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B. T. GALLOWAY, *Chief of Bureau.*

THE EFFECTS OF ARTIFICIAL SHADING ON PLANT GROWTH IN LOUISIANA.

BY

H. L. SHANTZ,

Physiologist, Alkali and Drought Resistant Plant Investigations.

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ALKALI AND DROUGHT RESISTANT PLANT INVESTIGATIONS.

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LETTER OF TRANSMITTAL.

U. S. Department of Agriculture,
Bureau of Plant Industry,
Office of the Chief,
Washington, D. C., December 4, 1912.

Sir: I have the honor to transmit herewith a manuscript entitled "The Effects of Artificial Shading on Plant Growth in Louisiana," by Dr. H. L. Shantz, Physiologist, Alkali and Drought Resistant Plant Investigations, and to recommend its publication as Bulletin No. 279 of this Bureau.

This manuscript describes experiments with various crop plants which were grown under artificial shades of different degrees of density, the purpose being to determine the effect of diminished light intensity upon the growth of plants. In nearly every case a moderate reduction in the intensity of the light resulted in an increased growth as compared with plants of the same species growing in the open. It was also observed that in the case of lettuce the quality was improved by a moderate degree of shade. These results are obviously significant in relation to plant growth in the arid regions, where the light is normally much more intense than in Louisiana. Cooperative experiments of a similar nature are now in progress in Colorado, the object being to determine the importance of light as a factor in the physiology of drought resistance.

The experiments here described were conducted by Dr. Shantz at the University of Louisiana while occupying the chair of botany and bacteriology at that institution.

Respectfully,

B. T. Galloway,
Chief of Bureau.

Hon. James Wilson,
Secretary of Agriculture.

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THE EFFECTS OF ARTIFICIAL SHADING ON PLANT GROWTH IN LOUISIANA.

INTRODUCTION.

In physiological studies of drought resistance light is a factor which must not be overlooked. The energy received from the sun is largely consumed in transforming water to water vapor, and hence is directly responsible for much of the transpiration from plant surfaces.

The investigation described in the following pages was carried on in a humid region and was completed before the writer took up [1] the investigation of light requirement in relation to drought resistance in the semiarid portion of the United States. Nevertheless, since practically the same methods of experimentation have been applied in both regions and since the results obtained in Louisiana have been found to be very useful for comparison with those obtained in Colorado, it is deemed advisable to publish the results of the earlier investigation, regarding it as complete in itself but closely related to work which is still in progress.

The experiments here described were conducted at Baton Rouge, La., during April and May, 1908. The purpose of the experiments was (1) to show the effect of different degrees of shade giving a definite series of light intensities on plant growth and (2) to show to what extent the so-called shade effects were independent of the resulting changes in other physical factors such as temperature and humidity.

The delay in publication [2] of results has to a certain extent rendered them of confirmatory value only, since Lubimenko (1908)[3] and Combes (1910) have covered part of the same ground in a very thorough way. Nevertheless, the experiments here described represent a distinct contribution to the subject, since the effects of shading are not the same in different localties, owing to differences in the initial or normal intensity of the light. The results are also of interest as affording indications of the comparative light requirements of a number of species not hitherto included in experiments of this

[1] In cooperation with Dr. L. J. Briggs, of the Office of Biophysical Investigations of the Bureau of Plant Industry.

[2] This delay was due to a desire on the part of the author to repeat the experiments before publication. Since this is now impracticable the results are published in the present form.

[3] All references to literature are indicated in the text by the name of the author and the year of publication. For full citations, see the list at the end of this bulletin.

character and in indicating the minimum amount of solar energy required by these plants.

Six different plants and six different degrees of light intensity were used in the present experiments, which were so planned as to minimize the influence of the resulting changes in physical conditions other than light.

EXPERIMENTAL METHODS.

