THE EFFECT OF LIGHT INTENSITY ON THE TRANSPIRATION OF CERTAIN PLANTS

by

Ben Nelson Stuckey

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V. R. Gardner

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Introduction

Transpiration may be defined as the loss of water in the form of vapor from the stem and leaves of the living plant. In general, transpiration is affected by those external changes which affect evaporation from an open water surface, amount of water available and by internal changes in the plant itself.

Light intensity is known to affect transpiration as well as other plant processes. Since the greater amount of transpirational water is lost during the day, the natural assumption is that with increased light intensity the transpirational curve would rise. When the light intensity is increased, however, more infra-red rays are given off and a rise in temperature is the result. Since transpiration is known to vary directly with the temperature, this transpirational increase, caused by increasing the infra-red rays, would be only indirectly caused by a change in the light intensity.

The increase in temperature, caused by higher light intensities, is thought to account for only a part of the total increase in transpiration. The remaining portion is generally thought to be produced by the opening of the stomata when subjected to high light intensities which increases the transpiring surface of a plant.

In view of the fact that the literature on the above generalities was found to be quite varied and in some cases contradictory, a plan of study was formulated in an effort to determine the effect of light intensity on transpiration while keeping all other factors constant.

Review of Literature

Kiesselbach (9) reports the first effort to measure water loss from plants was made by Woodward of England in 1699. Stephen Hales conducted transpiration experiments as early as 1736. By 1909 there were at least 394 publications on transpiration and since that date many more have been added.

The effect of light on transpiration and other plant functions has been studied extensively during the last 30 years. These studies have been conducted on the effect of total light intensity and certain wave lengths of light on water loss and on the opening of stomata, since stomatal action is thought to be a controlling factor in water loss.

Livingston (14), using Tradescantia zebrina measured the stomatal pores and found the capacity for diffusion to range from 1.92 to 6 times the evaporating power of the air. By using diffused light he concluded that the variation in size of the stomatal pores of Tradescantia zebrina was great enough to explain that portion of the daily rise in the transpiration rate which is not dependent upon the variation in the evaporating power of the air. In direct sunlight, however, he found that the variation in the stomatal opening is not large enough to account for the daily rise in transpiration. In further studies Livingston (15, 16) found that those environmental conditions which affect the rate of vaporization of water act directly to influence transpiration. Different species of plants were found to differ in their response to solar radiation and the same individual responds differently according to its stage of development, and to the previous treatment to which it has been subjected. He also reports that the influence of indirect solar radiation should not be neglected in discussions of the influence of sunshine on transpiration.

Livingston concluded that the total amount of transpirational water loss from a plant for any given period may be considered as a summation of the effects of the evaporating power of the air and of the radiant energy absorbed throughout the period, modified by certain secondary effects of these conditions and by certain responses to other conditions.

Bakke and Livingston (2), using Livingston's cobalt chloride method of measuring transpiration, studied the transpiration of Xanthium canadense and Helianthus annuus. They, as well as Blaydes (3) and Shreve (21), found that the transpiration of each varied greatly during the day. A large increase in transpiration occurred first at sunrise, in some cases amounting to 24 per cent of the average for 24 hours. They attributed this to the opening of the stomata with increasing light and to the excess water in the leaves which had accumulated during the night. These workers also pointed out the fact that the transpiration of a leaf varies inversely with its age.

Martin (17), using different thicknesses of cheese cloth to vary light intensity and, with the sun as his light source, obtained results which differed from those of Livingston. He tested Helianthus annuus for 4 to 5 hours on cloudless days by determining the loss in weight of plants growing in sealed cans. Records were kept on temperature, humidity and wind velocity for every hour and light was measured by a Smithsonian pyranometer 3 to 4 times hourly. Martin concluded that the acceleration of transpiration was due to the heating effects of the infra-red rays rather than the light intensity alone. He also states that the fraction of transpiration rate due to the direct effect of radiation for plants in full sunshine was found to vary 30 to 81 per cent, depending largely on the evaporating power of the air.

Le Clerc du Sablon (13), who tested a large number of plants by essentially the same method as Martin, reported as did Martin that the accelerating effect of radiation on transpiration is due to the heating of the leaves. He also states that this increase in leaf temperature probably causes an increase in the permeability of the protoplasm which would aid in increasing transpiration.

Sir Francis Darwin (5) studied the effect of light on transpiration at about the same time as did Martin and Le Clerc du Sablon. He measured transpiration by the potometer and weight methods on cut branches of _Prunus laurocerasus_ and _Hedera helix_, comparing the north light of a room with total darkness. The stomata were closed with cocoa fat and slits were made through which transpiration took place. This method was used to prevent changing of the evaporating surface by the opening and closing of the stomata. From his studies he concluded as did Martin and Le Clerc du Sablon, that the increase in transpiration caused by an increase in light is due to the chloroplasts being warmed by the absorption of radiant energy or that light produces an increased permeability of the plasma membrane to water.

Henderson (8), using somewhat the same technique as that of Darwin, studied the effect of light on water loss from the mesophyll. He used 100-watt gas-filled lamps suspended 3 ft. above the plants, which gave intensities sufficient for stomatal change. In using _Hedera helix_, _Eupatorium adenophorum_ and _Aster sp_. he smeared the leaves and stems with vaseline to prevent stomatal transpiration and made slits in the leaves down to the mesophyll layer of cells. Leaf temperatures were recorded by the use of thermocouples. Henderson found that apart from the temperature increase caused by light there was a slight increase in transpiration from increased light. This increase was found to vary greatly from plant to plant and even in individual leaves. Transpiration was also found to depend on the amount of water in the mesophyll cells.

Henderson found that when the light intensity increased there was very little effect up to a certain point and then the transpiration rate increased rapidly until a certain light intensity was reached. At this point the curve gradually straightened out until no transpirational increase resulted from increased light. The curve was found to vary greatly with different plants.

Henderson also studied the effects of intermittent light on transpiration. In giving plants intermittent light of 20 second intervals the transpiration was found to be about half that obtained if continuous light of the same intensity was given the plants. However, by increasing the speed of a rotating disk between the light source and the plants, which gave the plants shorter periods of light and darkness, the transpiration rate rose directly with the speed of the disk. Thus it is seen that light of the same intensity is more efficient in increasing transpiration with short rather than with long intermissions. From this Henderson concludes that conditions favorable to increased water loss induced by illumination are produced almost at once but a reversion to conditions less favorable for water loss is produced more slowly.

Thomas and Hill (23) made a continuous measurement of the transpiration of alfalfa and wheat growing under field conditions. These plants were grown in six-foot plots covered with cellophane and transpiration was calculated by measuring the amount of moisture in the incoming air and the outgoing air and comparing the two. They found that transpiration reached a maximum at 2:00 PM., which they attributed to rising temperatures and increased stomatal aperture. At night the transpiration curve was a straight line, due to low temperature and closed stomata. It was found that the transpiration curve followed the temperature curve, whereas photosynthesis followed the light curve.

Lachenmeier (12) made a study of the effect of light on transpiration after Veronica Sp., Hiercium and Myosotis palustris were kept in the darkness for one night. To maintain constant conditions the experiments were carried out in a cellar where temperature and humidity were practically constant. For a light source a 1 ½-watt Osram lamp and 1 normal opaque lamp of 40 watts were used. To vary intensity the distance of these bulbs from the plants was varied. The bulbs were kept in running water to decrease infra-red rays. Only 1-2° C. difference was found in the air temperature at low and high light intensities. The light intensity was measured by an Eder-Hect-Erayredge photometer. Transpiration was measured with a potometer and by weighing. Lachenmeier reports that during the day the transpiration of Veronica increased slowly from 3 to 5 hours to a maximum where it remained constant for 13 hours. Arcyanthium reached a maximum in one hour and then slowly decreased with fluctations. Light intensity seemed to have very little effect either way.

Shull (22), using a large number of species, measured the light reflected from both the upper and lower surfaces of leaves, since the lower surface was found always to reflect more light than the upper surface. He measured the light with a spectro-photometer at an angle of 90° to the leaf surface. Shull found that the amount of reflection varied with the wave length, the maximum reflection being usually at 540-560 Mu.

The value of reflection in this region ran from 6 to 8 per cent in the darkest green leaves and in the lighter leaves 20 to 25 per cent, but neither hairness nor smoothness of cuticle necessarily mean high reflection. Leaves of Verbascum thapsus and Abutilon theophrasti show very little more reflection than non-hairy plants.

The amount of reflection was found to decrease with the age of the leaf which Shull associated with the development of chlorophyll. Anthocyanin development was accompanied by a shift in the position of the maximum reflection to longer wave lengths. In Psedera the maximum reflection occurred at 640 Mu., while the normal reflection for green leaves is 540-560 Mu. In a large number of cases there is a depression of the reflection curve at 680 Mu. which corresponds to the maximum absorption band of chlorophyll.

Pokrowski (18), using practically the same technique as Shull, found that in the blue region of the spectrum there was 4 to 5 percent reflection, in the green 8 to 17 per cent, and in the red 4 to 5 per cent. These percentages are averages from the leaves of Populus tremuloides, Tilia europeae, Fraxinus excelsior, Ulmus pubescens, and Acer platanoides.

Knight (10) used Helianthus tuberosus and Upatorium adenophorum in studying the interrelations of stomatal apertures, leaf water content and transpiration. He concluded that under ordinary conditions changes of stomatal apertures and transpiration did not run parallel. The stomata were chiefly influenced by conditions of illumination rather than by small changes in the water content. Knight found that in a bright light the stomata are wide open and therefore changes in the transpiring power are brought about chiefly by changes in the leaf water content.

On the other hand under low light intensity the lower transpiration rate is a result of a failure of the stomata to open widely.

Gray and Peirce (7), working on certain grains, measured the effects of light intensity on stomatal openings. They measured stomata at changing light intensities and found that at equal illuminations all stomatal openings were of equal size. They concluded that there is a minimum and maximum light intensity below and above which light has no effect, however, within this range the stomatal openings vary directly with the light intensity. This held true for all the grains studied. They believed that intense artificial light disturbs or interferes with the natural action of the guard cells.

Sayre (19), who studied the stomata of Rumex patientia, concluded in contrast to Knight (10), that the opening and closing of the stomata are the principal causes of the periodicity in leaf transpiration. When open the stomata modify the rate of water loss from the intercellular spaces of the leaf in proportion to changes in the perimeter, not to changes in area. Sayre states that sunlight is the principal environmental factor concerned in the opening and closing of the stomata while the amount of water in the leaves and acidity of the guard cells are the two internal conditions directly concerned with stomatal measurement. Sayre (19) in further work on Rumex patientia studied the effects of different wave-lengths of light on the stomata. He concluded that the stomata of patience dock do not open in wave lengths longer than 640 Mu., which is the limit of the red end of the spectrum.

Eltinge (6), working on the effect of ultra violet light on higher plants found that when leaves of Phaesolus, Cucumis, Lactuca, and *Coleus* were subjected to ultra-violet rays, transpiration was not effected immediately. This was followed by a period of very little or no loss in weight, which was in turn followed by a period in which transpiration equaled that of leaves in total darkness. When the stomata were examined those which had been subjected to ultra violet rays were completely closed, while those in total darkness were partially opened.

Arthur and Stewart (1), studying the effects of visible rays and infra-red on transpiration, worked under constant conditions and used 1000 watt Mazda bulbs as a light source. They found that when the energy was increased 2.3 times, the transpiration rate was doubled at 73-78° F. This relation appeared to be independent of a humidity range of 50 to 80 per cent. At high temperatures (98-100° F.), high humidity appeared to decrease transpiration slightly. At a temperature of 73-78° F. plants under a total spectrum transpired 2.5 times more than those under infra-red alone. At high temperatures (98-100° F.) however, the infra-red transpiration rate was only 1.3 less than that of the total spectrum. Under infrared the stomata were completely closed.

Conclusive proof of the effect of light intensity alone on transpiration is apparently lacking in the above literature. The general tendency of these experiments has been to vary more than one environmental factor and correlate the change in transpiration with one of these factors which makes the exact determination of the effect of each factor very difficult. It is practically impossible to separate the effect of combined factors on transpiration from the effect of single factors.

The object of this study was to determine the effect of a single factor, light intensity, on the transpiration of certain plants, while keeping all other factors constant. If a reduction in the intensity of light causes a reduction of transpiration, shading agents could be combined with certain spray materials. These shading agents would probably act as an aid to spray materials which are mechanical barriers to the loss of water vapor. By this means a greater reduction of transpiration could be obtained by applying a spray to transplants or plants having large water requirements.

Preliminary Experiments

Preliminary experiments to determine the influence of light intensity were begun in 1939. In some cases, entire plants were shaded by glass frames which had been sprayed with 6 per cent metallic aluminum, and 6 per cent carbon suspended in water. Light intensities, temperature and relative humidity were recorded along with the rate at which these plants transpired. In other experiments these aluminum and carbon sprays were applied directly to the plants.

The spray coatings, as applied above, provided shade but likewise served to reflect or absorb infra-red waves and thus increase leaf temperatures as measured by a thermometer. Leaves which were sprayed with the carbon suspension were from 6-10° F. warmer than those sprayed with aluminum. This spray method, therefore, was discarded as temperature is one of the controlling factors in transpiration.

A second preliminary method which followed closely the technique of Martin (17) was tried. In this method plants were shaded with different thicknesses of cheese cloth to vary the light. Light intensity reduction was determined by use of a photo-electric cell and transpiration measurements were recorded daily. Leaf temperatures were obtained by use of a thermocouple and air temperatures were recorded hourly. The data from an experiment using this method are presented in Table III.

As may be seen from Tables I and II the leaf temperatures of the shaded plants were consistently lower than those of the unshaded plants. Table III shows that when the light intensity was lowered by shading with cheese cloth a reduction of transpiration took place. However, since the leaf temperatures of the shaded plants were consistently lower than those of the unshaded plants this reduction of transpiration may have been due to a reduction of the temperature. Another error found in this method was that on bright days the shading effect of the cheese cloth was much greater than on cloudy days. The values given on the reduction of light intensity, Table III, are only averages of sunny and cloudy weather. Owing to these errors this method was also discarded as a means of measuring the effect of light intensity on transpiration.

Table I. Leaf Temperature Differences as Determined by Thermocouples

Plants - Tomatoes under Cheese Cloth Shades

Flat #1 - 2 layers cloth Flat #2 - no shade

Time	Air temperature of Flat #1 in degrees C.	Air temperature of Flat #2 in degrees C.	Air temperature difference between Flat 1 and Flat 2 in degrees C.	Leaf temperature increase of Flat 2 over Flat 1 in degrees C.	Weather
9:00 AM	22.2	21.0	.8	2	Cloudy
10:00 AM	22.0	20.5	2.5	1.5	"
11:00 AM	24.1	23.0	1.1	2.5	Part cloudy
12:30 PM	26.6	25.1	1.5	3.0	"
1:15 PM	29.6	30.1	.5	6.5	Sun
1:30 PM	30.0	31.0	1.0	8.5	Sun
2:15 PM	28.1	28.9	.8	3.5	Cloudy
3:15 PM	27.6	27.0	.6	3.5	"
4:15 PM	29.4	29.8	.4	5.5	Part cloudy
5:15 PM	29.0	29.2	.2	7.0	Sun
6:15 PM	26.4	25.8	.6	3.5	Part cloudy
8:00 AM	23.4	21.9	1.5	2.0	Sun
10:15 AM	29.0	27.8	1.2	3.5	Hazy
10:30 AM	27.1	26.0	1.1	2.5	Hazy
11:15 AM	25.4	24.0	1.4	2.5	Hazy
12:45 PM	25.9	24.5	1.4	2.0	Hazy
1:15 PM	26.9	25.2	1.7	2.5	Hazy
2:30 PM	29.8	29.9	.1	1.5	Hazy
3:30 PM	29.0	28.2	.8	4.0	Hazy

Table II. Leaf Temperature Differences as Determined by Thermocouples

Plants - Catalpa under Cheese Cloth Shades

Flat #1 - 2 layers cloth Flat #2 - 1 layer cloth

Time	Air temperature of Flat #1 in degrees C.	Air temperature of Flat #2 in degrees C.	Air temperature difference between Flat 1 and Flat 2 in degrees C.	Leaf temperature increase of Flat 2 over Flat 1 in degrees C.	Weather
8:00 AM	22.5	23.0	.5	1	Sun
1:00 PM	29.1	33.0	3.9	1.5	Sun
8:30 AM	22.0	24.2	2.2	1	Sun
9:30 AM	22.0	24.2	2.2	2.5	Sun
10:30 AM	21.9	24.5	2.6	3.0	Sun
11:30 AM	20.8	20.5	.3	0.5	Cloudy
1:30 PM	24.1	27.0	2.9	5.5	Sun
3:00 PM	26.0	31.5	5.5	6.0	Sun

