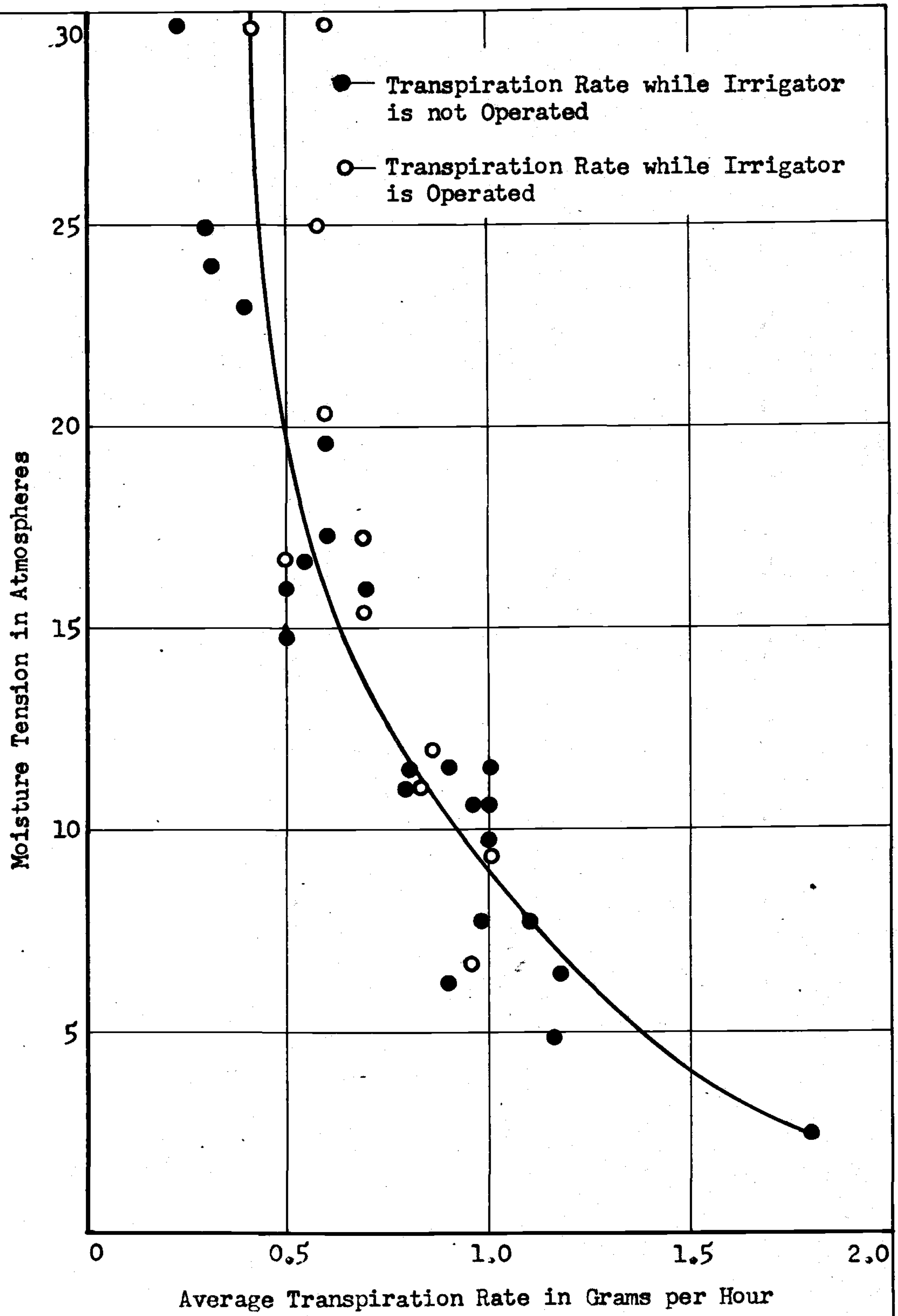


Figure 5. Soil moisture tension and transpiration rate.
(From Chen's Thesis)

total weight of the sunflower including the root was 12.90 grams. During the 11 days from June 19 to July 1, the height of the plant increased 1.5 inches. On June 23, the second pair of leaves dropped off. The total leaf area measured on June 26, when the plant recovered from the test of highest moisture tension, was 142 square centimeters. At the end of the experiment the total leaf area was 165 square centimeters. After considering these facts it seemed unreasonable to assume that the weight of the plant was not changing through the period of the experiment. A linear increase of the weight of the plant between May 16 to July 1 was assumed and the corresponding correction was made on this basis.