Two beds, A and B, 6 by 24 feet each, were prepared for seeding. On April 2, 1908, one row each of the following six plants was planted in each bed: Radish, French Breakfast; lettuce, New Orleans Improved Passion; potato, Triumph; cotton, Lee's; corn, St. Charles Red Cob; mustard, Bloomdale White.

As soon as the seedlings began coming through the soil each bed was covered with a framework over which cloths of different texture

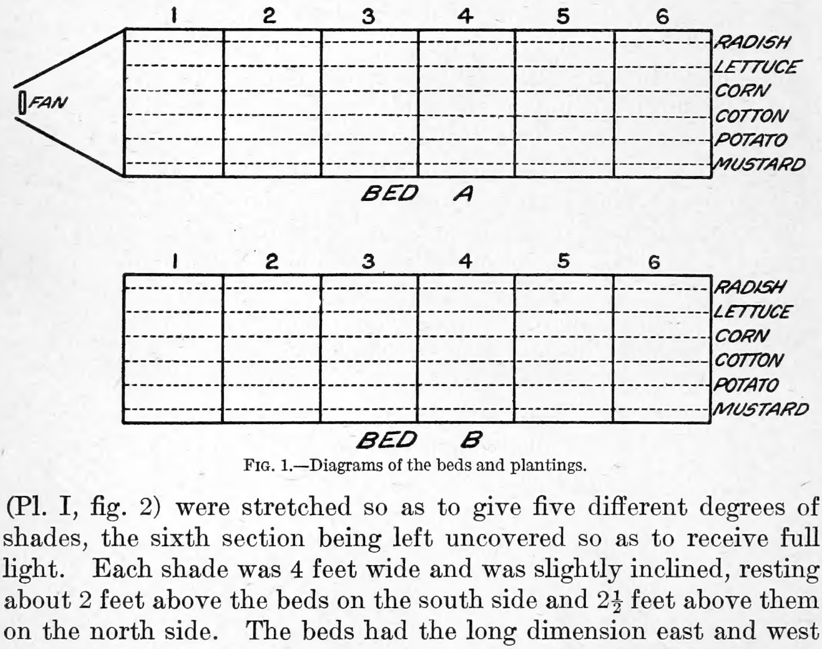


FIG. 1.—Diagrams of the beds and plantings.

(Pl. I, fig. 2) were stretched so as to give five different degrees of shades, the sixth section being left uncovered so as to receive full light. Each shade was 4 feet wide and was slightly inclined, resting about 2 feet above the beds on the south side and 2½ feet above them on the north side. The beds had the long dimension east and west and were closed by boards on the sides and on the ends. The diagram (fig. 1) shows the arrangement, and the general appearance of the beds is shown in Plate I, figure 1.

Section 1 (east end) received the deepest shade and section 6 (west end) was left open to the full light. Since the shades were not separated by partitions, it will be seen that a small portion of the bed between each two shades was under the next deeper shade in the morning and under the next lighter shade in the afternoon. The result was that only the center of each section received the characteristic light reduction afforded by the corresponding shade, and there