Table III. Influence of Cheese Cloth Shading on the Transpiration of Tomato

Lot I - 20 plants Total leaf area - 7314 sq. inches

Lot II - 20 plants Total leaf area - 6222 sq. inches

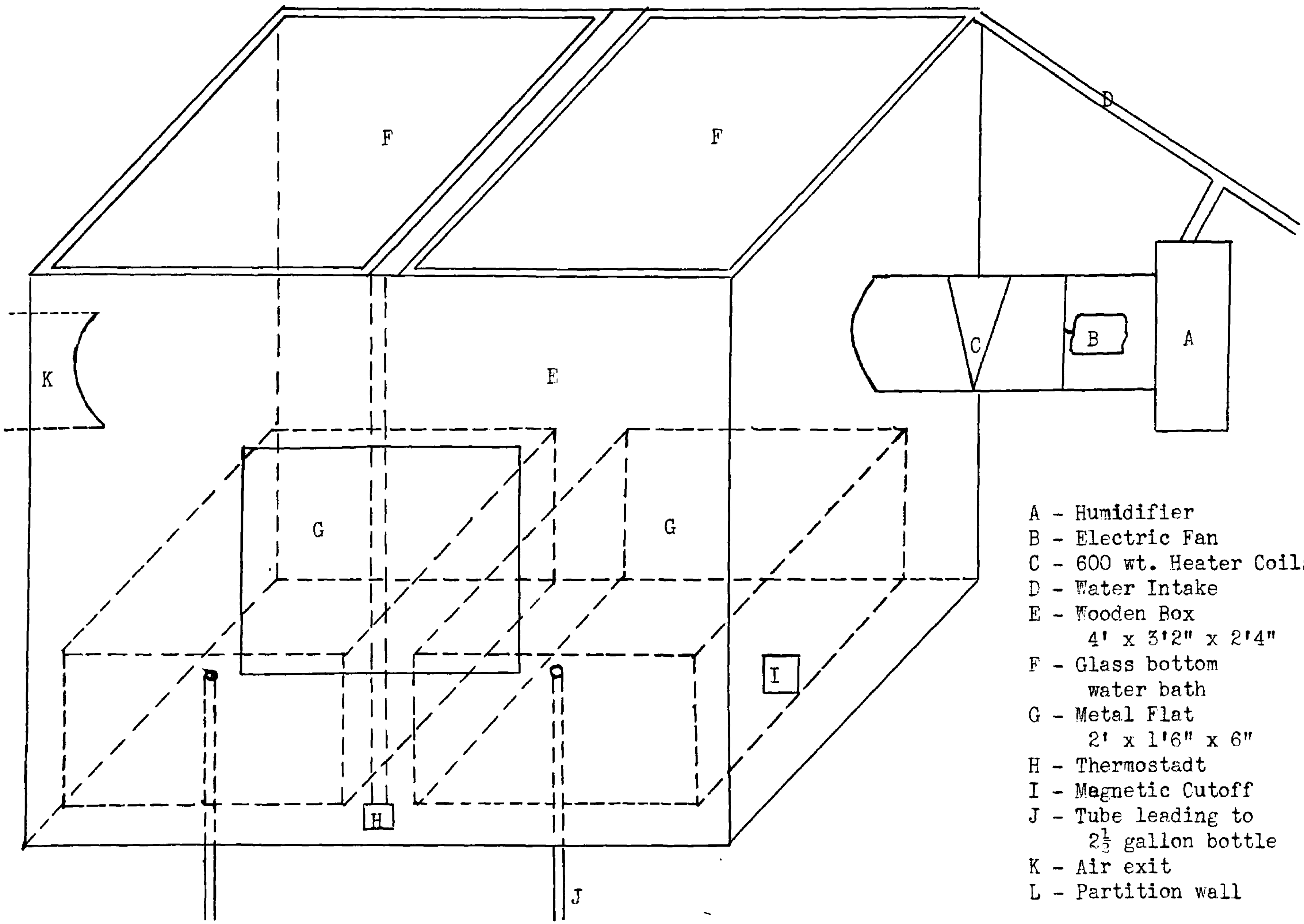
Lot I				Lot II							
Layers of cheese cloth shade	Average transpiration per day for 3 day period in c.c.	Leaf area in sq.in.	Transpiration per sq. in.	Layers of cheese cloth shade	Average transpiration per day for 3 day period in c.c.	Leaf area in sq.in.	Transpiration per sq. in.	Ratio of average transpiration of each lot 1/2	2/1	Light reduction by shading in per cent	Reduction of transpiration by shading in per cent
0	811.6	2256	.36	0	742.5	2036	.36	1.00	1.00		
1	481.3	5486	.09	0	516.2	5400	.10	.90	1.11	65.1	7.6
1	846.6	7445	.11	0	1061.7	6153	.17	.65	1.55	65.1	29.3
1	970.0	5149	.19	1	682.5	4541	.15	1.27	.79		
1	1122.5	6540	.17	2	712.5	5572	.13	1.31	.76	14.7	35.6
2	810.0	7314	.11	2	1107.5	6222	.18	.61	1.64		
2	1025.0	7314	.14	0	1202.5	6230	.19	.74	1.36	79.9	19.5
0	222.5	7314	.30	0	235.0	6230	.38	.79	1.27		

Apparatus

From the preliminary experiments described above it was observed that a chamber should be constructed in which temperature, humidity and light intensity could be controlled. For this purpose an apparatus was constructed with simplicity, economy and accuracy in mind. This apparatus could be used in either a laboratory or greenhouse where external changes in atmospheric conditions are not too great or too rapid.

A chamber (E in Figure I) was made from an air-tight box 4' x 3'2" x 2'4". A partial partition (L in Figure I) divided the box into two equal chambers 2' x 1'7" x 1'2". A 6-inch space was left at the top and bottom of this partition and covered with cheese cloth to permit the passage of air, allowing a minimum of light to pass from one side to the other. The top of the chamber was made of two glass-bottom waterbaths (F in Figure I) which were constructed so as to keep one inch of water in them at all times. At one end of this chamber a hole of 9 inches diameter was made in which was inserted a metal tube. Two 600-watt heater coils (C in Figure I) were placed in this tube. Behind these coils in the pipe was placed an 8-inch fan (B in Figure I) which circulated air over the coils into the chamber. This current of air hit a light-tight metal flange which caused the air to circulate evenly over the chamber at a velocity of 6 miles per hour without a direct current of air on the plants in the box. The 9-inch metal tube containing heater coils and fan was attached to a humidifier (A in Figure I). This humidifier consisted of a square metal box 12" x 14" x 4" with a one-half inch drain pipe in the bottom. A hole 9-inches in diameter was cut in each end of the box and covered by a 1/4 inch mesh wire screen. The box was then filled with excelsior and covered with a top containing 20- 1/4 inch holes. Water poured on this top, filtered evenly through the excelsior, and passed out the bottom drain. Air, sucked in by the fan through the excelsior, absorbing moisture in proportion to the amount of water running through the excelsior, was blown over the heating coils and circulated in the chamber passing out a tube in the opposite end of the chamber (K in Figure I). This air at the exit tube had a velocity of 6 miles per hour. The heater coils were attached to a relay (I in Figure I) which was attached to a thermostat in the chamber (H in Figure I) having an accuracy of -2° C. Eight 300-watt Mazda lamps were used for a light source. These bulbs were put in aluminum photoflood reflectors, as this type was found to give about 50 per cent more reflection than any other kind tried. These reflectors (A in Figure II) were arranged on movable stands (C in Figure II), four to a stand. All light which entered the chamber passed through the water baths which removed a large portion of the infra-red rays. These lights were cooled by three 10-inch electric fans (B in Figure II) which also aided in cooling the water baths. To vary the light intensity the stands holding the reflectors were moved either up or down into positions designated 1, 2, 3, 4, 5 or 6 of Table IV, thus varying the distance of the lights from the plants. All light measurements were made with a G.M. photo-electric cell and measured in foot candles. Each figure in Table IV is an average of five measurements taken at five different points on a plane at the stated distance from the light source.

These intensities were checked at two week intervals, as the Mazda lamps were found to deteriorate after a short time. To obtain low light intensities a ground glass plate was put between the light source and the



A - Humidifier
B - Electric Fan
C - 600 wt. Heater Coils
D - Water Intake
E - Wooden Box
4' x 3'2" x 2'4"
F - Glass bottom
water bath
G - Metal Flat
2' x 1'6" x 6"
H - Thermostadt
I - Magnetic Cutoff
J - Tube leading to
$2\frac{1}{2}$ gallon bottle
K - Air exit
L - Partition wall

Fig. 2. Diagram of Apparatus Excepting Light Arrangement

A - Humidifier
B - Electric Fan
C - 600 wt. Heater Coils
D - Water Intake
E - Wooden Box
4' x 3'2" x 2'4"
F - Glass bottom water bath
G - Metal Flat
2' x 1'6" x 6"
H - Thermostadt
I - Magnetic Cutoff
J - Tube leading to 2½ gallon bottle
K - Air exit
L - Partition wall

Fig. 2. Diagram of Apparatus Excepting Light Arrangement

water bath. This reduced the light intensity but had very little effect on the quality of light falling on the plants. With the above lighting arrangement light intensity could be varied from 350 F.C. to 1700 F.C.

The method of measuring transpiration used in this chamber was actually a measure of absorption. Kramer (11) found that the rate of intake of water was determined by the amount of transpiration. Changes in transpiration, however, usually preceded changes in absorption by from 2 to 4 hours.

Two steel flats (G in Figure I), 2' x 1'6" x 6", were placed in the chamber. These were later replaced by four flats having the same total area and constructed similarly. The bottom of these flats had a 1" slope to the middle at which point was fastened a copper drain tube. The inside of the flats was coated with neutral asphalt to prevent action of the nutrients on the metal and filled with washed gravel, 1/4" - 1/8" diameter. Three-gallon bottles containing nutrient solution were connected to the drain tubes of these flats. The bottles were connected in such a manner that compressed air could be forced in all bottles from one source. Potted plants were washed free from soil and planted in gravel. This method was later changed as the transplants were very slow in starting growth. The later method was to wrap the plant roots and soil in burlap and plant the entire mass. Nutrient solution was then forced into the gravel flats by compressed air twice daily and allowed to drain back. That amount of solution which was absorbed by the plants from the gravel obviously failed to drain back and was a measure of transpiration. Glass wool was used to cover the top of the gravel to prevent excessive evaporation. The glass wool was found to reduce evaporation from the exposed

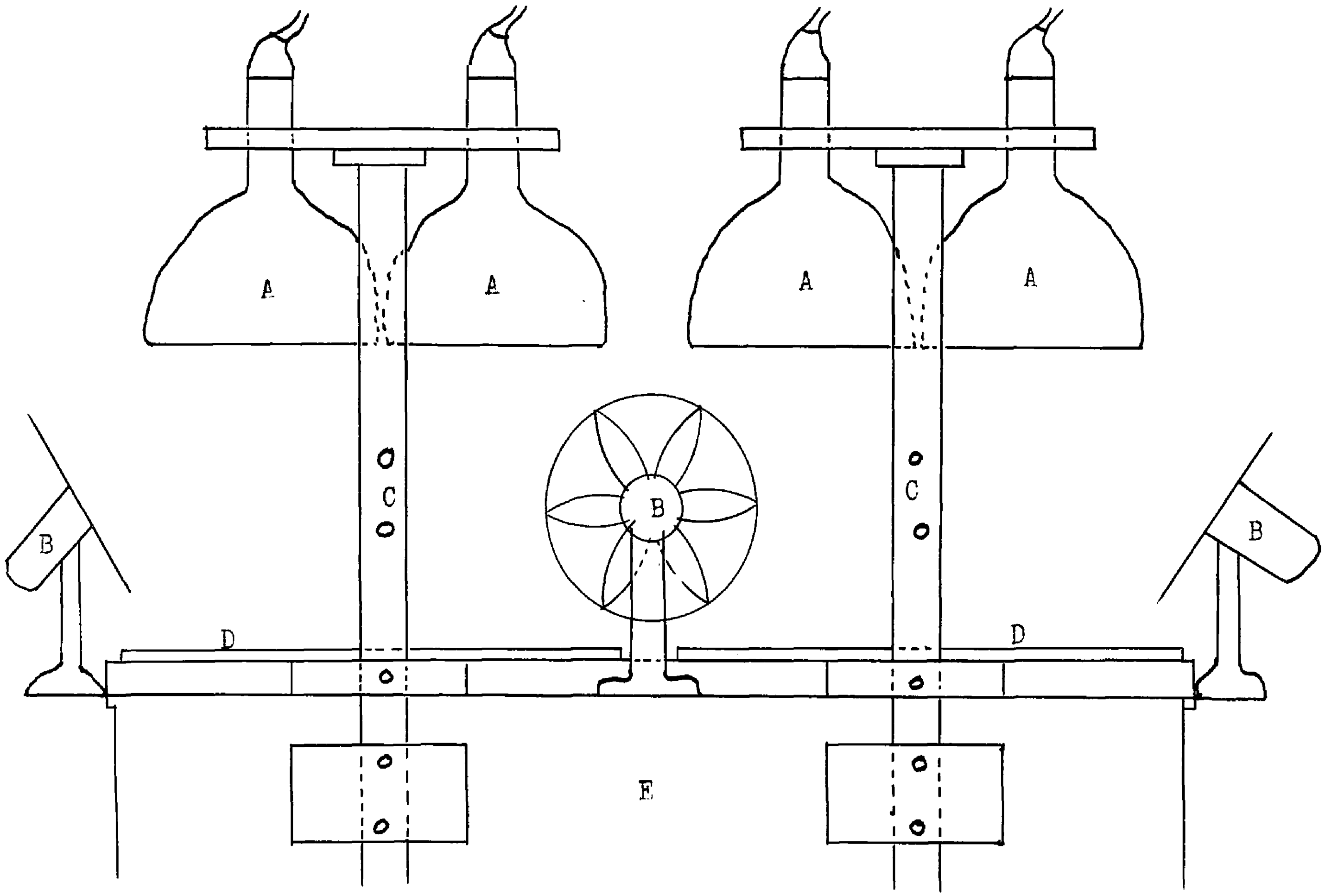


Fig. 3. Diagram of Light Arrangement

A - 16 in. Photoflood Reflectors

B - 10 in. Electric Oscillating Fans

C - Movable Stand for Lights

D - Water Bath with Glass Bottom

E - Constant Temperature Box

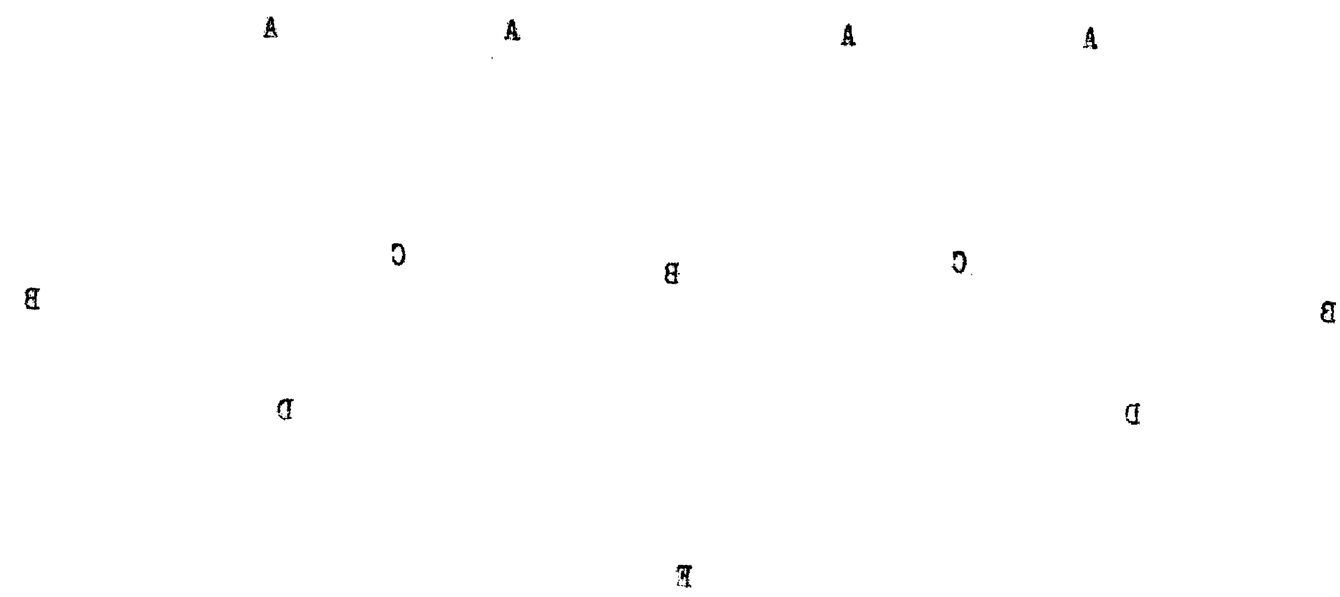


Fig. 5. Diagram of Light Arrangement

A - 16 in. Photoflood Reflectors

B - 10 in. Electric Oscillating Fans

C - Movable Stand for Lights

D - Water Bath with Glass Bottom

E - Constant Temperature Box

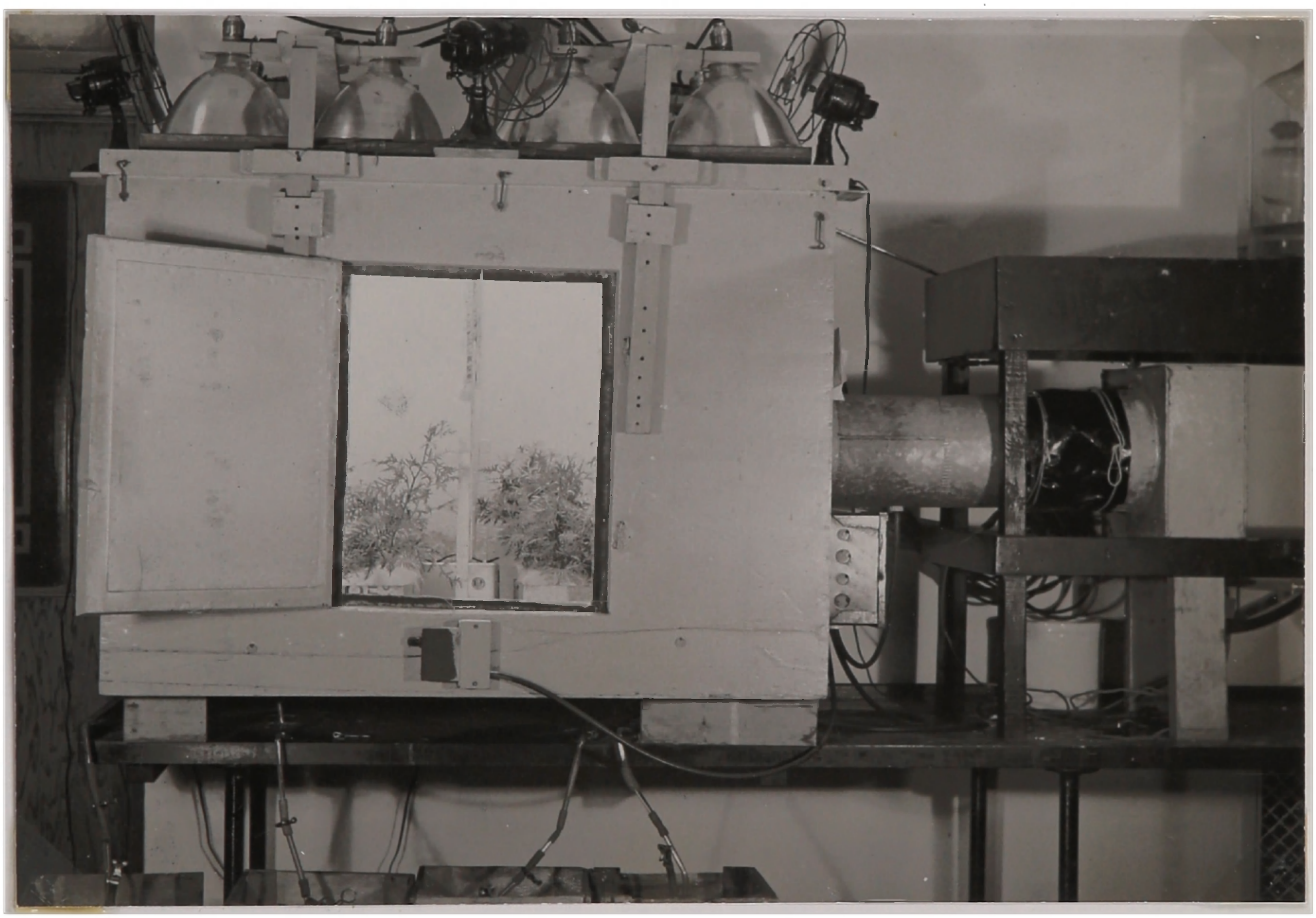


Fig. 3. Constant Conditions Apparatus used to test the effect of light on transpiration

Table IV. Light Intensities as Measured in Foot Candles at Varying Distances from Light Source

Plot 1

Position of Reflectors	1	2	3	4	5	6
Distance in inches from light source	Intensity in foot candles as measured by photo-electric cell					
30	850 *	630*	495 *	515 *	460 *	282 *
24	990	855	660	585	565	309
20	1130	910	750	660	650	334
16	1160	990	860	750	710	377
12	1355	1125	1005	885	860	425
8	1595	1330	1215	1075	970	595
4	1720	1590	1500	1290	1190	680

Plot 2

30	900	625	575	545	480	272
24	1085	810	715	630	565	300
20	1155	860	800	695	660	334
16	1160	970	890	775	720	375
12	1315	1085	1005	895	810	415
8	1640	1240	1155	1025	950	545
4	1700	1495	1385	1265	1165	630

* Each of these values is an average of five measurements made at different points in the chamber.

gravel surface from 75 to 80 per cent.