The moisture content was sampled after the plant was cut. The sampling of the soil was done in the constant temperature room. The soil column was divided into ten layers, one layer above the top grill and one layer below the bottom grill, two layers out of each of four intervals between successive grills. The top and bottom layers were not taken into computation. Moisture content was determined by oven drying. The result is shown in Figure 6.

In Figure 6, the moisture distribution at the end of the experiment is plotted and compared with the fifth run of the experiment described in (39). The general tendency of the moisture distribution in (39) showed higher moisture

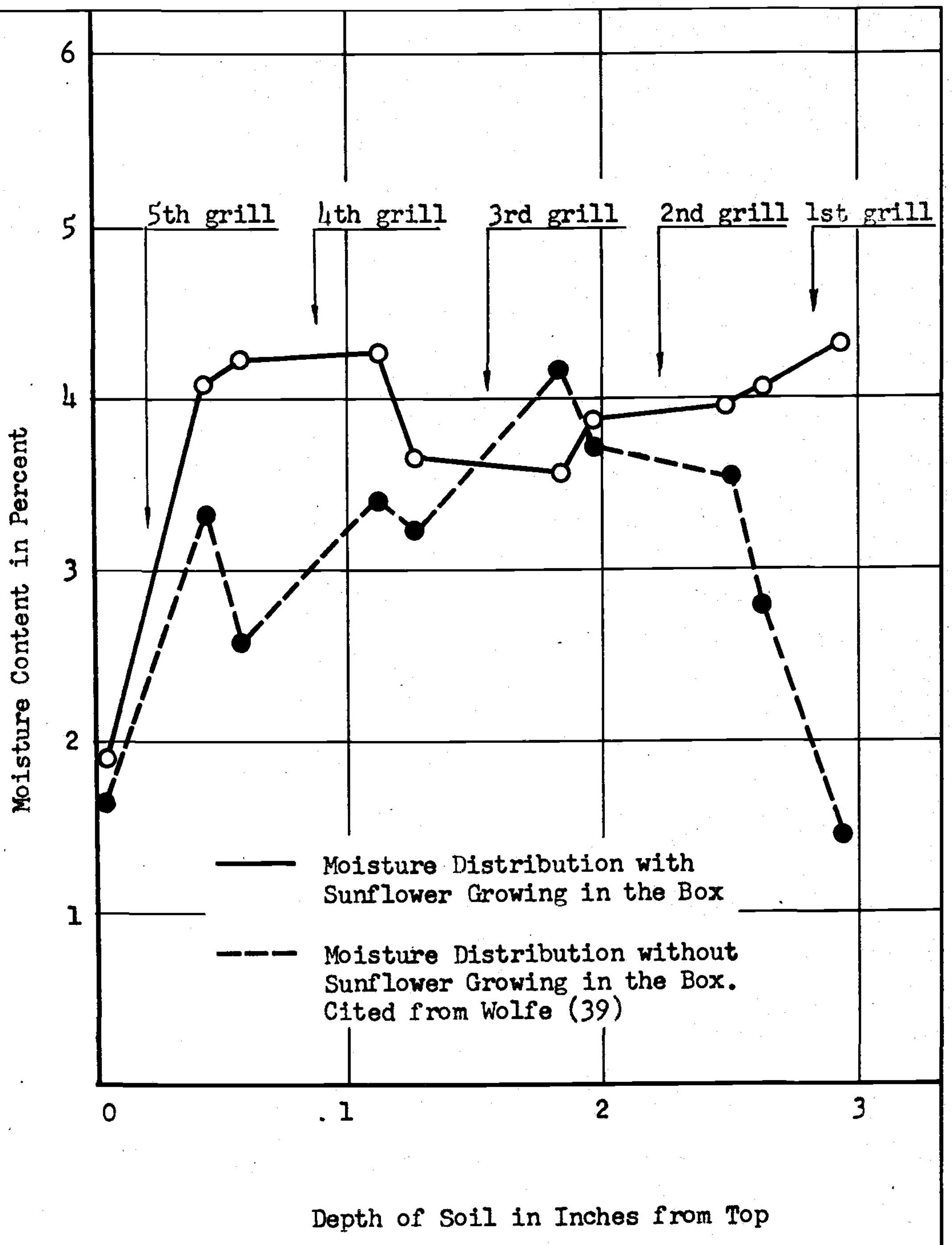


Figure 6. The moisture content distribution at the end of the experiment, moisture tension at 9.4 atmospheres.

content of the middle of the soil column. But the moisture content distribution of this experiment differed from this tendency, showing lower moisture distribution at the middle of the soil column. The differences in condensation control between these two runs were 0.02° C. rise of temperature of grill 3 and 0.01° C. rise of temperature of grill 4.