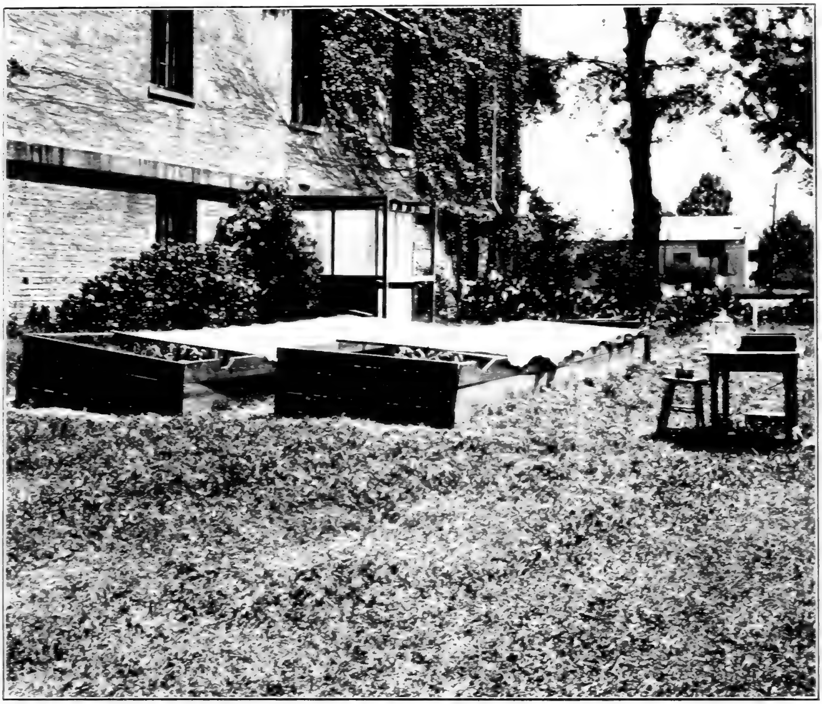


FIG. 1.—BEDS USED IN THE SHADE EXPERIMENTS AT BATON ROUGE, LA.: BED A AT THE RIGHT; B AT THE LEFT. THE LONG DIMENSION OF EACH BED IS EAST AND WEST.

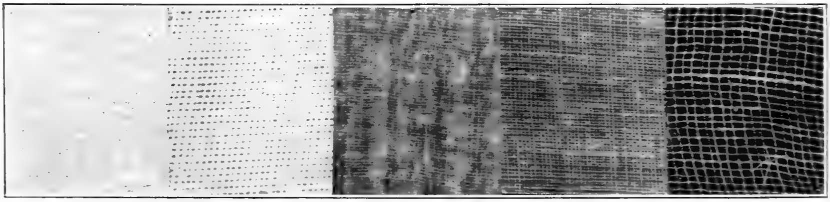


FIG. 2.—REPRODUCTIONS FROM PHOTOGRAPHIC PRINTS, SHOWING THE TEXTURE OF THE CLOTHS USED ON SECTIONS 1 TO 5 AND INDICATING THE RELATIVE LIGHT PENETRATION.

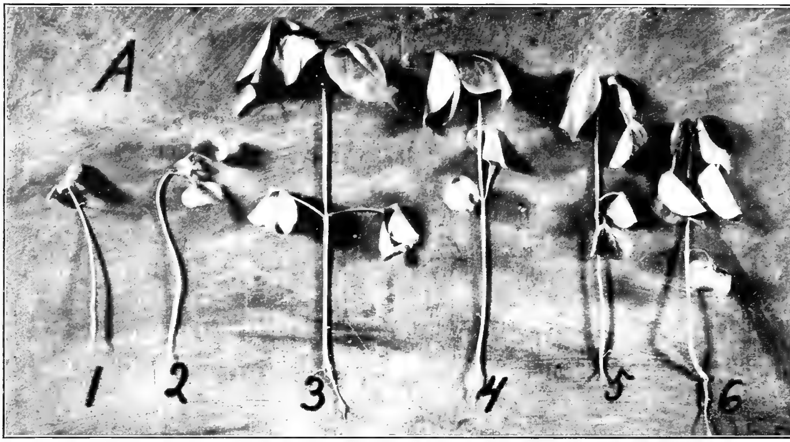


FIG. 1.—GENERAL APPEARANCE OF COTTON PLANTS 30 DAYS AFTER GERMINATION IN BED A. SHADES AS NUMBERED; 1 INDICATES LEAST ILLUMINATION AND 6 NORMAL LIGHT.