With the apparatus described above light could be closely controlled and fairly constant temperature and humidity could be maintained, as may be seen from Figure 4.

To determine if increased light intensity caused increased leaf temperatures, measurements were made with thermocouples. One point of the couple was attached to a leaf under high intensity and the other point to a leaf under low intensity which gave only the difference in temperature rather than the actual temperatures of each leaf. These points were fastened to the epidermis of the leaves by "Scotch tape." This caused no injury to the leaves as does the older method of sticking the points under the epidermis. The deflections of the galvanometer were recorded and converted to degrees C difference. Table V shows that, regardless of light intensity, no consistent difference in temperature was recorded.

In those cases where stomatal measurements were made, a Leitz Ultra-Pak was used. The stomata were measured directly on the living leaves. This method was preferable to the alcohol strip method as the stomatal aperture may change when fixed in Chrom-Acetic or similar type of killing solution.

The apparatus which has been described (pp. 15-25) was found to be very useful in studying plant reactions under constant conditions. From Tables IV and V and Figure 4 it may be seen that light intensity and temperature were controlled within very narrow limits. The relative humidity was controlled except during extreme weather changes. During long periods of rainy weather the humidity would rise as much as 20 per

Table V. Leaf Temperature Differences as Determined by a Thermocouple

Plants - Peaches - Constant Conditions Chamber

Flat I - 1600 F. C. Flat II - 1000 F.C.

Time	Air Temp. I in degrees c.	Air Temp. II in degrees c.	Leaf temp. difference in degrees c.	Remarks
6:30 PM	30.5	30.7	0	No lights
10:30 PM	30.5	30.6	0	Lights on
8:30 AM	31.0	31.2	#1 = .25° warmer	"
9:00 AM	31.0	31.2	0	"
10:00 AM	31.4	31.5	#2 = .50° warmer	"
10:30 AM	31.4	31.5	0	"
10:45 AM	31.4	31.5	0	No lights

Plants - Catalpa - Constant Conditions Chamber

Flat I - 1600 F.C. Flat II - 350 F.C.

Time	Air Temp. I in degrees c.	Air Temp. II in degrees c.	Leaf temp. difference in degrees c.	Remarks
6:30 PM	31.0	31.6	0	No lights
7:30 PM	31.0	31.5	0	"
8:30 PM	30.0	30.2	#2 = .25° warmer	Lights on
9:30 PM	30.0	30.2	#1 = .25° warmer	"
10:30 PM	31.0	30.8	#2 = .50° warmer	"
11:30 PM	31.0	30.8	0	"
8:00 AM	30.5	30.7	0	"
9:00 AM	30.7	30.6	#2 = .25° warmer	"
10:00 AM	30.7	30.6	#2 = .25° warmer	"
10:30 AM	31.0	31.2	0	"
11:00 AM	31.0	31.5	0	No lights

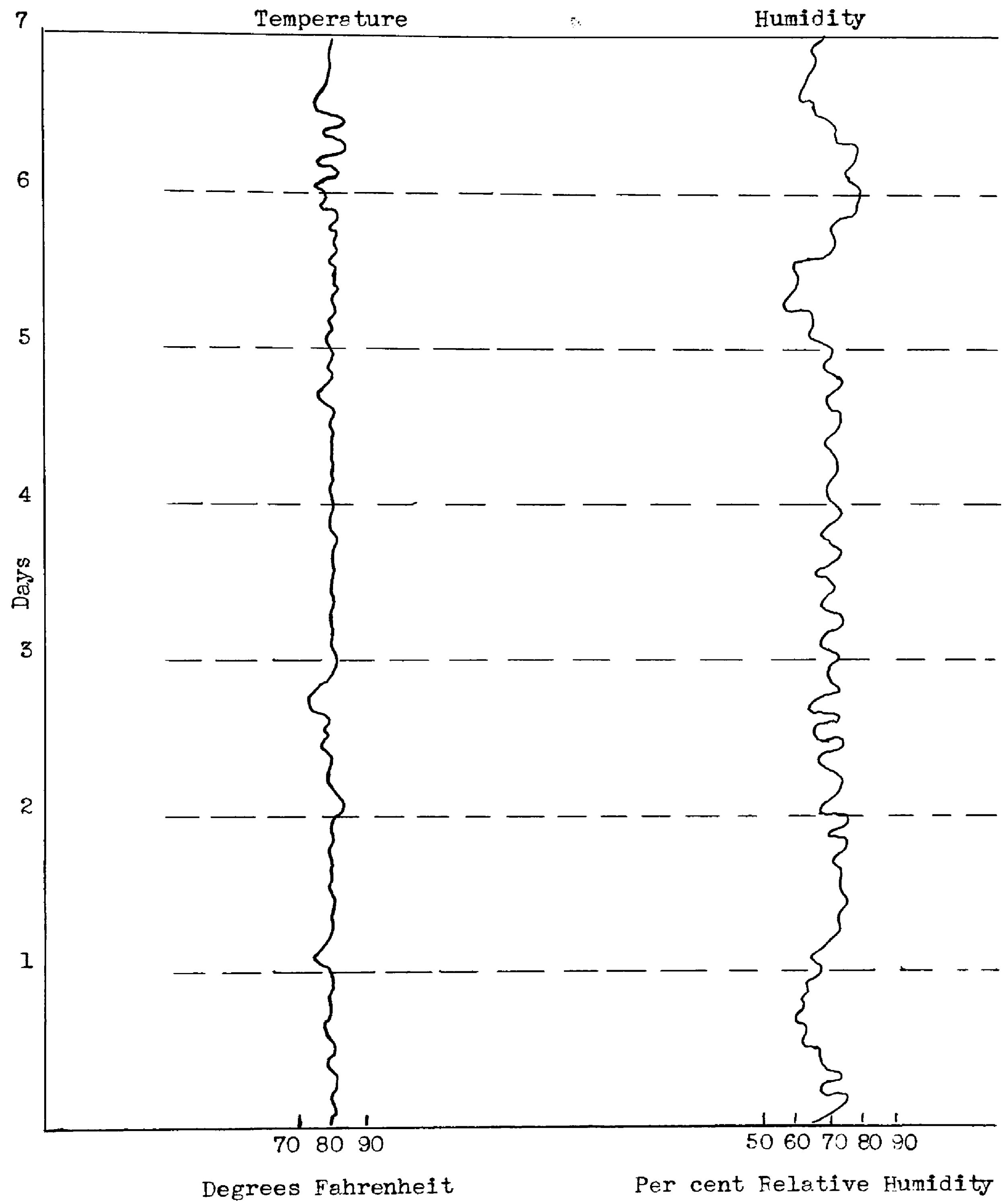


Figure 4. Chart taken from Hygrothermograph showing temperature and humidity in chamber for seven days.

7 Temperature Humidity

6

5

4

3

2

1

70 80 90 50 60 70 80 90

Degrees Fahrenheit Per cent Relative Humidity

Figure 4. Chart taken from Hygrothermograph showing temperature and humidity in chamber for seven days.

cent. This amount, however, was not enough to disrupt transpiration studies.

The light intensity attained on each side of the chamber was practically equal when the distance from the light source was equal. In no case was the difference in intensity over 100 foot candles. Differences which were this great were at high intensities where the accuracy of the photo-electric instrument used in this study becomes a factor to be considered. At low intensities the difference in light between the two sides was negligible. No chlorosis appeared even when plants were grown under the Mazda lamps for 8 weeks. Spindly growth resulted, however, since this light source was very strong in the red end of the spectrum and weak in blue and violet. This weakness could probably be overcome if mercury vapor lamps, complete spectrum carbon arc lamps, or some other type having a more complete spectrum than the ordinary Mazda lamp had been used.

The method of measuring transpiration used in this apparatus was found to be rapid and accurate when large numbers of plants were used. Better results were obtained when plants whose transpiration was over 300 c.c. per flat were tested. For those plants which lose very little water, such as conifers, a large number of plants per flat should be used.

Method

The general method of procedure used to determine the effect of light on transpiration was as follows: The plants to be tested were planted in the metal flats and allowed to grow in the greenhouse until they had overcome the setback from transplanting. The metal flats were then moved into the constant conditions chamber and the leaves were counted. The leaf count was used in determining the total area of transpiring surface. Transpiration measurements were then made with the light intensity on each side of the chamber equal. These measurements were continued for four or five days until the ratio between the transpiration of the two sides was constant. Then the light intensity on one side of the chamber was changed and the transpiration measurements were made for three days. The light intensities were then changed every three days and records were kept of the transpiration of each flat. Three control periods were made in each experiment by having the light intensity equal throughout the chamber and comparing the transpiration of the flats. These periods were spaced so as to have one at the beginning, one in the middle and one at the end of each experiment. One flat could not be kept under a constant light intensity during the entirety of the experiment and used as a check flat because large differences in the growth occurred unless the total light given each flat was approximately equal. In all cases humidity and temperature were kept constant during each experiment and the plants were given 15 hours of light and 9 hours of darkness. Leaf counts were made at three to four day intervals and at the end of the experiment leaf areas were obtained from these. In the case of the California Privet and Maiden Hair fern the areas of 300 representative leaves were measured and the total area obtained by the leaf counts. No effort was made to obtain leaf area in the Arbor Vitae. In all other cases the total area was measured after the experiment was finished and the areas during the experiment were calculated from the leaf counts.

Stomatal measurements were made only on those plants having large and unobstructed stomata. Measurement of very small stomata or of those having obstructed perimeters was not attempted, as the accuracy of the Leitz Ultra-Pak method is questionable under these conditions and the alcohol strip method was not feasible in this case. The stomata were measured by putting an entire leaf under the Ultra-Pak and measuring the stomatal aperture on both the upper and lower leaf surfaces. Twenty-five measurements were made in each case. At no time was more than ten minutes allowed to elapse between the time the leaves were taken from the chamber and the stomatal measurements were made. This was done to prevent a change in the stomatal opening after removing the plant from the chamber.

The chief trouble found in using this method for measuring stomatal apertures is that the perimeter of the stomata is difficult to distinguish due to the structure of the guard cells and other surrounding tissue which obstruct the view.

Presentation of Data

In the following tables, wherever feasible, transpiration measurements are given in cubic centimeters of water lost per square inch of leaf surface. The water loss of the petioles and stems was considered too small to change the transpiration trends as indicated by the leaf blade areas. All light measurements are given in foot candles and calculated as percentage reduction of the lower light intensity from the higher light intensity. Transpiration reduction was calculated as percent, by comparing the ratios of the transpiration of each flat when under different light intensities to that when they were at the same intensity. The average of these ratios was obtained by use of the geometric mean.

Experiment I

Forty Michigan State Forcing tomato (Lycopersicon esculentum) plants about six inches high were planted in two metal flats after the soil had been washed from their roots. Daily transpiration records were kept for 12 days, by which time the leaf area had approximately doubled. A temperature of 80° F. and a relative humidity of 65 per cent was maintained throughout the experiment and the light intensities tested were 725, 1060 and 1085 foot candles. Transpiration data are presented in Table VI and shown graphically in Figure 5.

The transpiration of tomato plants, data of Table VI, was found to decrease with a reduction of light. The wide variance in the transpiration reduction is probably due to the short length of this test and to differences in growth of the two lots.

Experiment II

In this test 50 bean (Phaseolus vulgaris) plants of the Ruby Dwarf Horticultural variety were employed. They were 12 days old and

Table VI. Influence of Light Intensity on Transpiration Rate in the Tomato

Experiment I. Temperature 80° F. : Relative Humidity 65 per cent :

20 plants under each treatment : Duration of test - 12 days.

Lot I		Lot II				
Light intensity in foot candles	Average daily transpiration of 3 day period in c.c.	Light intensity in foot candles	Average daily transpiration of 3 day period in c.c.	Ratio of average daily transpiration of Lot I and II II/I	Light reduction in percent	Transpiration reduction by reduction of light in percent
1060	615	1085	638	.96		
1060	683	725	628	.91	33.2	1.0
1060	836	1085	723	.87		
1060	773	725	518	.67	33.0	26.5

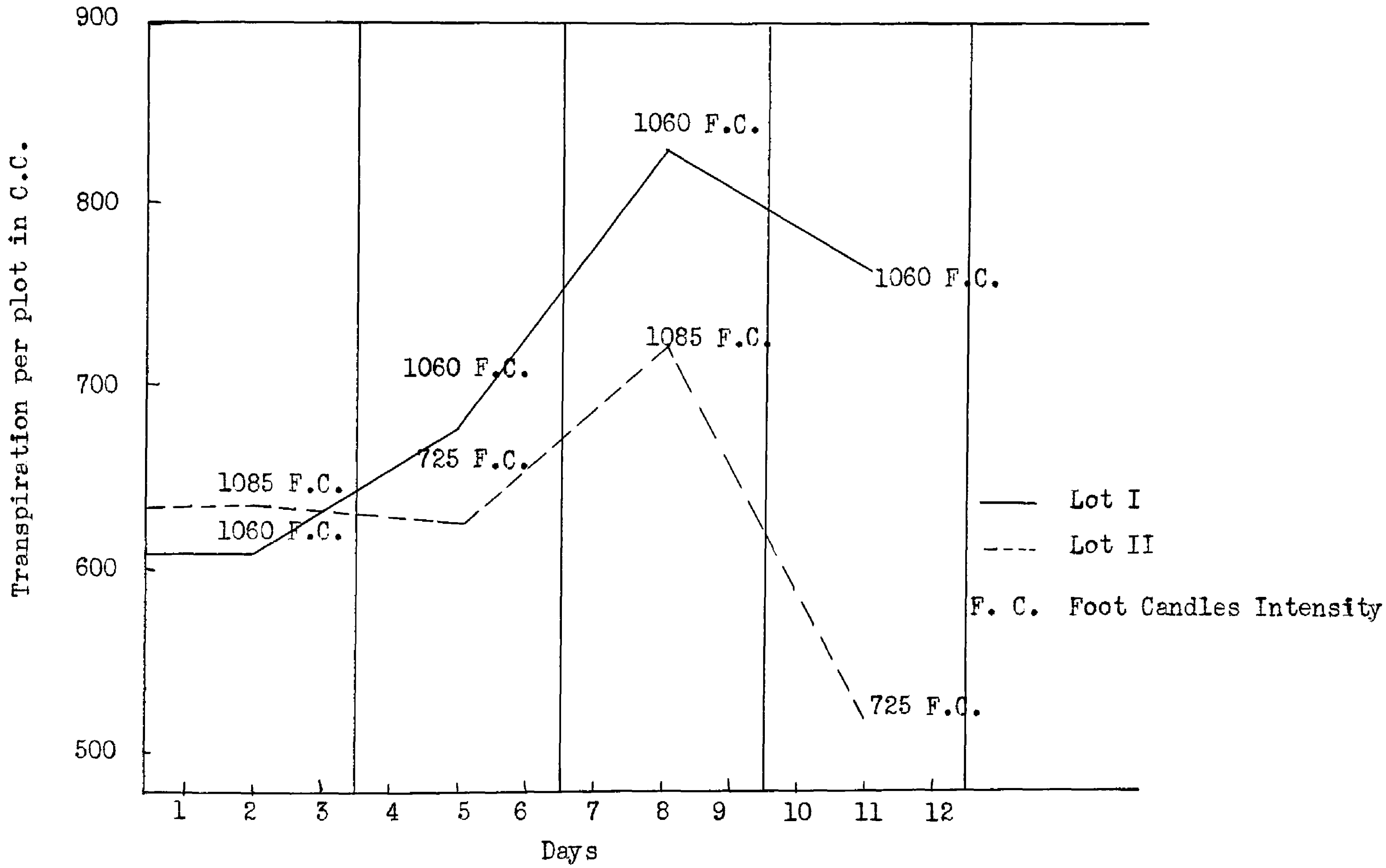


Fig. 5. Influence of Light Intensity on Transpiration Rate in Tomato

Experiment I. Temperature 85° F. : Relative humidity 65 per cent

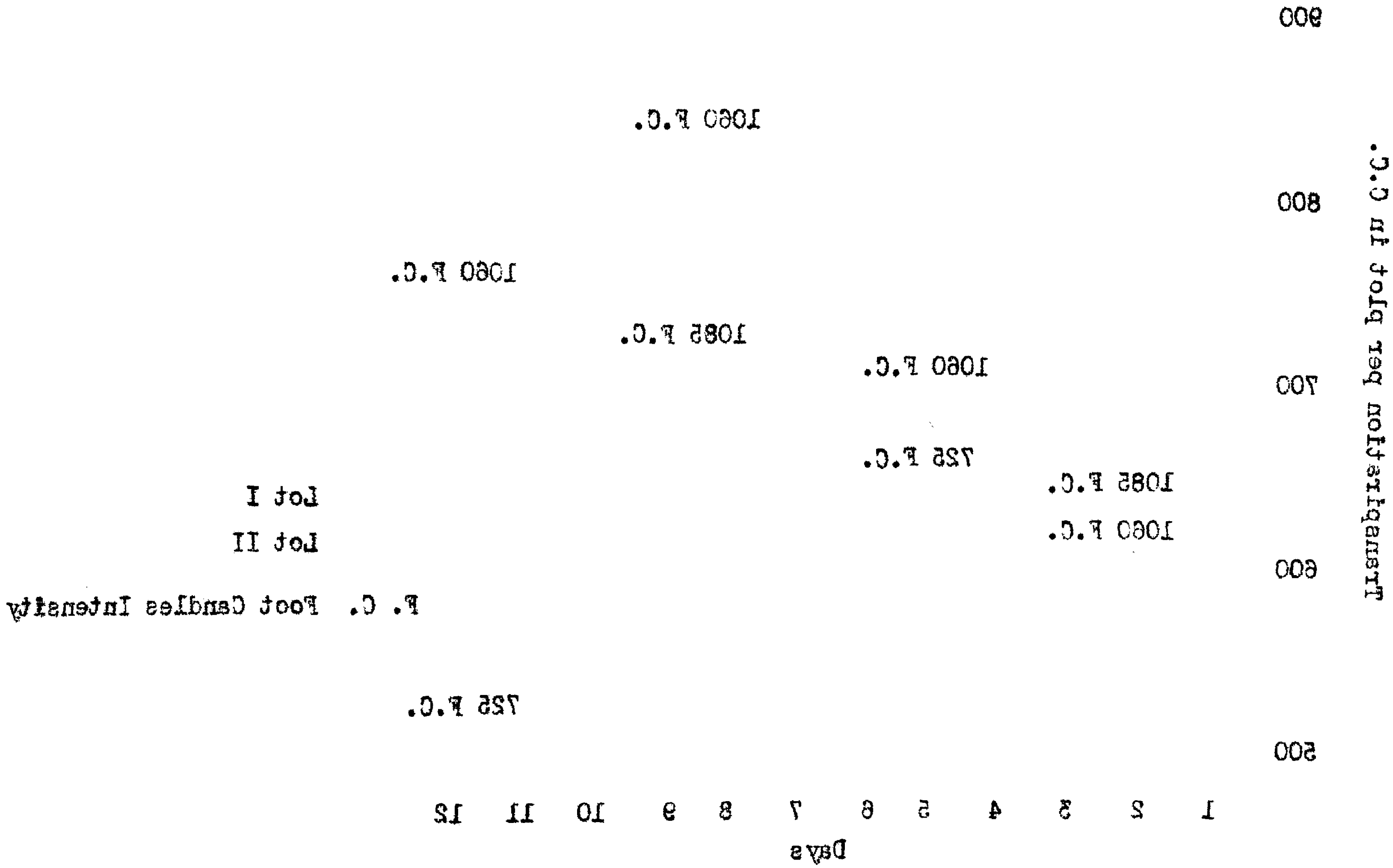


Fig. 5. Influence of Light Intensity on Transpiration Rate in Tomato

Experiment I. Temperature 85° F. : Relative humidity 65 per cent averaged about four leaves at the time the test was started. As in Experiment I with tomatoes, a temperature of 80° F. and a relative humidity of 65 per cent was maintained and light intensities were varied from 720 to 1355 foot candles. The experiment was continued for 18 days, by which time the plants averaged about 8 leaves and had twice the original area. Transpiration data are presented in Table VII and shown graphically in Figure 6.