The root distribution was quite uniform when observed at the end of the experiment. All ninety samples had roots penetrating through them. The second layer from the top had dense horizontal distribution of roots over the section.

The mean moisture content of the 72 samples was 3.97 percent corresponding to 9.6 atmospheres tension. The weight of the plastic box was related to the moisture-tension curve on this basis. The weight of the plastic box at 3.97 percent moisture content was 2416.00 grams including the plant weight 12.90 grams. The change of weight of the plastic box of 6.40 grams corresponds to 1 percent change of moisture content. Thus the weight of the plastic box can be correlated to moisture content, and the corresponding moisture tension obtained from the moisture-tension curve.

The factors affecting the uniformity of the moisture distribution were the compaction of the soil, the deviation of the temperature control, and the moisture extracting pattern of the plant.

DISCUSSION

There was no previous work done by the condensation method on this problem. Workers reported in the literature have found several defects in the methods with which they attempted to investigate the relation between moisture tension and plant transpiration. Inability to maintain uniform moisture content and defective root distribution are the most significant.

When comparing the condensation method with the other methods, the following point is noticeable. Under field condition plants are not always capable of penetrating every part of the root zone equally. When the root distribution is defective, the mean distance through which the soil moisture moves through capillary action is relatively greater. Since capillary movement is very slow in soil when moisture content approaches the non-available region, the portion of the soil not penetrated by roots would have a somewhat higher moisture content. Consequently, an imperfect root distribution would give an erroneous result. It causes an indication of lower tension than actually exists immediately surrounding the roots. In the condensation method the effect of the root system on the moisture distribution is reduced by continuous uniform moisture supply when the rate of supply is adjusted to the rate of removal or transpiration rate.

It is possible that the air permeability of the soil around the root would be increased slightly due to removal of moisture from the pore space. There might be a tendency to replace the moisture removed in the vicinity of the root by the increase of the saturated air flow which is in turn due to the increase of the air permeability.

It has been observed that poor aeration retards absorption and transpiration of rooted plants. The harmful effects of accumulation of carbon dioxide and reduced oxygen supply has been discussed. The enforced aeration, as has been done in this experiment by pushing saturated air through the soil column under pressure, might increase the absorption and transpiration of the plant.

From Wolfe's data (39) and the sampling result of this experiment, the complete uniformity of the moisture distribution was not obtained. However, to obtain, below field capacity at 9.4 atmospheres tension, a condition close to uniformity in moisture distribution, ± 0.35 percent, while the plant is continuously extracting the moisture from the soil seems impossible by the methods appearing in the literature.

In some cases the data reported were in terms of consumptive use rather than transpiration and percent moisture rather than moisture tension. In many sandy soils moisture may be regarded as being equally available over the range from field capacity to permanent wilting percentage. It is possible in sandy soil that most of the readily available water is removed before the tension exceeds 1 atmosphere tension and only a small fraction is held with sufficient force to hinder the transpiration. Another soil might reach this tension very shortly after the irrigation and still contain much available moisture. Thus more precise methods of controlling and reporting moisture tension are needed.

The movement of the water to the root zone in the condensation method is thought to follow two ways--

(1) The movement of the vapor due to the pressure gradient from bottom of the box to the top of the soil column.

(2) The movement in liquid phase, in which the water film on the surface of the soil particles moved due to the capillary tension and pressure gradient. Under the natural condition, the movement of the water in the soil between the range of field capacity and wilting percentage depends on the capillary tension. The accelerating pressure gradient is never the case.

There was a consistent tendency, for a pair of observations obtained from the run and after the run, that the transpiration rate obtained from being supplied with saturated air was higher than that obtained while not being supplied, whether it was located above or below the curve. For instance, take any pair of continuous observations, one from Table 3 and the corresponding one from Table 4. The transpiration rate from Table 3 will always be higher than that from Table 4. This will suggest the possibility that the transpiration rate increases under the condition being supplied with saturated air under pressure. It is most likely due to accelerated moisture movement and the direct condensation of moisture on the root surface.

The soil temperature ranged from 14.44 to 23.89° C. in this experiment. The effect of this temperature difference at the top and bottom of the root zone was unknown, but from the previous works (6, p. 619-630) it was found that the temperature changes of this range were not significant. For this particular case more investigation will be profitable.