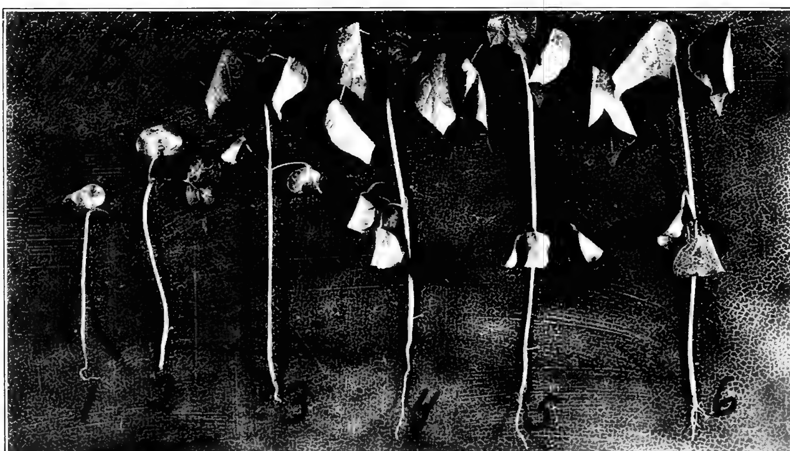


FIG. 2.—GENERAL APPEARANCE OF COTTON PLANT 30 DAYS AFTER GERMINATION IN BED B. SHADES AS NUMBERED; 1 INDICATES LEAST ILLUMINATION AND 6 NORMAL LIGHT.

FIG. 3.—RELATIVE GROWTH OF MUSTARD PLANTS AT THE END OF 24 DAYS IN BEDS A AND B. SHADES AS NUMBERED, RANGING FROM 2 (N/15 LIGHT) TO 6 (NORMAL).

was a complete gradation in light intensity from one section to another. At the east end of bed A a pointed extension of the board frame was built and an electric fan was placed in the small opening at the point (fig. 1). In this way outside air was constantly supplied during the day, and the effects of overheating, rise in atmospheric humidity, and change in water content of the soil in the deeper shades were reduced to a minimum. The other bed was covered in exactly the same way but without the extension, since no fan was used. At the back or north side of each frame a door was provided for taking observations under each different shade. The experiment was continued until May 23, or for a period of 51 days.

PHYSICAL CONDITIONS.

LIGHT.

At New Orleans, the nearest point at which light conditions are recorded by the United States Weather Bureau, the following is the record for April and May, 1908, the period of experimentation:

TABLE I.—*Record of light conditions at New Orleans, La., for April and May, 1908.*

Month.	Cloudy days.	Days partly cloudy.	Clear days.	Percentage of possible sunshine.
April	10	9	11	68
May	8	9	14	73

These measurements should indicate fairly well the conditions at Baton Rouge, which is only 70 miles distant.

In the measurement of the light reduction a photographic "printing-out" paper was used. The time required for this paper to reach a definite shade was recorded. The chief objection to be made to this method, as well as to the Wiesner (1907) method is that it measures only the chemical rays. But since the light which reached the plants passed through cloth, the amount of reduction is probably nearly the same for the heat rays as for the chemical rays. Moreover, the recent work of Kneip and Minder (1909) indicates that too great a distinction has been made in the effect of different wave lengths on photosynthesis. Consequently, where only relative intensities are to be measured, a "printing-out" photographic paper offers a ready means of comparing the degree of shade under different cloths. In the cooperative experiments above referred to Dr. L. J. Briggs and the writer have developed a method for measuring by means of the pyrheliometer the relative transmission of energy by screens when placed normal to the sun's rays. The reduction of light by the cloth covers used in the Louisiana experiment has since been measured in this way by means of the pyrheliometer devised by Abbot (1910), and the measurements found to be in practical agreement with those made by means of the "printing-out" photographic paper.

The cloths designated in Table II were used and gave reductions in light intensity as indicated after each. The expressions n, n/2, n/93, etc., are convenient in referring to normal illumination, one-half normal illumination, one ninety-third normal illumination, etc.

TABLE II.—*Sectional coverings and light intensities.*

Section.	Cloth.	Fraction of normal light.
1	Black duck	1/93 or n/93.
2	Light canvas cloth (black)	1/15 or n/15.
3	Chambray	1/7 or n/7.
4	Light chambray	1/5 or n/5.
5	Voile	1/2 or n/2.
6	No cover	1 or n.