As may be seen in Table VII the data of this investigation showed that transpiration of the bean plant varied directly with the light intensity striking the plant. As in Experiment I, the gradual rise of the transpiration corresponded to the increase in leaf area due to the growth of the plants.

Experiment III

In Experiment III 50 may apple (Podophyllus peltatum) plants were tested. They were about two weeks old, contained one and two leaves and had an average height of 14 inches. They were tested at a temperature of 70° F. and a relative humidity of 70 per cent, given light ranging from 334 foot candles to 1155 foot candles in intensity and the experiment lasted for 21 days. Stomatal measurements under different light intensities were taken and the results are shown in Table XVI. At the end of the experiment, leaf areas were measured and the transpiration per square inch was obtained for the entire trial as the leaves of the may apple had grown very little during the test. The transpiration measurements are recorded in Table VIII and are shown graphically in Figure 7.

Table VII and Figure 7 show that with may apple, just as with tomato and bean, transpiration when plotted against light intensity would give a straight line curve. The stomatal aperture as well as transpiration paralleled the light intensity.

Table VII. Influence of Light Intensity on Transpiration Rate in the Horticultural Bean

Experiment II. Temperature 80° F. : Relative humidity 65 per cent :

25 plants under each treatment : Duration of test - 18 days.

Lot I		Lot II					
Light intensity in foot candles	Average daily transpiration of 3 day period in c.c.	Light intensity in foot candles	Average daily transpiration of 3 day period in c.c.	Ratio of average daily transpiration of Lot I and II II/I	I/II	Light reduction in per cent	Transpiration reduction by reduction of light in percent
990	393	970	412	1.05	.95		
1300	406	720	268	.66	1.51	44.6	32.0
990	453	970	416	.92	1.09		
860	453	810	436	.96	1.04		
1355	712	810	495	.70	1.44	40.2	27.8
860	607	810	540	.96	1.05		

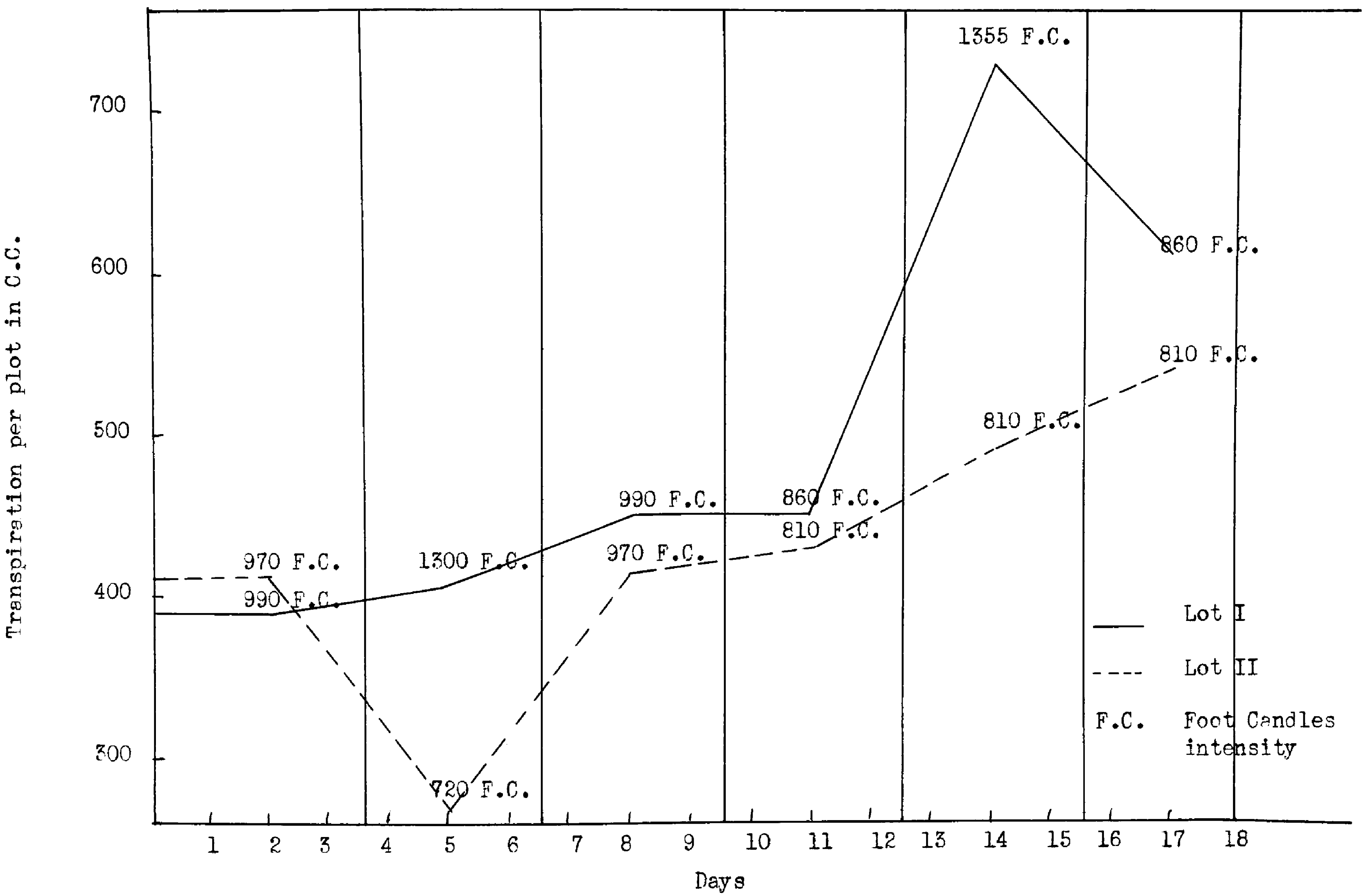


Fig. 6. Influence of Light Intensity on Transpiration Rate in Horticultural Bean

Experiment II. Temperature 85° F. : Relative humidity 65 per cent

Experiment II. Temperature 85° F. : Relative humidity 65 per cent

Fig. 6. Influence of Light Intensity on Transpiration Rate in Horticultural Bean

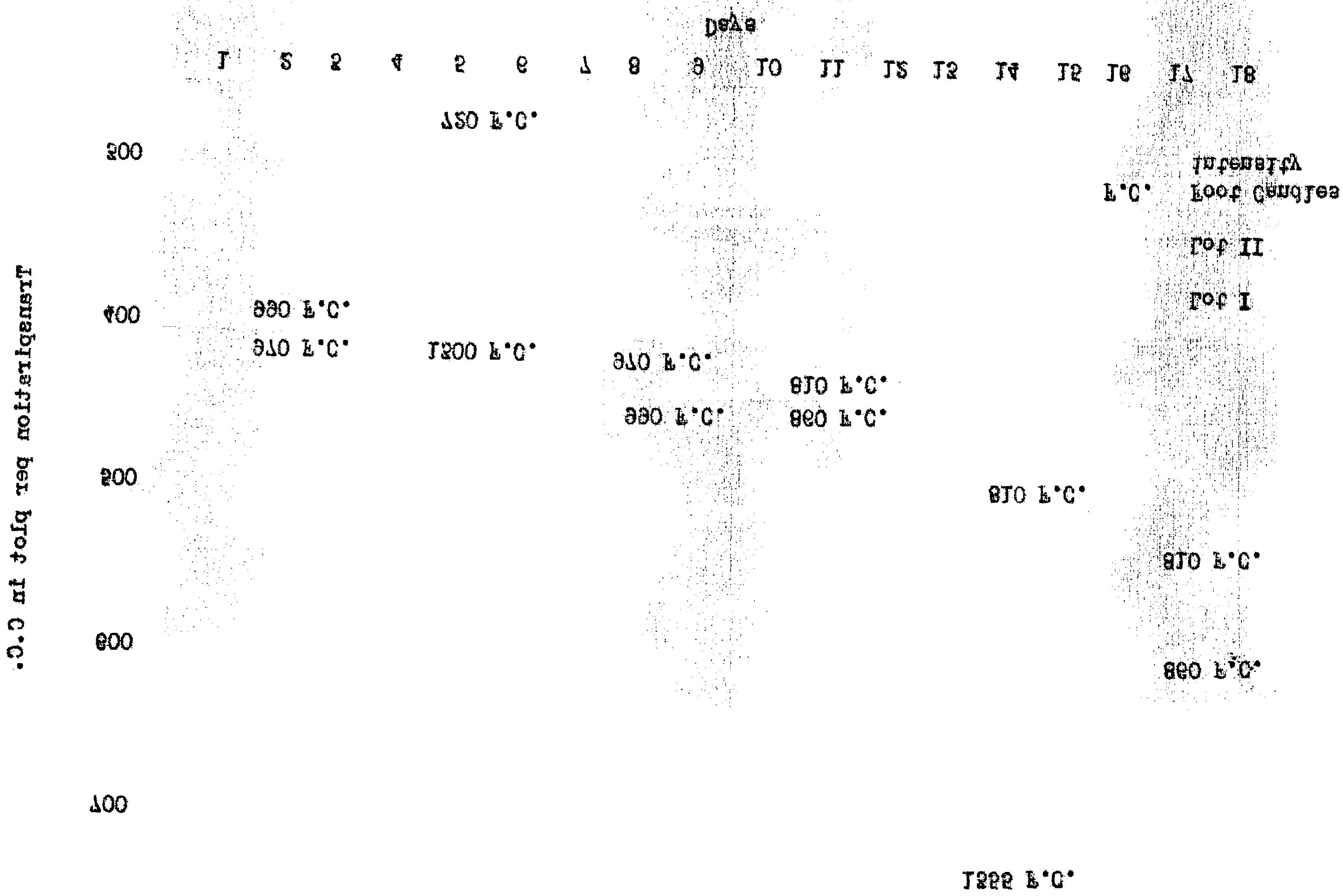


Table VIII. Influence of Light Intensity on Transpiration Rate in the May Apple

Experiment III. Temperature 70° F. : Relative humidity 70 per cent :

25 plants in each treatment averaging 885 sq. inches leaf area per lot :

Duration of test - 21 days.

Lot I			Lot II			Ratio of average daily transpiration per sq. in. of Lot I and II			
Light intensity in foot candles	Average daily transpiration of 3 day period in c.c.	Average daily transpiration per sq. in. in c.c.	Light intensity in foot candles	Average daily transpiration of 3 day period in c.c.	Average daily transpiration per sq. in. in c.c.	II/I	I/II	Light reduction in percent	Transpiration reduction by reduction of light in per cent
334	177	.188	334	119	.144	.77	1.31		
650	229	.243	334	154	.186	.77	1.31	48.6	13.5
650	253	.269	660	212	.256	.84	1.05		
650	210	.223	1155	262	.317	1.42	.70	43.7	35.2
1130	260	.276	1155	234	.283	1.03	.98		
1130	280	.298	334	160	.193	.65	1.54	70.4	43.0
1130	288	.306	1155	248	.300	.98	1.02		

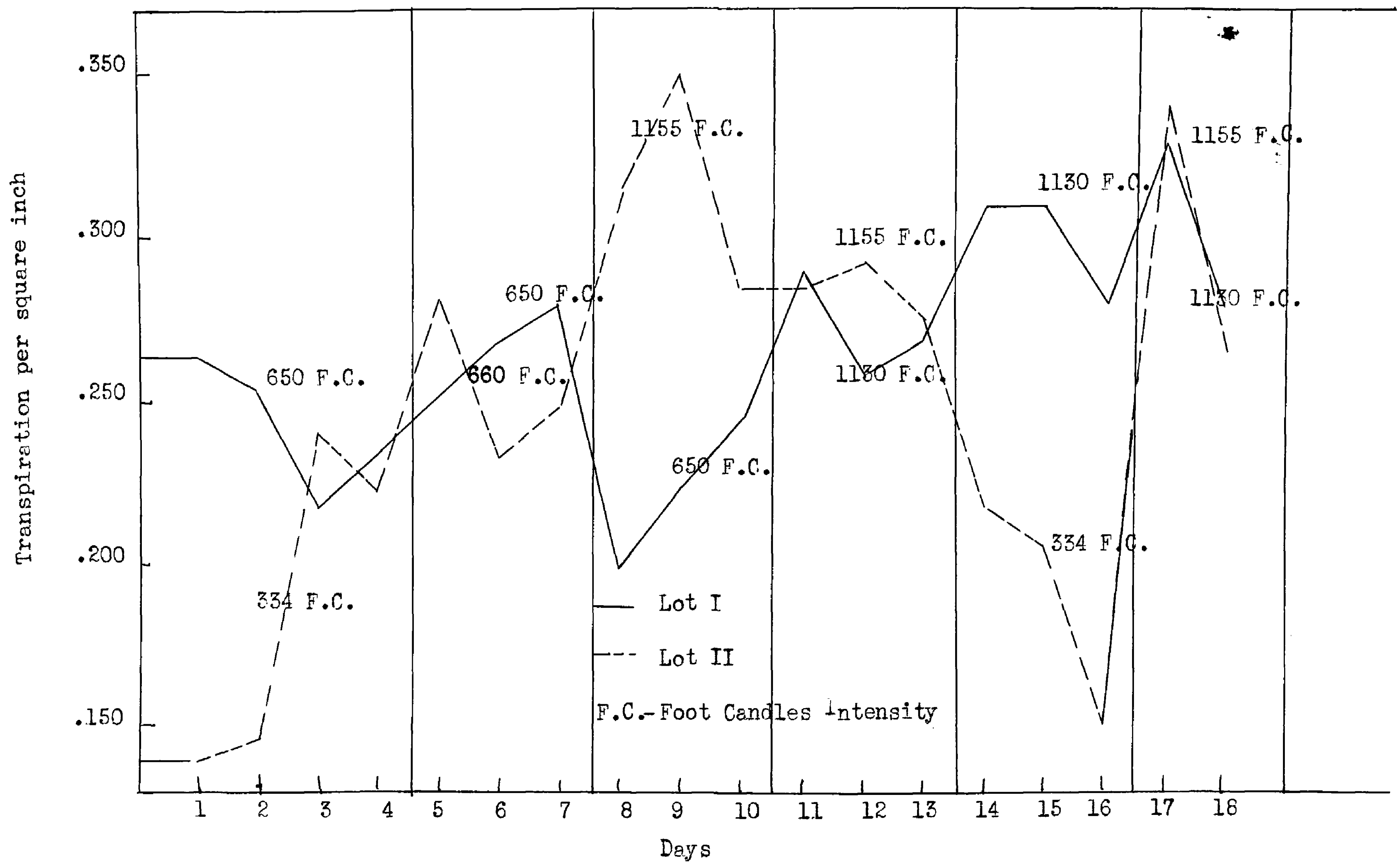


Fig. 7. Influence of Light Intensity on Transpiration Rate in May Apple

Experiment III. Temperature 85° F. : Relative humidity 65 per cent

Transpiration per square inch

.350

.300

.250

.200

.150

1155 F.C.

1155 F.C.

1130 F.C.

1155 F.C.

1130 F.C.

650 F.C.

1130 F.C.

660 F.C.

650 F.C.

650 F.C.

554 F.C.

554 F.C.

Lot I

Lot II

F.C.-Foot Candles Intensity

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

Days

Fig. 7. Influence of Light Intensity on Transpiration Rate in May Apple

Experiment III. Temperature 85° F. : Relative humidity 65 per cent

Experiment IV

In this test 30 Elberta peach (Prunus Persica) seedlings four months old, 16 inches high and with an average leaf area of about 1200 square inches per lot were used. They were tested at a temperature of 80° F., a relative humidity of 70 per cent and at light intensities ranging from 545 to 1720 foot candles. Transpiration measurements were taken daily for 27 days. Leaf area measurements were taken at the end of this test and the area averaged about 2200 square inches per lot. Transpiration data are shown in Table IX and graphically in Figure 8. Stomatal measurements were made under different light intensities and the data are shown in Table XVI.

This test showed that with peaches, as with the other plants tested, transpiration reduction was directly proportional to the light reduction. Tables IX and XVI show that light intensity, transpiration, and stomatal aperture run parallel with each other.

Experiment V.

Twenty-four catalpa (Catalpa speciosa) seedlings two years old, 16 inches high and averaging 2100 square inches leaf area per lot were tested. A temperature of 80° F. and a relative humidity of 85 per cent were maintained and the light intensity was varied from 545 to 1700 foot candles. This experiment lasted for 15 days by which time the leaves had increased in area to an average of 2500 square inches per lot. Table X and Figure 9 show the transpiration data obtained during this study.

Transpiration in catalpa as in other plants tested, was directly proportional to the light intensity.

Table IX. Influence of Light Intensity on Transpiration Rate in the Peach

Experiment IV - Temperature 70^{o} F. : Relative humidity 70 per cent : 15 plants per treatment averaging 2275 sq. inches leaf area per plot : Duration of test - 27 days.