On June 30, the irrigator was operated overnight after the artificial light was turned off. The purpose was to increase the moisture content in the soil. It was found that one day of continuous operation of the irrigator was required to increase 1 percent moisture content when the plant was transpiring about 1 gram per hour. Improvement on the moisture supplying capacity is necessary if a larger plant is to be tested.

The root distribution observed at the end of the experiment showed dense horizontal distribution in the second layer from the top. There are a few factors, one or more, of which may be accountable for this fact. These are:

(1) Incomplete uniform compaction of soil.

(2) The soil temperature of second layer is suitable for the root development.

(3) It was developed during the greenhouse period due to the continuous surface watering.

(4) Moisture supply by condensation method was not uniform in the experiment. This, however, seems in contradiction to the result of moisture content sampling.

From Figure 5, it is clear that the rate of change of transpiration rate decreases gradually from low moisture tension to high moisture tension. The point of 15 atmospheres tension may be taken as a dividing point. Plant transpiration rate was increased rapidly as the moisture tension decreased below this point. From the observation in the greenhouse, the curve should intersect at the vicinity of the point of 2 grams per hour transpiration rate at zero moisture tension. Beyond 30 atmospheres tension, the transpiration process will become slower and slower until a state of equilibrium between the soil and air is established (4, p. 20-21) and (5, p. 229-235).

The possible error in this experiment can be concluded as the following items:

(1) Error due to the sensitivity of the balance and the stiffness of Tygon tube used to conduct air circuits.

(2) Deviation from the true moisture tension due to the extension of the moisture-tension curve above 15 atmospheres tension. Slight change of the weight of plastic box at this range will change considerably the moisture tension. The 30 atmospheres point on moisture-tension curve was estimated as the range of 2.45 to 2.75 percent moisture content.

SUMMARY AND CONCLUSION

The transpiration rate of a young sunflower with respect to the soil moisture tension under a constant environment was studied by supplying moisture by a condensation method. The result showed definite correlation between the transpiration rate and soil moisture tension.

For a young sunflower, as used in this experiment, it was found that increase in the soil moisture tension will cause a decrease in the transpiration rate, in accordance with the results obtained by some other investigators. The transpiration appeared to continue even at 30 atmospheres tension. The rate of change of the transpiration was higher at moisture tension lower than 15 atmospheres tension, and then slowed at higher moisture tension up to 30 atmospheres tension.

The transpiration rate under two conditions in the same constant environment were compared. The transpiration rate while moisture was being supplied showed higher than that of while not being supplied with moisture, significantly at high tension range. The reason was not clear.

The condensation method in studying the relation between the soil moisture tension and the plant transpiration was tested. The method may be used in the soil of comparatively permeable and homogeneous nature. The moisture distribution at the end of the experiment showed close to uniform. The deviation was 8.8 percent of the mean moisture content. The effects of the saturated air flow under pressure to the plant transpiration, and the compaction of the soil to the uniform condensation need further investigation.

BIBLIOGRAPHY

1. Aldrich, W. W. and R. A. Work. Evaporating power of the air and top-root ratio in relation to rate of pear fruit enlargement. Proceedings, American Society for Horticultural Science 32:115-123. 1934.

2. Ashcroft, Gaylen and Sterling A. Taylor. Moisture tension as a measure of water removal rate from soil and its relation to weather factors. Proceedings of the Soil Society of America 17:171-174. 1953.

3. Ayers, A. D., C. H. Wadleigh and O. C. Magisted. The interrelationships of salt concentration and soil moisture content with growth of beans. Journal of the American Society of Agronomy 35:796-810. 1943.

4. Briggs, Lyman J. and H. L. Shantz. The wilting coefficient and its indirect determination. Botanical Gazette 53:20-21. 1912.

5. Briggs, Lyman J. and H. L. Shantz. The relative wilting coefficients for different plants. Botanical Gazette 53:229-235. 1912.

6. Clements, F. E. and E. V. Martin. Effect of soil temperature on transpiration in Helianthus Annuus. Plant Physiology 9:619-630. 1934.

7. Daubenmire, R. F. and H. E. Charter. Behavior of woody desert legumes at the wilting percentage of the soil. Botanical Gazette 103:762-770. 1942.

8. Davis, C. H. Absorption of soil moisture by maize roots. Botanical Gazette 101:791-805. 1940.

9. Delf, E. Marion. The influence of temperature on the permeability of protoplasm to water. Annals of Botany 30:283-310. 1916.

10. Edlefsen, N. E. Some thermodynamic aspects of the use of soil moisture by plants. Transactions of the American Geophysical Union 917-940. 1941.