Natural-size prints, made by placing the cloths used on the "printing-out" paper and exposing them to full sunlight, are reproduced in Plate I, figure 2. These prints show the texture of the different cloths and indicate their comparative efficiency in reducing light intensity.

TEMPERATURE.

Air temperatures under each section were read every day at 6 a. m., at noon, and at 6 p. m.; and a thermograph record was taken in section 1 of each bed. The temperatures of the soil at the surface and at a depth of 8 inches were read at the same time. It must be understood that the differences which would naturally result from

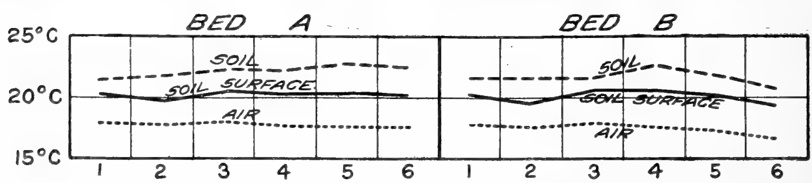


FIG. 2.—Diagrams showing temperatures at 6 a. m., averaged for the entire period of the experiments.

shading would not show markedly except at or near the period of maximum light. It is therefore evident that the morning and evening determinations should show only slight differences under the different shades.

The mean temperatures as recorded at 6 a. m. are shown in figure 2. There was no appreciable difference in the temperatures recorded in the two beds, nor for that matter under the different shades. The air temperatures averaged about 4° C. below the soil temperatures at the depth of 8 inches, and approximately 2° C. below the temperature of the soil surface. These results are due to the retention of a portion of the heat absorbed by the soil on the previous day.

The temperatures at noon showed some important differences (fig. 3). The temperatures of the soil surface were highest in the open air (sec. 6) and lowest in the deepest shade (sec. 1). The soil temperature was practically uniform in the bed without the fan. In the bed with the fan the soil temperature was relatively low in the deeper shades, probably as a result of increased evaporation due to the air movement.

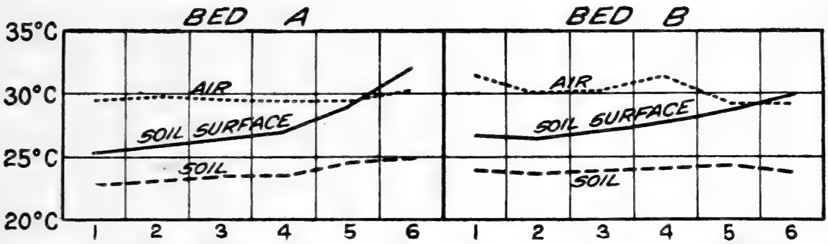


FIG. 3.—Diagrams showing temperatures at noon, averaged for the entire period of the experiments.

The air temperatures in sections 1 to 4 were noticeably higher in bed B than in the corresponding sections in bed A. These differences in air temperature were less clearly expressed in the averages for the entire period of the experiments than they otherwise would have been, because of the occurrence of a number of dark or rainy days. The absolute maximum temperatures of the air recorded at noon for the period of experimentation bring out clearly the fact that higher temperatures prevailed in the bed without the fan.

TABLE III.—*Absolute maximum temperatures during the experiments.*

Bed.	Section.					
	1	2	3	4	5	6
	°C.	°C.	°C.	°C.	°C.	°C.
A (with fan)	34.0	35.5	32.2	32.5	33	32
B (without fan)	38.0	36.0	34.5	33.5	33	32

The important facts here shown are the comparative uniformity of air temperatures in all of the different sections of bed A, and the relatively great variation in bed B.

The temperatures of the air, of the soil at the surface, and of the soil at a depth of 8 inches at 6 p. m. show only slight differences (fig. 4). In bed A the temperatures of the soil at the surface and at the depth of 8 inches were comparatively low in the deeper shades, as a result of the wind movement and the increased evaporation caused by the fan.