Lot I				Lot II							
Light intensity in foot candles	Leaf area in sq. in.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration per sq.in. in c.c.	Light intensity in foot candles	Leaf area in sq.in.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration per sq. in. in c.c.	Ratio of average daily transpiration per sq. in. of Lot I and II II/I	I/II	Light reduction in percent	Transpiration reduction by reduction of light in percent
710	1373.6	375	.273	720	1170.3	309	.264	.97	1.03		
710	1542.9	464	.301	1160	1304.3	562	.431	1.43	.70	38.8	34.0
1355	1667.8	698	.419	1315	1442.9	447	.310	.74	1.39		
1595	1839.8	765	.416	545	1562.8	277	.177	.43	2.35	65.8	54.7
595	1864.8	369	.198	545	1633.3	376	.230	1.16	.86		
595	1995.2	443	.222	1155	1769.6	615	.348	1.57	.64	48.5	39.6
1500	2117.3	787	.372	1385	1882.4	653	.347	.93	1.07		
1720	2245.0	1123	.500	1385	2016.3	803	.398	.80	1.26	19.5	15.8
1720	2275.8	1095	.481	1700	2124.1	1007	.474	.99	1.01		

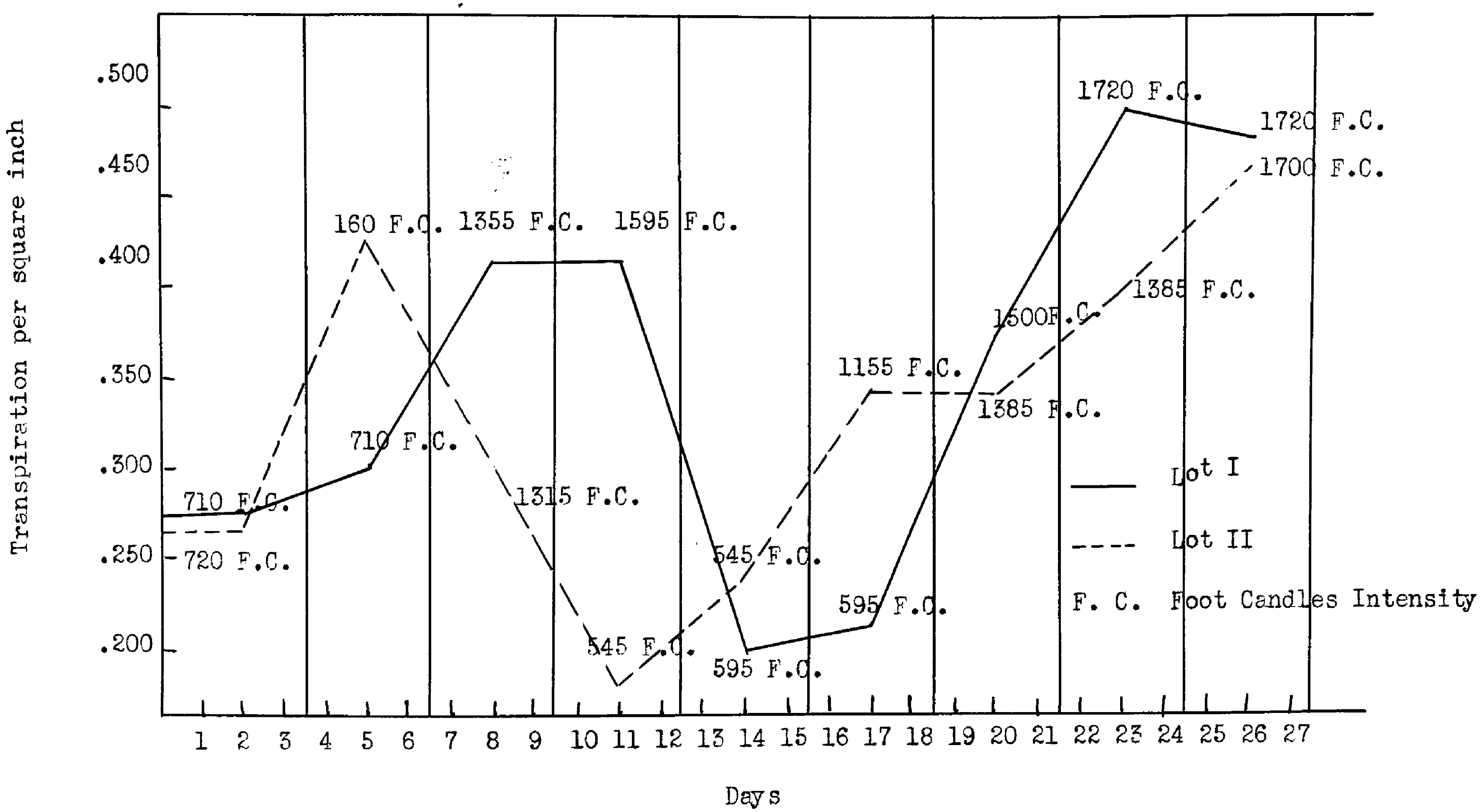


Fig. 8. Influence of Light Intensity on Transpiration Rate in the Peach

Experiment IV. Temperature 70° F. : Relative humidity 70 per cent

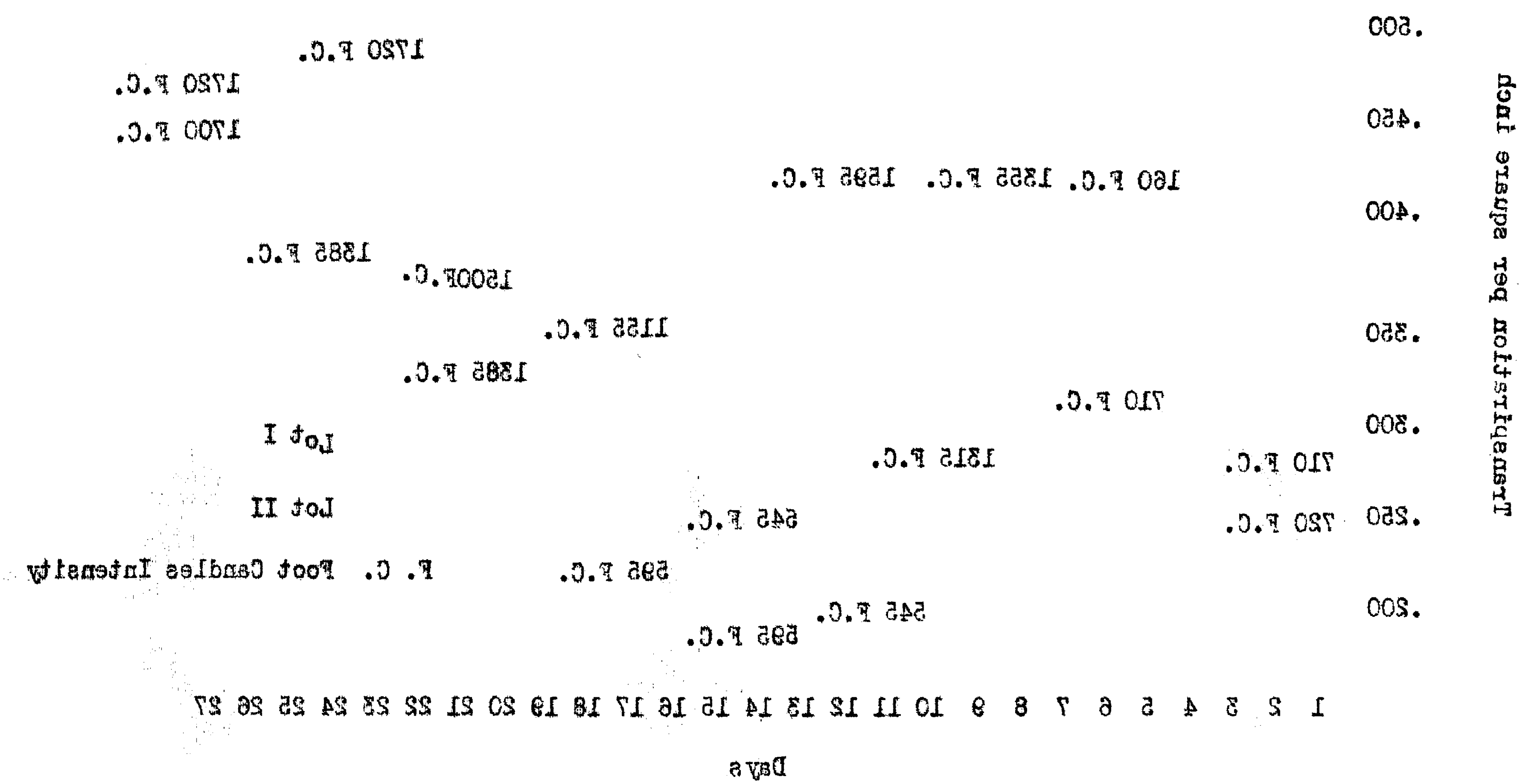


Fig. 8. Influence of Light Intensity on Transpiration Rate in the Peach

Experiment IV. Temperature 70° F. : Relative humidity 70 per cent

Table X. **Influence of Light Intensity on Transpiration Rate in the Catalpa**

Experiment V. Temperature 80° F. : Relative humidity 85 per cent : 12 plants per treatment averaging 2500 sq. inces leaf area per plot : Duration of test - 15 days.

Lot I				Lot II							
Light intensity in foot candles	Leaf area in sq.in.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration per sq.in. in c.c.	Light intensity in foot candles	Leaf area in sq.in.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration per sq. in. in c.c.	Ratio of average daily transpiration per sq. in. of Lot I and II: II/I	I/II	Light reduction in per cent	Transpiration reduction by reduction of light in percent
710	2081	607	.292	720	2163	613	.283	.97	1.03		
860	2410	912	.378	1315	2736	1125	.407	1.08	.93	34.6	17.0
1595	2485	1398	.563	545	2551	880	.345	.61	1.63	65.8	30.7
1590	2485	1058	.426	1700	2551	1083	.425	1.00	1.00	6.9	10.6
1500	2485	962	.387	1385	2551	775	.304	.79	1.27		

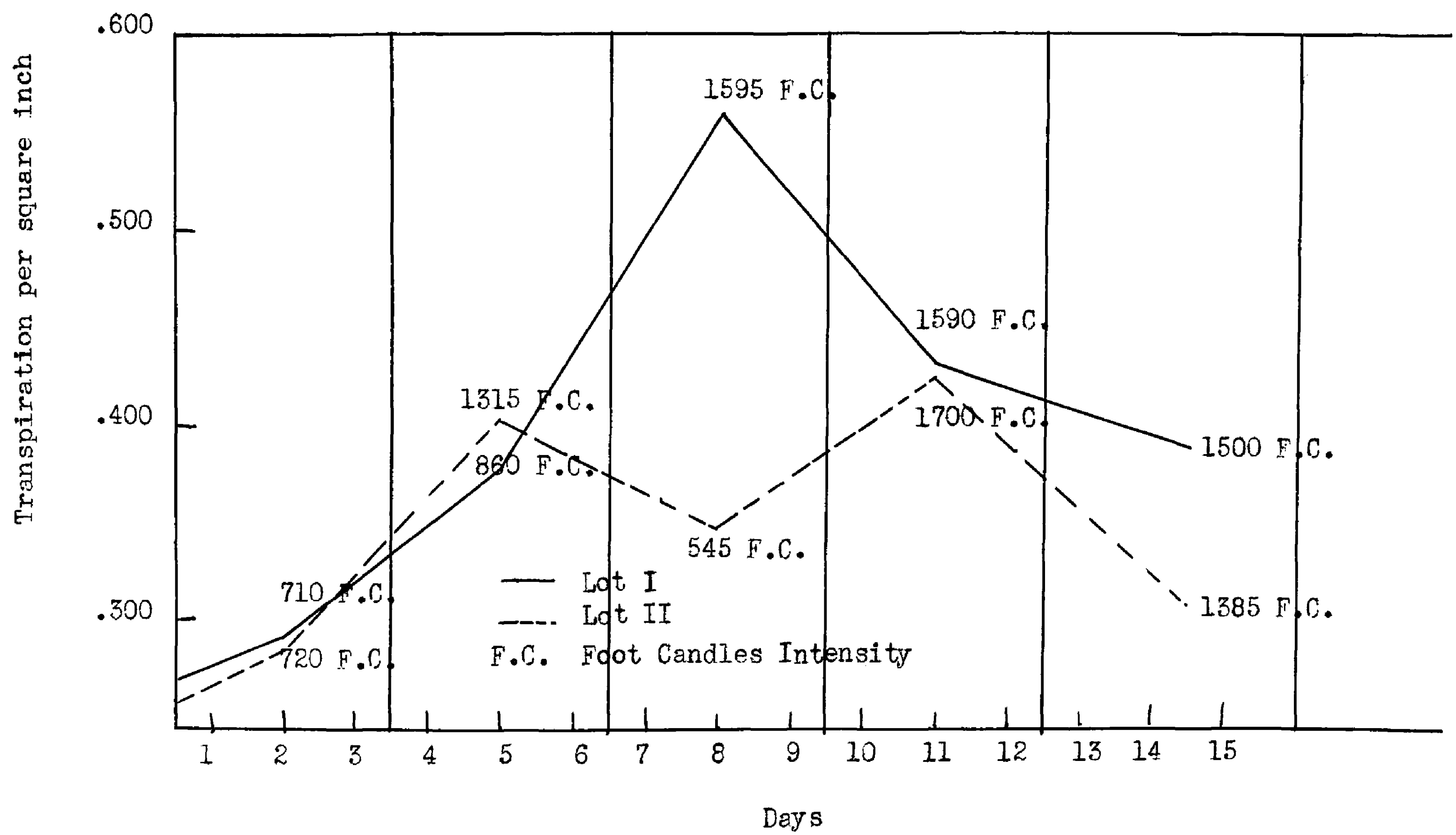


Fig. 9. Influence of Light Intensity on Transpiration Rate in the Catalpa

Experiment V. Temperature 80° F. : Relative humidity 85 per cent

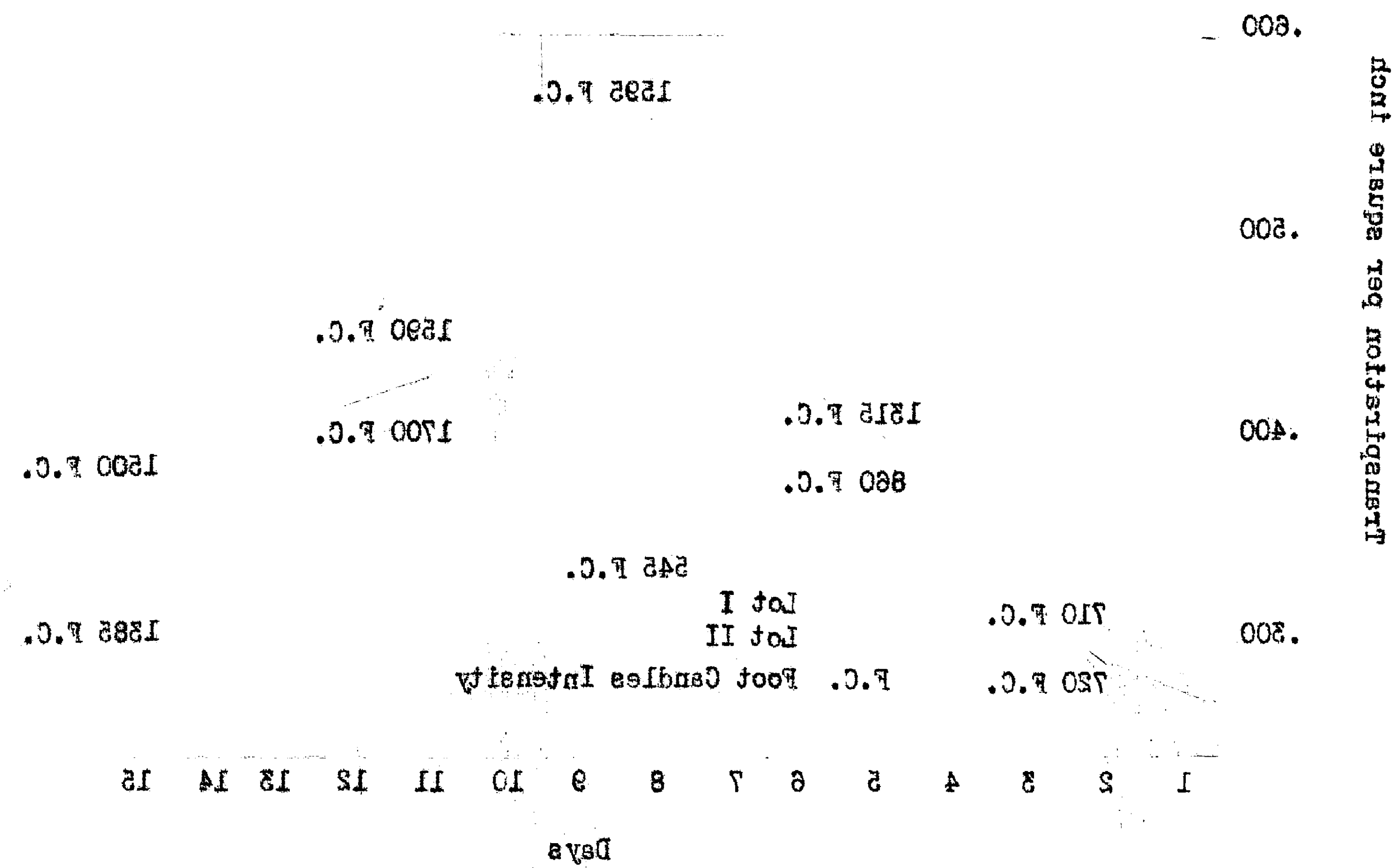


Fig. 9. Influence of Light Intensity on Transpiration Rate in the Catalpa

Experiment V. Temperature 80° F. : Relative humidity 85 per cent

Experiment VI

In this test 48 Maiden Hair fern (*Adiantum capillus-veneris*) plants averaging 8 inches in height and with an average leaf area of 390 square inches per lot were employed. They were tested at a temperature of 90° F. and a relative humidity of 85 per cent and the light intensity was varied from 334 to 1155 foot candles. Daily transpiration records were obtained for 21 days by which time the plants had attained an average leaf area of 410 square inches per lot. These transpiration data are shown in Table XI and graphically in Figure 10. Stomatal apertures were measured at different light intensities and the data are presented in Table XVI.

These data show that the transpiration of Maiden Hair fern does not run parallel with the light intensity over the entire range as with the other plants tested. Table XI shows that the maximum transpiration was at a light intensity of 600 to 800 foot candles with very little change at higher intensities. The stomatal openings, as shown on Table XVI, however, reached their maximum at 334 foot candles intensity. These data indicate that the maximum transpiration in Maiden Hair fern took place between 400 and 800 foot candles light intensity.

Experiment VII

In experiment VII, as in experiment V, 24 catalpa (*Catalpa speciosa*) seedlings, two years old, 16 inches high and averaging 970 square inches of leaf area per lot were used. A temperature of 80° F. and a relative humidity of 85 per cent were maintained and the light intensity was varied from 377 to 1130 foot candles. This experiment lasted for 24 days by which time the leaves had attained an average area of 900 square inches per lot. This reduction of leaf area was due to

Table XI. Influence of Light Intensity on Transpiration Rate in the Maiden Hair Fern

Experiment VI. Temperature 90° F. : Relative humidity 85 per cent : 12 plants per treatment averaging 780 square inches leaf area per lot. Duration of test - 21 days.