11. Emmert, E. M. and F. K. Ball. The effect of soil moisture on the availability of nitrate, phosphate and potassium to the tomato plant. Soil Science 35: 295-306. 1933.

12. Furr, J. R. and J. O. Reeve. The range of soil-moisture percentages through which plants undergo permanent wilting in some soils from semi-arid irrigated areas. Journal of Agricultural Research 71:149-170. 1945.

13. Haynes, J. L. The effect of availability of soil moisture upon vegetative growth and water use in corn. Journal of the American Society of Agronomy 40:385-395. 1948.

14. Kramer, P. J. Effect of soil temperature on the absorption of water by plants. Science 79:371-372. 1934.

15. Kramer, P. J. Plant and soil water relationships. New York, McGraw-Hill, 1949. 347 p.

16. Lewis, M. R., R. A. Work and W. W. Aldrich. Influence of different quantities of moisture in a heavy soil on rate of growth of pears. Plant Physiology 10:309-323. 1939.

17. Livingston, B. E. A method for controlling plant moisture. Plant World 2:39-40. 1908.

18. Livingston, B. E. Porous clay cones for the auto-irrigation of potted plants. Plant World 21:202-208. 1918.

19. Long, E. M. The effect of salt additions to the substrata on intake of water and nutrients by roots of approach-grafted tomato plants. American Journal of Botany 30:594-601. 1943.

20. Magness, J. R. Status of orchard soil moisture research. Proceedings, American Society for Horticultural Science 32:651-661. 1934.

21. Magness, J. R., E. S. Degman and J. R. Furr. Soil moisture and irrigation investigations in eastern apple orchards. Washington, U. S. Government Printing Office, 1935. 36 p. (U. S. Dept. of Agriculture. Technical Bulletin no. 491)

22. Marsh, A. W. et al. Frequency and amount of irrigation for selected crops. Corvallis, Oregon State College, 1955. 5 p. (Mimeographed progress report).

23. Martin, E. V. Studies of evaporation and transpiration. Carnegie Institution of Washington Publications 550:15-35. 1943.

24. Maximov, N. A. The plant in relation to water. London, George Allen & Unwin, 1929. 451 p.

25. Richards, L. A. and H. L. Blood. Some improvements in auto-irrigator apparatus. Journal of Agricultural Research 49:115-121. 1934.

26. Richards, L. A. and W. E. Loomis. Limitations of auto-irrigators for controlling soil moisture under growing plants. Plant Physiology 17:223-235. 1942.

27. Schofield, R. K. Control of grassland irrigation based on weather data. Proceedings, 6th International Grassland Congress 1:757-762. 1952.

28. Scofield, C. S. The water requirement of alfalfa. Washington, U. S. Government Printing Office, 1945a. 11 p. (U. S. Dept. of Agriculture. Circular no. 735)

29. Schopmeyer, C. S. Transpiration and physio-chemical properties of leaves as related to drought resistance in loblolly pine and shortleaf pine. Plant Physiology 14:447-462. 1939.

30. Shantz, H. L. Soil moisture in relation to the growth of plants. Journal of the American Society of Agronomy 17:705-711. 1925.

31. Shull, C. A. Measurement of the surface forces in soils. Botanical Gazette 62:1-31. 1916.

32. Thornthwaite, C. W. An approach toward a rational classification of climate. The Geographical Review 38:55-94. 1948.

33. Transeau, E. N. Apparatus for the study of comparative transpiration. Botanical Gazette 52:54-60. 1911.

34. Veihmeyer, F. J. Some factors affecting the irrigation requirements of deciduous orchards. Hilgardia 2:125-284. 1927.

35. Veihmeyer, F. J. and A. H. Hendrickson. Does the transpiration decrease as soil moisture decreases? Transaction of the American Geophysical Union 36(3): 425-448. 1955.

36. Wadleigh, C. H. and A. D. Ayers. Growth and biochemical composition of bean plants as conditioned by soil moisture tension and salt concentration. Plant Physiology 20:106-132. 1945.

37. Wilson, J. D. A double-walled pot for the auto-irrigation of plants. Bulletin of the Torrey Botanical Club 56:139-154. 1929.

38. Whitfield, C. J. Ecological aspects of transpiration. II. Pike's Peak and Santa Barbara regions; climatic and edaphic aspects. Botanical Gazette 94:183-196. 1932.

39. Wolfe, John W. The development and evaluation of a method for the condensation of moisture uniformly in soil without exceeding field capacity. Ph.D. thesis. Logan, Ut h State University, 1958. 50 numb. leaves.