Lot I

Lot II

Flat I			Flat II			Flat III		
Leaf area in sq. in.	Average daily transpiration of 3 day period in c.c.	Average daily transpiration per sq. in. in c.c.	Leaf area in sq. in.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration per sq. in. in c.c.	Leaf area in sq. in.	Average daily transpiration of 3 day period in c.c.	Average daily transpiration per sq.in. in c.c.
399	315	.79	402	350	.87	421	300	.71
403	393	.98	402	390	.97	430	333	.77
403	376	.93	405	424	1.05	430	288	.67
406	395	.97	406	420	1.03	430	352	.82
410	487	1.19	409	450	1.10	440	408	.93
410	470	1.15	409	453	1.11	440	390	.89
410	491	1.20	409	498	1.22	440	485	1.10

Table XI - continued

Lot II

Flat IV

Leaf area in sq. in.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration per sq. in. in c.c.	Average daily transpiration per sq. in. in Lot I in c.c.	Average daily transpiration per sq. in. of Lot II in c.c.	Light intensity of Lot I in foot candles	Light intensity of Lot II in foot candles	Ratio of average daily transpiration per sq. in. of Lot I and II I/II	II/I	Light reduction in per cent	Reduction of transpiration by reduction of light in per cent
349	273	.78	.83	.75	750	1155	1.11	.90	35.1	-4.3
350	348	.99	.98	.88	1130	1155	1.11	.90		
353	278	.79	.99	.73	650	1155	1.36	.74	43.7	17.2
360	288	.80	1.00	.81	650	800	1.23	.81	18.7	6.0
360	419	1.16	1.15	1.05	650	334	1.10	.91	48.6	-5.1
360	397	1.10	1.13	1.00	1130	334	1.13	.88	70.4	-2.6
360	320	.89	1.21	1.00	1130	1155	1.21	.83		

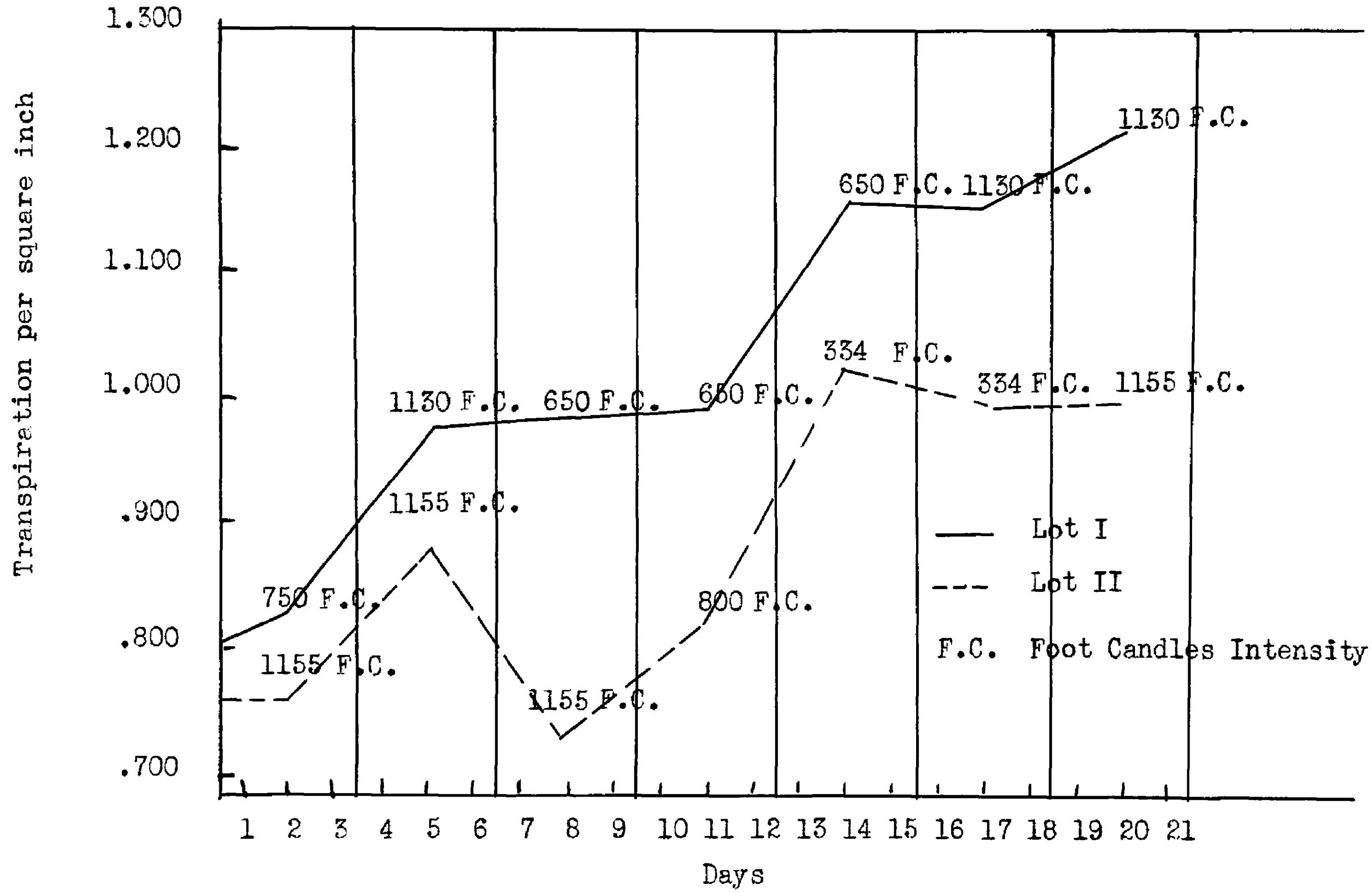


Fig. 10. Influence of Light Intensity on Transpiration Rate in the Maiden Hair Fern

Experiment VI. Temperature 90° F. : Relative humidity 85 per cent

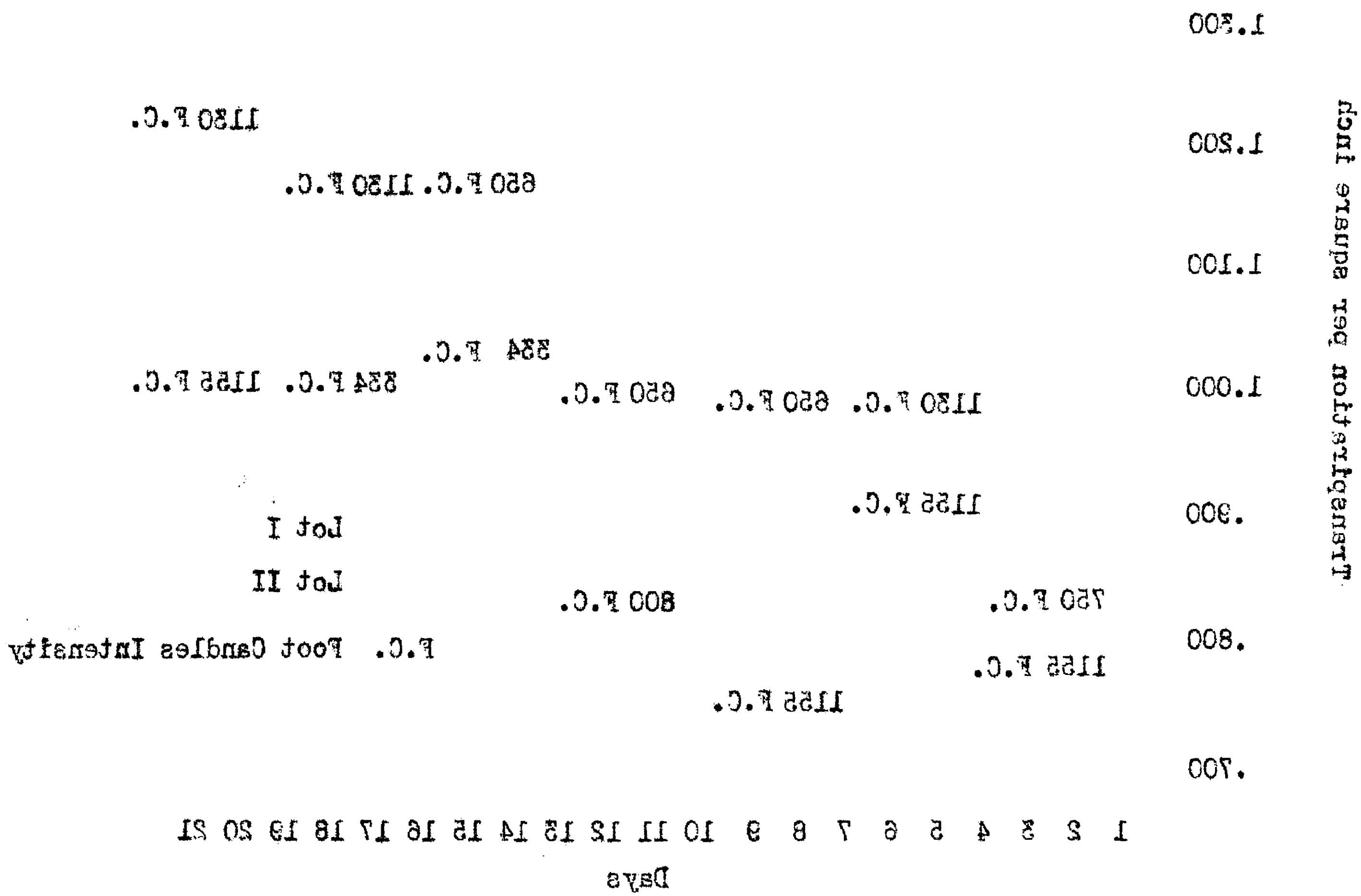


Fig. 10. Influence of Light Intensity on Transpiration Rate in the Maiden Hair Fern

Experiment VI. Temperature 90° F. : Relative humidity 85 per cent

Table XII. Influence of Light Intensity on Transpiration Rate in the Catalpa

Experiment VII. Temperature 80^{o} F. : Relative humidity 85 per cent : 12 plants per treatment averaging 1810 square inches leaf area per lot : Duration of test - 24 days.

Lot I Lot II

Flat I			Flat II			Flat III		
Leaf area in sq. in.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration per sq. in. in c.c.	Leaf area in sq. in.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration per sq. in. in c.c.	Leaf area in sq. in.	Average daily transpiration of 3 -day period in c.c.	Average daily transpiration per sq. in. in c.c.
995	329	.33	986	249	.25	1035	238	.23
995	276	.28	986	310	.31	1031	303	.29
995	399	.40	986	372	.38	845	258	.31
895	370	.41	927	277	.30	845	287	.34
895	385	.43	927	310	.33	845	295	.35
895	523	.58	927	377	.41	845	263	.31
872	310	.36	963	250	.26	945	287	.30
872	433	.50	963	317	.33	945	327	.35

Table XII - continued

Lot II

Flat IV

Leaf area in sq.in.	Average daily transpiration of 3 day period in c.c.	Average daily transpiration per sq. in. in c.c.	Average daily transpiration per sq. in. in Lot I in c.c.	Average daily transpiration per sq. in. of Lot II in c.c.	Light intensity of Lot I in foot candles	Light intensity of Lot II in foot candles	Ratio of average daily transpiration per sq. in. of Lot I and II I/II	II/I	Light reduction in per cent	Reduction of transpiration by reduction of light in per cent
904	362	.40	.29	.32	565	565	.91	1.10		
904	477	.53	.30	.41	565	1085	.73	1.37	47.9	26.2
904	292	.32	.39	.32	990	715	1.22	.82	7.6	18.0
999	327	.33	.34	.34	750	800	1.00	1.00		
999	375	.38	.36	.37	750	660	.97	1.03	12.0	2.02
999	340	.34	.49	.33	1130	334	1.48	.67	70.4	34.0
782	263	.34	.31	.32	377	720	.97	1.03	47.6	2.02
782	343	.44	.42	.39	710	720	1.08	.93		

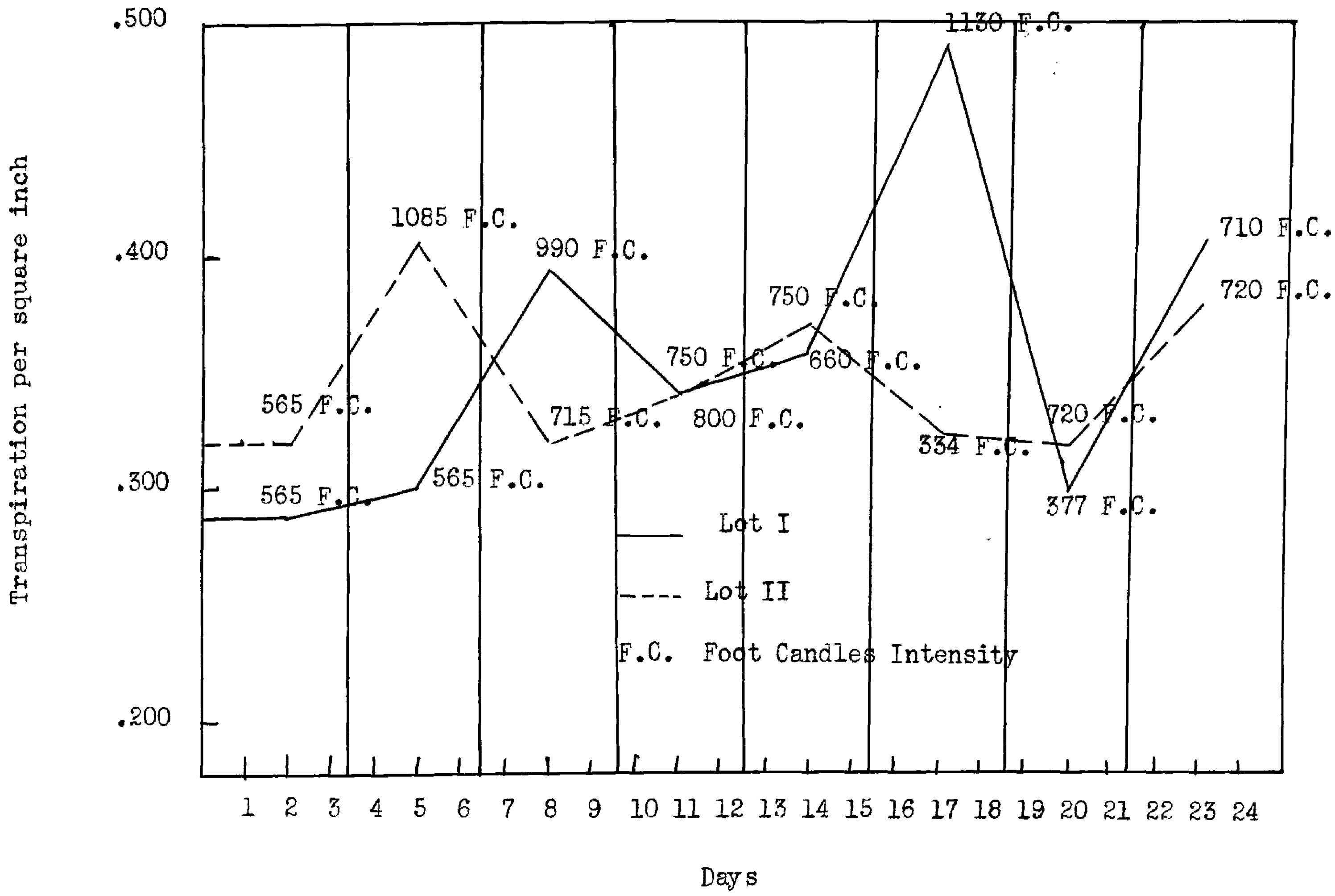


Fig. 11. Influence of Light Intensity on Transpiration Rate in the Catalpa

Experiment VII. Temperature 80° F. : Relative humidity 85 per cent

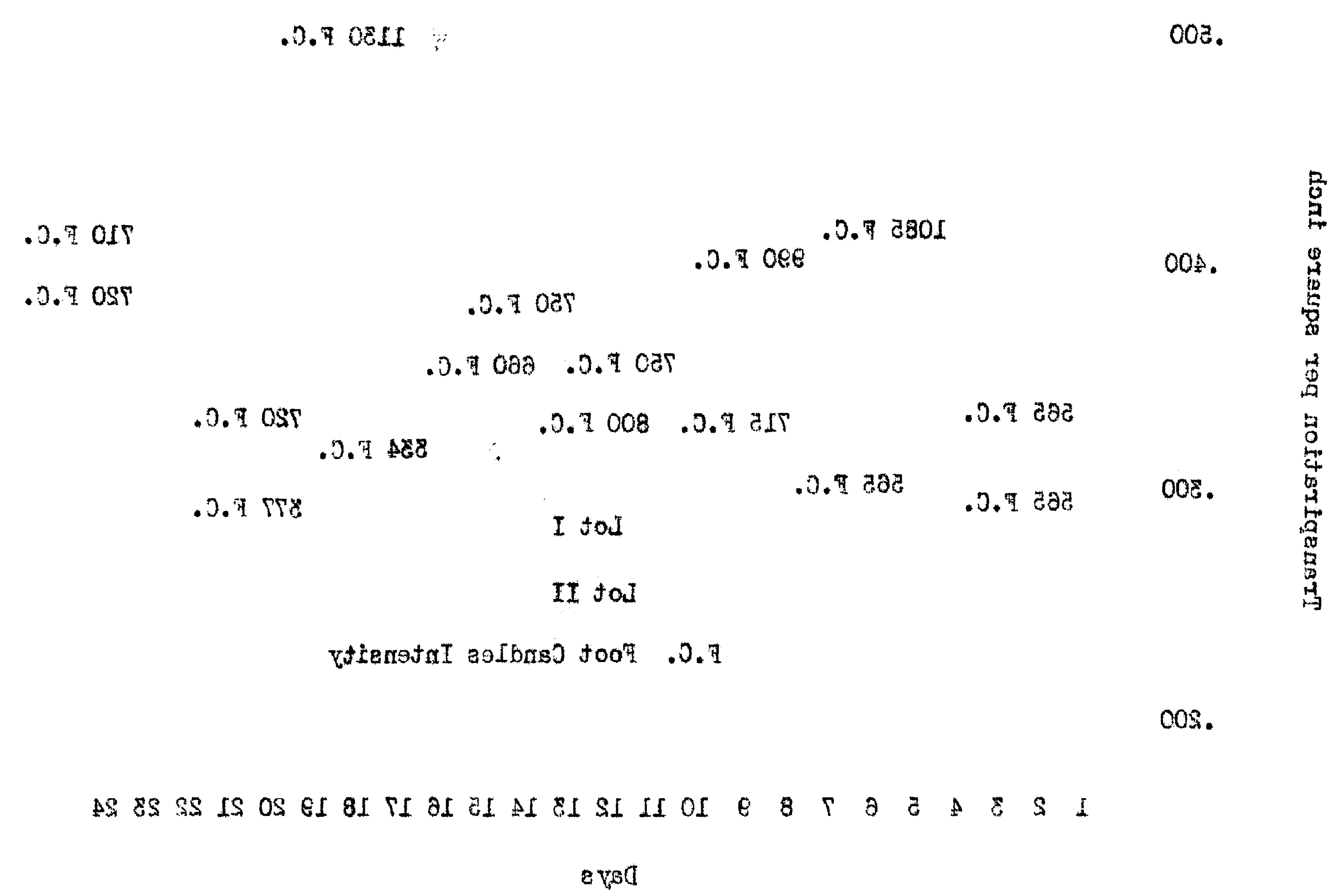


Fig. 11. Influence of Light Intensity on Transpiration Rate in the Catalpa

Experiment VII. Temperature 80° F. : Relative humidity 85 per cent the large older leaves dropping off and being replaced by smaller ones. Table XII and Figure 11 show the transpiration data obtained during this study. The data, shown in Table XII, correspond to those of Table IX in that they show a direct relationship between the light intensity and the transpiration of Catalpa. This held true over the entire light intensity range of these two experiments.

Experiment VIII

In this test, 24 California Privet (Ligustrum vulgare) plants, two years old, 16 inches high, and with an average leaf area of 160 square inches per plot were tested. Light intensities ranged from 415 to 1355 foot candles and a temperature of 90° F. and a relative humidity of 85 per cent were maintained. The experiment lasted for 24 days, by which time the plants had an average leaf area of 280 square inches per lot. Transpiration data are presented in Table XIII and graphically in Figure 12.

These data show that with privet, as with all other plants tested, except Maiden Hair fern, transpiration and light intensity are in direct proportion to each other.

Experiment IX

Twenty-four Arbor Vitae (Thuja occidentalis) plants, two years old and averaging 12 inches in height were employed in this test. A temperature of 80° F. and a relative humidity of 50 per cent were maintained and the light intensity was varied from 415 to 1355 foot candles. This experiment was continued for 24 days, by which time the Arbor Vitae had approximately doubled in area. The transpiration data taken are presented in Table XIV and graphically in Figure 13. Stomatal measurements were made under different light intensities and the results are

Table XIII. Influence of Light Intensity on Transpiration Rate in the California Privet

Experiment VIII. Temperature 80° F. : Relative humidity 85 per cent :

12 plants per treatment averaging 550 square inches leaf area per lot. :

Duration of test - 24 days.

Lot I						Lot II		
Flat I			Flat II			Flat III		
Leaf area in sq.in.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration per sq. in. in c.c.	Leaf area in sq. in.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration per sq. in. in c.c.	Leaf area in sq.in.	Average daily transpiration of 3 day period in c.c.	Average daily transpiration per sq. in. in c.c.
187	383	2.05	173	330	1.91	189	277	1.47
187	222	1.19	173	230	1.33	189	320	1.69
187	320	1.71	173	273	1.58	189	163	.86
260	227	.87	248	330	1.34	220	307	1.40
260	540	2.08	248	497	2.00	220	113	.51
302	493	1.63	300	437	1.46	231	543	2.35
302	443	1.47	300	473	1.58	231	393	1.70
302	293	.97	300	337	1.12	231	367	1.59

Table XIII - continued

Lot II

Flat IV

Leaf area in sq. in.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration per sq. in. in c.c.	Average daily transpiration per sq.in. in Lot I in c.c.	Average daily transpiration per sq.in. of Lot II in c.c.	Light intensity of Lot I in foot candles	Light intensity of Lot II in foot candles	Ratio of average daily transpiration per sq. in. of Lot I and II I/II	II/I	Light reduction in per cent	Reduction of transpiration by reduction of light in per cent
144	307	2.13	1.98	1.80	1160	1160	1.10	.91		
144	248	1.72	1.26	1.71	710	1160	.73	1.36	38.8	18.0
144	187	1.30	1.65	1.08	1160	890	1.53	.65	23.3	43.0
200	200	1.00	1.10	1.20	1005	810	.92	1.09	19.4	4.4
200	137	.69	2.04	.60	1355	415	3.40	.29	69.3	74.6
270	393	1.46	1.55	1.91	1355	1315	.81	1.23		
270	403	1.49	1.54	1.60	1355	1085	.96	1.04	19.9	8.8
270	317	1.17	1.05	1.38	860	810	.76	1.31		

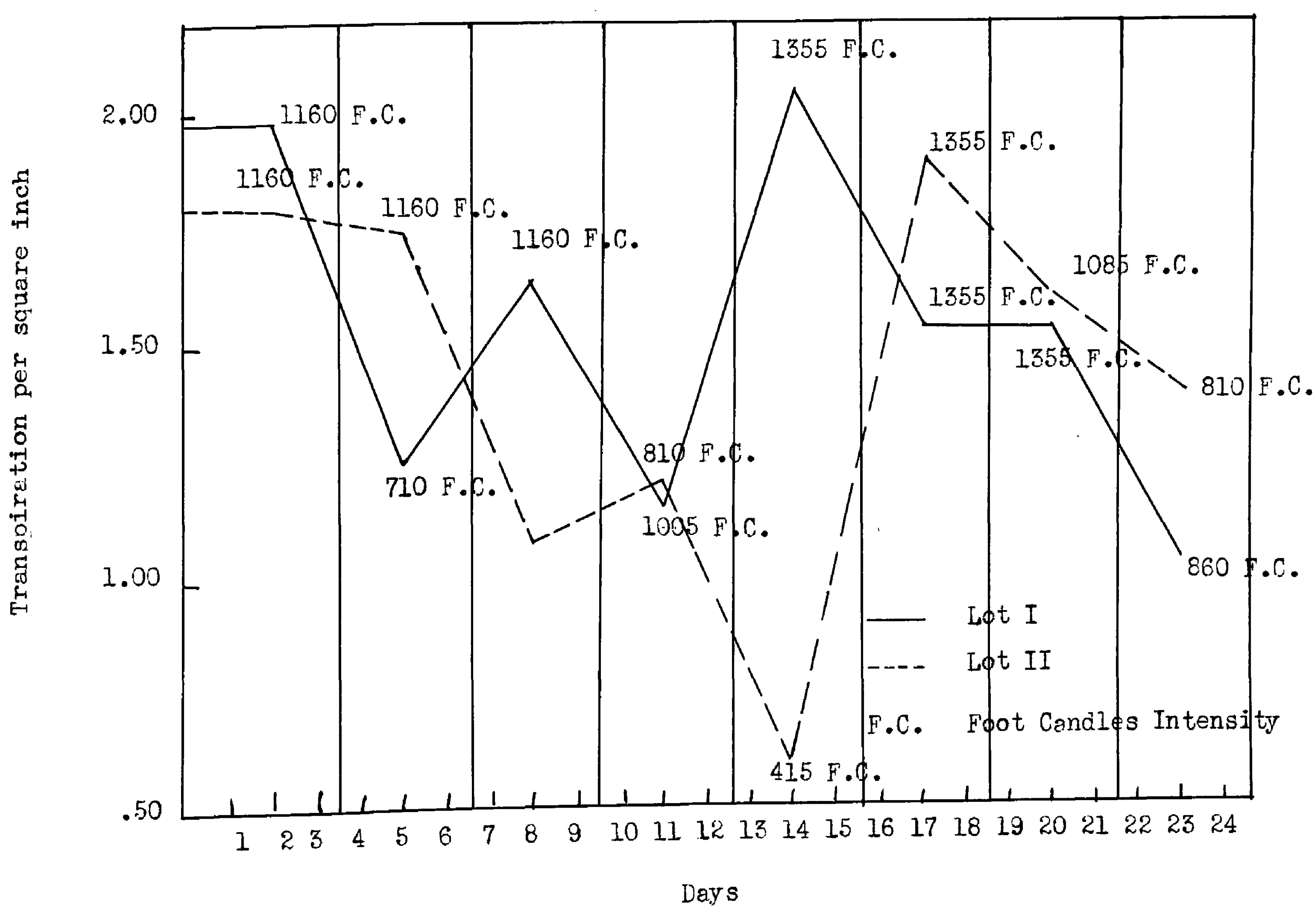


Fig. 12. Influence of Light Intensity on Transpiration Rate in the California Privet

Experiment VIII. Temperature 80° F. : Relative humidity 85 per cent

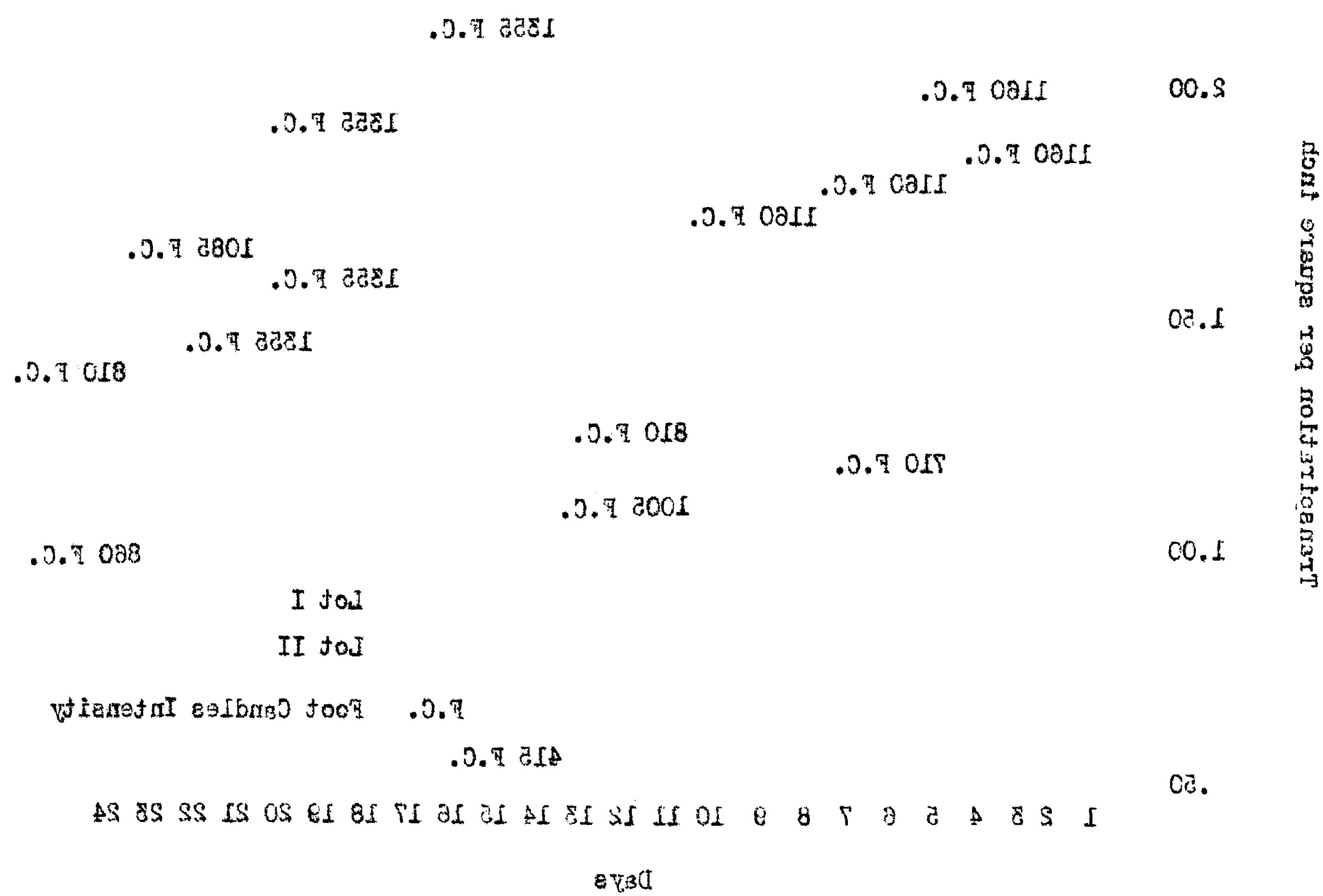


Fig. 12. Influence of Light Intensity on Transpiration Rate in the California Privet

Experiment VIII. Temperature 80° F. : Relative humidity 85 per cent shown on Table XVI.

This test shows that with Arbor Vitae transpiration varies directly with the light intensity over a range of 415 to 1355 foot candles. As may be seen from Tables XIV and XVI, in Arbor Vitae, transpiration, light intensity and stomatal opening were directly proportional to each other.

Experiment X

In this test, as in Experiment VI, 48 Maiden Hair fern (Adiantum Capillus-Veneris) plants, averaging 8 inches in height and with an average leaf area of 250 square inches per lot, were used. They were tested at a temperature of 90° F. and a relative humidity of 85 per cent and the light intensity ranged from 300 to 1130 foot candles. This experiment lasted for 27 days by which time the plants had attained an average leaf area of 350 square inches per lot. The transpiration data of this study are shown in Table XV and graphically in Figure 14. Stomatal apertures were measured under different light intensities and are shown on Table XVI.

The data in Table XV correspond to those in Table XI in that they show that transpiration does not run parallel to the light intensity within the range of 300 to 1130 foot candles. As in Experiment VI the maximum transpiration was reached between 600 and 800 foot candles at which point the curve tended to become level. The stomatal openings were also at their maximum at 334 foot candles, becoming smaller at higher intensities. This test shows, as does Experiment VI, that the maximum transpiration for Maiden Hair fern took place between a range of 400 and 800 foot candles light intensity.

Table XIV. Influence of Light Intensity on Transpiration Rate in the Arbor Vitae

Experiment IX. Temperature 80° F. : Relative humidity 85 per cent. 12 plants per treatment. Duration of test - 24 days.

Light intensity in foot candles	Average daily transpiration of 3-day period in c.c.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration of Flat I and II in c.c.	Light intensity in foot candles	Average daily transpiration of 3-day period in c.c.	Average daily transpiration of 3 day period in c.c	Average daily transpiration of Flat III and IV in c.c.	Ratio of average daily transpiration of Lot I and II I/II	II/I	Light reduction in per cent	Reduction of transpiration by reduction of light in per cent
1355	255	328	292	1315	193	283	238	1.23	.82		
1355	313	386	349	810	173	117	145	2.41	.42	40.2	50.0
1355	283	343	313	415	97	103	100	3.13	.32	69.3	62.0
860	220	180	200	1005	193	190	192	1.04	.96	14.4	15.4
1005	273	320	297	1005	183	227	205	1.45	.69		
1125	303	407	355	1315	260	390	325	1.09	.92	14.4	11.4
860	233	237	235	415	153	101	127	1.85	.54	51.7	35.7
860	273	267	270	810	200	317	258	1.05	.96		

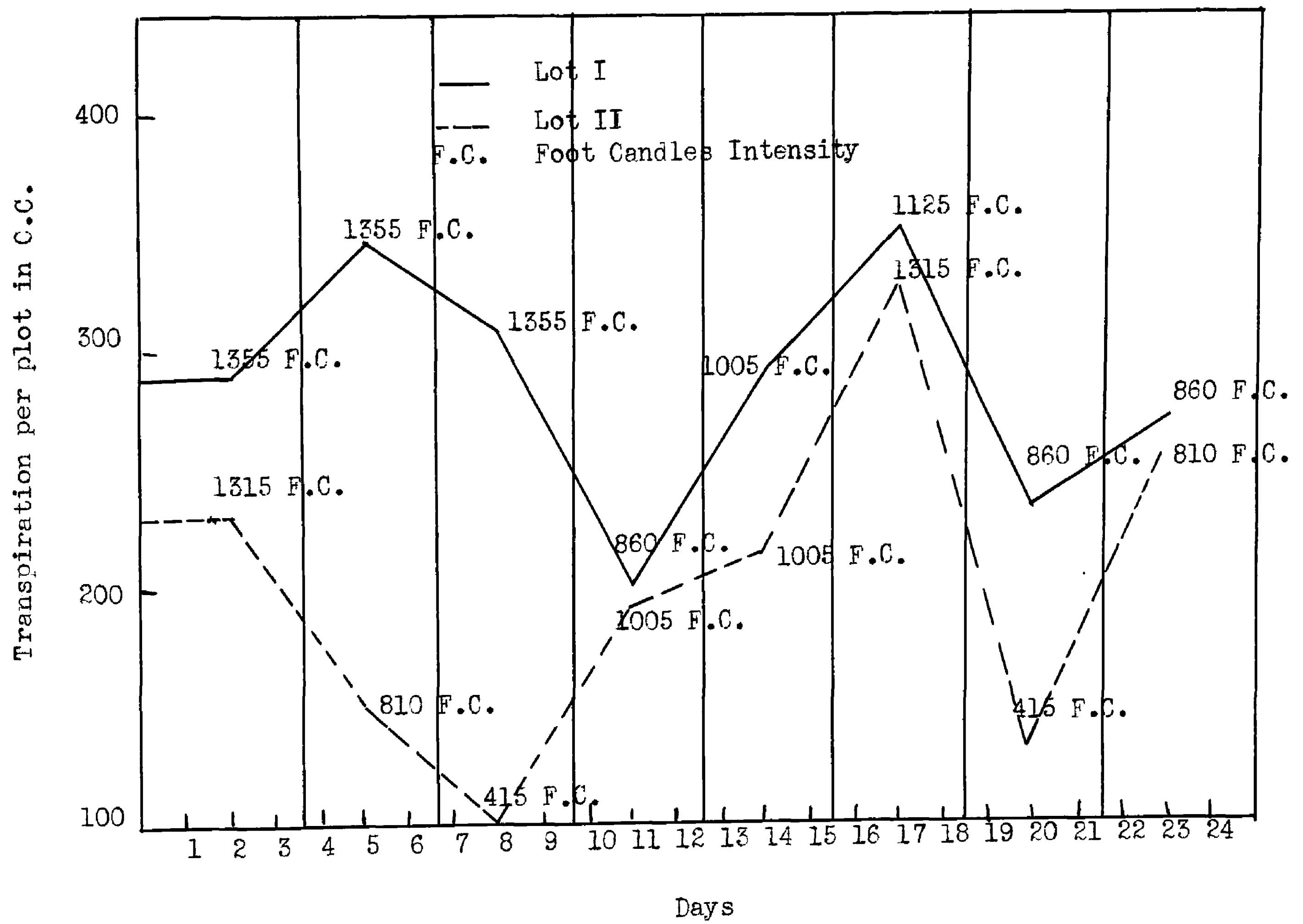


Fig. 13. **Influence of Light Intensity on Transpiration Rate in the Arbor Vitae**

Experiment IX. Temperature 80° F. : Relative humidity 85 per cent

Experiment IX. Temperature 80° F. : Relative humidity 85 per cent

Fig. 13. Influence of Light Intensity on Transpiration Rate in the Arbor Vitae

Days

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

100

415 F.C.

810 F.C.

415 F.C.

1005 F.C.

200

880 F.C.

1005 F.C.

1315 F.C.

880 F.C. 810 F.C.

880 F.C.

1555 F.C.

1005 F.C.

300

1555 F.C.

1315 F.C.

1555 F.C.

1125 F.C.

F.C. Foot Candles Intensity

400

Lot II

Lot I

Transpiration per plot in C.C.

Table XV. **Influence of Light Intensity on Transpiration Rate in the Maiden Hair Fern**

Experiment X. Temperature 90° F. : Relative humidity 85 per cent : 12 plants per treatment averaging 290 square inches leaf area per lot : Duration of test - 27 days.

Lot I						Lot II		
Flat I			Flat II			Flat III		
Leaf area in sq.in.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration per sq. in. in c.c.	Leaf area in sq. in.	Average daily transpiration of 3-day period in cc.	Average daily transpiration per sq. in. in c.c.	Leaf area in sq. in.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration per sq. in. in c.c.
210	197	.94	320	287	.96	295	193	.65
210	190	.91	320	216	.68	295	157	.53
230	177	.77	343	210	.61	312	177	.57
230	173	.75	343	253	.74	312	163	.52
250	167	.67	370	223	.60	330	267	.81
250	160	.64	370	223	.60	330	297	.90
273	197	.72	393	277	.71	375	343	.91
273	180	.66	393	260	.66	375	320	.85
230	185	.80	343	280	.82	312	183	.59

Table XV - continued

Lot II

Flat IV

Leaf area in sq. in.	Average daily transpiration of 3-day period in c.c.	Average daily transpiration per sq. in. in c.c.	Average daily transpiration per sq. in. in Lot I in c.c.	Average daily transpiration per sq. in. of Lot II in c.c.	Light intensity of Lot I in foot candles	Light intensity of Lot II in foot candles	Ratio of average daily transpiration per sq. in. of Lot I and II I/II	II/I	Light reduction in per cent	Reduction of transpiration by reduction of light in per cent
380	253	.67	.92	.66	565	565	1.39	.72		
380	167	.44	.80	.49	565	1085	1.63	.61	48.0	-33.0
409	190	.46	.69	.63	990	300	1.09	.91	70.0	- 1.0
409	210	.51	.75	.64	309	300	1.17	.85		
409	253	.62	.81	.70	405	300	1.15	.86	26.0	4.3
420	180	.43	.64	.73	405	715	.88	1.14	43.1	20.8
420	160	.38	.62	.76	750	800	.82	1.23		
501	210	.42	.72	.82	1130	800	.88	1.14	29.2	-20.0
501	303	.61	.66	.75	334	800	.88	1.14	58.1	20.2

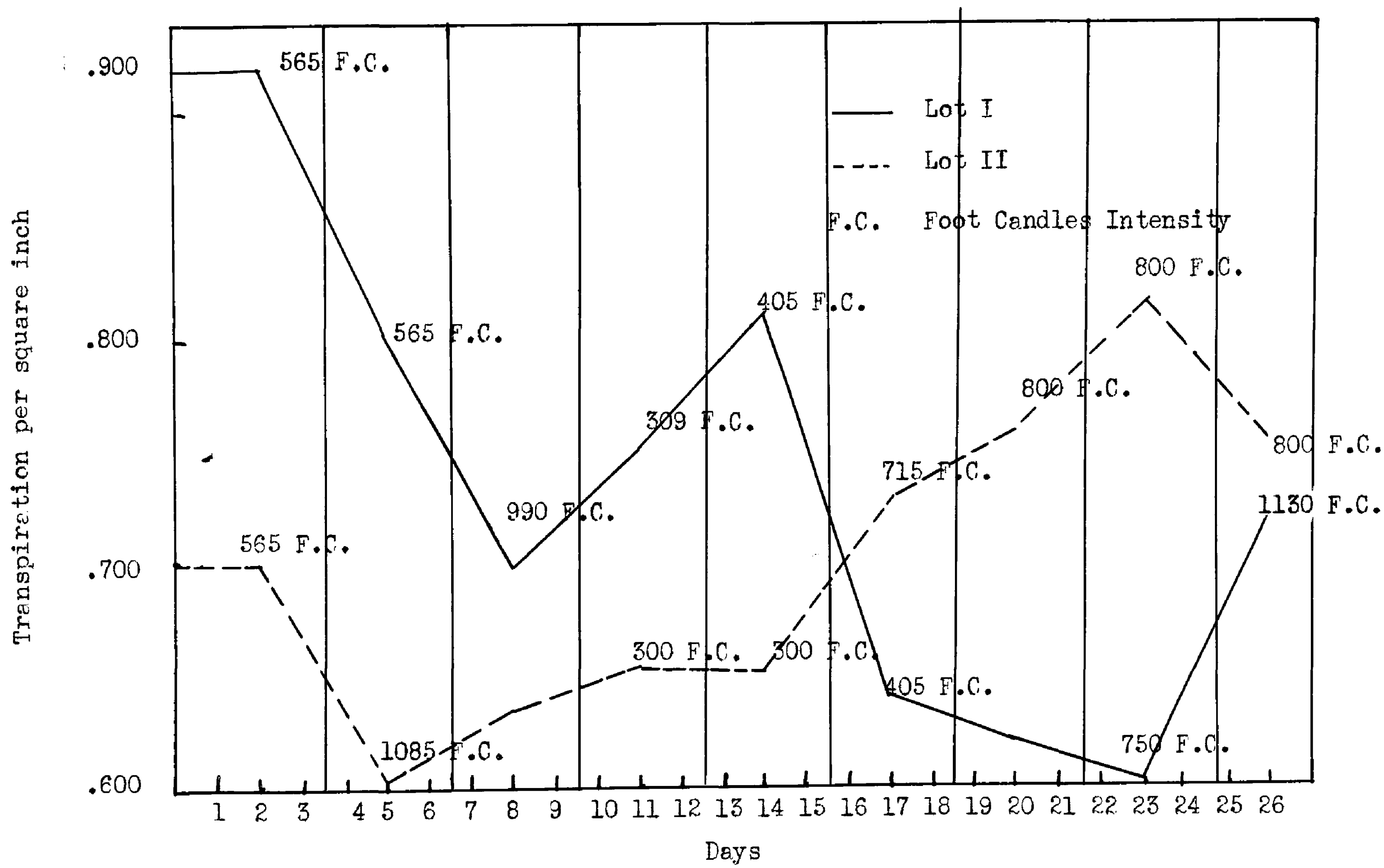


Fig. 14. Influence of Light Intensity on Transpiration Rate in the Maiden Hair fern

Experiment X. Temperature 90° F. : Relative humidity 85 per cent

Transpiration per square inch

.900 565 F.C.

Lot I

Lot II

F.C. Foot Candles Intensity

800 F.C.

405 F.C.

.800 565 F.C.

800 F.C.

809 F.C.

800 F.C.

715 F.C.

1130 F.C.

990 F.C.

.700 565 F.C.

800 F.C. 800 F.C.

405 F.C.

750 F.C.

1085 F.C.

.600

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26

Days

Fig. 14. Influence of Light Intensity on Transpiration Rate in the Maiden Hair fern

Experiment X. Temperature 30^{o} F. : Relative humidity 85 per cent

Table XVI. Stomatal Measurements Under Different Light Intensities

Light intensity in foot candles	Width of stomatal aperture in microns
May Apple	
1155	13.6
650	12.8
334	7.9
Peaches	
1720	10.5
1700	11.5
1595	9.8
1500	7.2
1385	7.9
1160	8.6
1155	6.5
710	6.0
595	4.1
545	4.8

Light intensity in foot candles	Width of stomatal aperture in microns
Arbor Vitae	
1355	12.7
1125	10.7
1005	6.7
860	5.5
810	5.8
415	3.6
Maiden Hair Fern	
1085	7.2
715	6.0
565	8.9
405	7.9
300	9.6
0	1.2

Fig. 15. May Apple in Chamber

Leaves of left side wilted due to excessive transpiration of .306 cubic centimeters per square inch under light intensity of 1155 foot candles for 15 hours. Right side transpired .144 cubic centimeters under 334 foot candles of light.

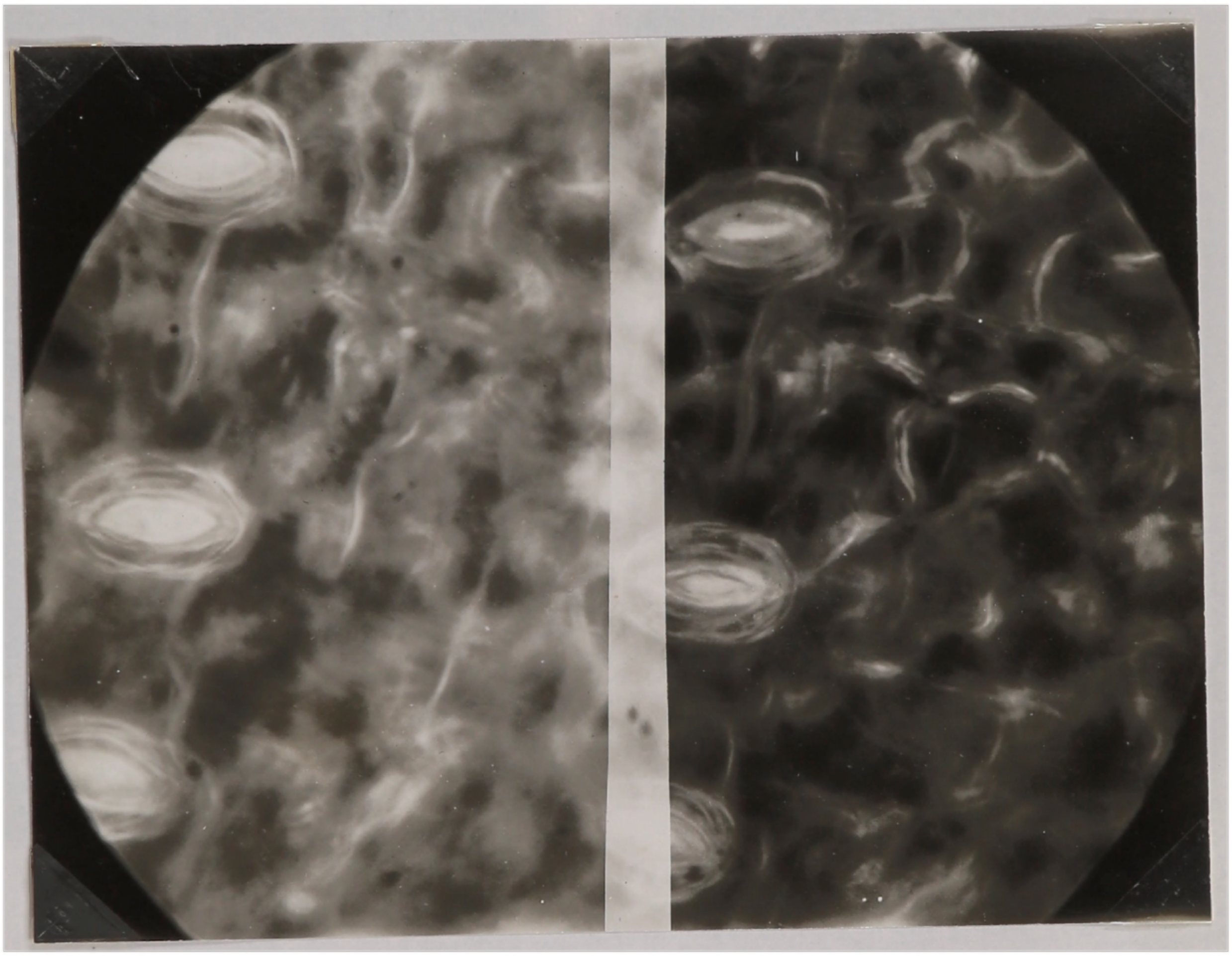


Fig. 16. Microphotograph of Peach Stomata showing open stomata on left under 1700 foot candles while closed stomata on right are under 340 foot candles.

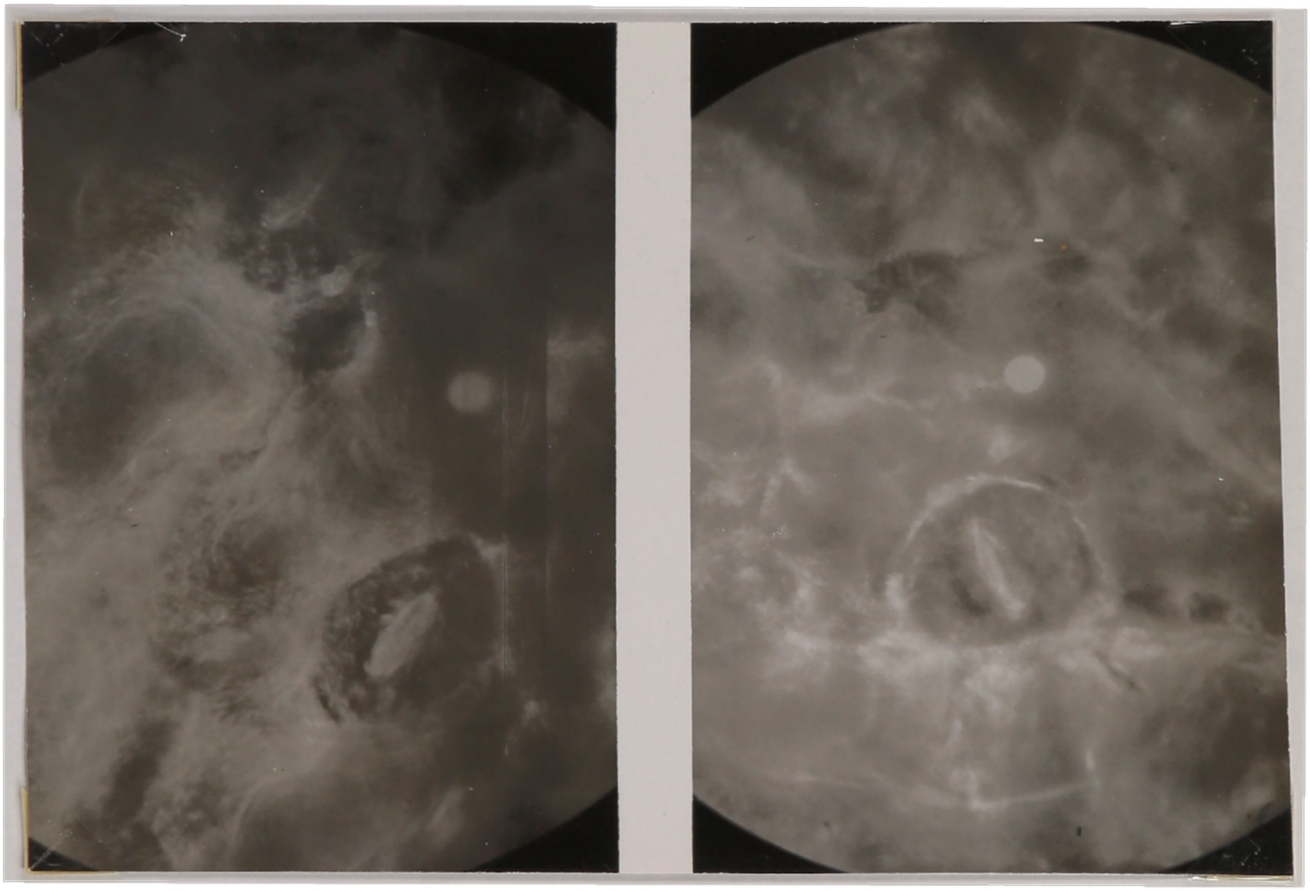


Fig. 17. Microphotograph of Maiden Hair fern. Stomata at left under 1085 foot candles. Stomata at right under 300 foot candles. Very little difference in aperture.

Discussion

Some investigators (5,13,16) have concluded that the increase in transpiration caused by light is due to the infra-red rays which increase the temperature of the leaves. Others (8) have found that light, apart from raising the temperature of the leaves, causes a higher rate of transpiration. Some (12) have found that light intensity had no effect on transpiration. The writer found, however, that when the infra-red rays were eliminated from the spectrum by use of water screens or filters, as was done in the apparatus previously described, increased light intensity still caused a transpirational increase. The effectiveness of this bath may be seen in Tables I, II and V which show, that, regardless of light intensities, the leaf temperatures never varied more than 1° F. When the plants were subjected to high intensities the increased transpiration may have been a factor in keeping the leaf temperatures constant. However, in no place in the literature was there found a case where transpiration cooled leaves more than 5° F. When no water screens were used and infra-red rays were allowed to strike the leaves, as was done in certain tests the data for which are given in Table I and II, the temperature difference was as much as 8° F. So with use of water baths the leaves should have been at least 3° F. higher. This, however, did not occur in any test in which leaf temperatures were measured while the water screens were used.

From Tables VI - XV it may be seen that a reduction of transpiration in the tomato, bean, peach, catalpa, may apple, privet and Arbor Vitae was caused by decreasing the light intensity. This held true over the entire light range of 300 to 1700 foot candles. When the Maiden Hair fern was tested, however, the highest transpiration was found at an intensity of from 500 to 800 foot candles. Tables X and XV show that the results were very irregular, possibly due to the inaccuracy of measuring the leaf area of small fern leaves. From 800 foot candles to 1200 foot candles, the transpiration curve tended to decrease. Since all plants have an optimum range of light for growth and other functions, these data suggest that the optimum range for transpiration in the Maiden Hair fern was from 500 to 800 foot candles. It is probable that if the light intensity were increased to 5000 foot candles or even more (which is the intensity of the sunlight in Michigan in July) the transpiration curve of the other plants tested would tend to decrease or straighten out at the higher intensities as did the Maiden Hair fern above 900 foot candles.

The reason for higher transpiration with increased light intensity was found to be due to or at least associated with increased stomatal aperture. The stomatal aperture, as measured by the Leitz-Ultra-Pak, Table XVI, was found to vary directly with the light intensity in all plants tested except the Maiden Hair fern. This follows the results reported by Gray and Peirce (7). Sayre (19,20) found that the periodicity of transpiration was caused by the opening and closing of the stomata with light and darkness respectively. This work substantiates the results obtained by Sayre, although Knight (10) concluded that stomatal openings and transpiration do not run parallel. The stomata under the light intensities used in this test were completely open only at the highest intensities. Since Brown and Escombe (4) proved that diffusion thru stomata is proportional to the linear dimension of the aperture and not the area, these data imply that transpiration is something more than a physical process such as evaporation or diffusion. In the case of

Maiden Hair fern, the stomatal opening did not run parallel to transpiration as did the other plants tested. The largest stomatal apertures in the Maiden Hair fern, however, were found at 400 foot candles intensity while the highest transpiration occurred at between 600 and 800. These differences are possibly due either to inaccuracy in stomatal measurements or to inaccuracy in obtaining leaf areas.

From the data here reported, transpiration is reduced by a reduction of the light intensity. In any general effort to reduce the transpiration of plants under cultivation, due consideration should be given to the possibilities that lie in shading them. Light reduction would be especially beneficial to transplants, before the roots have become established, and during dry seasons to those plants which have large water requirements.

Summary

I. A plan of study was formulated in an effort to determine the effect of a single factor, light intensity on the transpiration of certain plants.

II. Preliminary transpiration experiments using carbon and aluminum sprays and cheese cloth shading to vary the light intensity are described.

III. An apparatus to measure transpiration under controlled humidity, temperature and light intensity is described with the aid of two diagrams. Tables are given to show the accuracy of this apparatus.

IV. Experiments using tomatoes, beans, May apple, peaches, catalpa, California privet, Arbor Vitae and Maiden Hair fern are described, with tables and graphs to show the effect of differences in intensity of light on transpiration.

V. Stomatal measurements on leaves under different light intensities were made. The transpiration in all plants studied was found to vary directly with the stomatal aperture. In all cases except the Maiden Hair fern the stomatal aperture was found to vary directly with the light intensity.

VI. The transpiration of all the plants studied except Maiden Hair fern varied directly with the light intensity of Mazda lamps over the range of 300 to 1700 foot candles. The Maiden Hair fern showed maximum transpiration from 600 to 800 foot candles and reduced transpiration occurred at higher light intensities.

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