The temperatures of bed A show remarkable uniformity in the different sections at all hours of observation. The only important differences are to be found in the slightly lower temperatures of the deeper shades, due to the introduction of outside air by the use of the fan. It is clear that overheating in the deeper shades was completely overcome by this method.

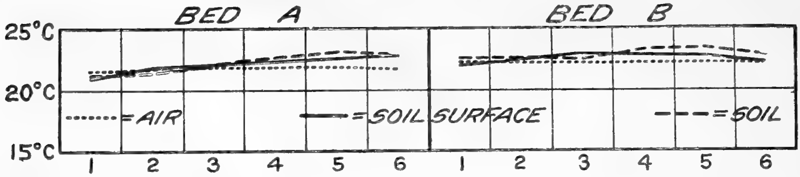


FIG. 4.—Diagrams showing temperatures at 6 p. m., averaged for the entire period of the experiments.

In bed B the differences were more marked, the most important differences having been the higher temperature of the air in the deeper shades.

SATURATION DEFICIT.

The saturation deficits recorded are shown in figure 5. The differences at 6 a. m. and at 6 p. m. were only slight. At noon the differ-

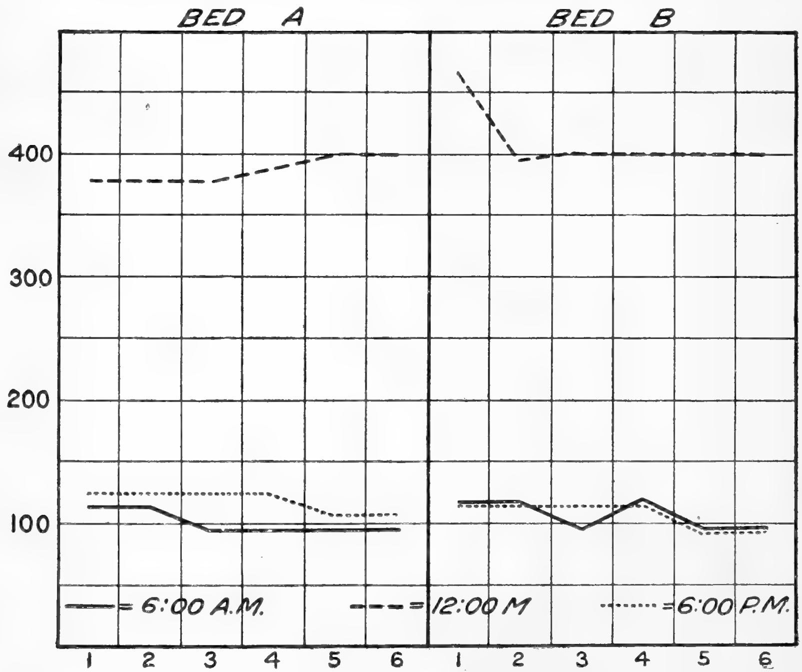


FIG. 5.—Diagrams showing the saturation deficit (in thousandths of an inch) at 6 a. m., at noon, and at 6 p. m., averaged for the entire period of the experiments.

ences between the two beds were very marked, the saturation deficits having been comparatively low in the deeper shades of bed A and comparatively high in the deeper shades of bed B. This high saturation deficit in section 1 of bed B was the result of the higher air temperature. This difference in the relative evaporating power of the air in the different sections of bed B was very largely equalized in bed A as a result of the wind movement caused by the fan. Standardized porous cup evaporimeters somewhat similar to those devised by Livingston (1906) showed increased evaporation as a direct result of the increase in light (fig. 6), independent of the relative evaporating power of the air. It is also interesting to note that the increased evaporation from the porous cup in the sections under the deeper shades is due in bed A to the wind movement and in bed B to the higher temperature, while the increased evaporation in section 6 in both beds was due to a third factor—increase in intensity of illumination.

SUMMARY OF PHYSICAL CONDITIONS.

In regard to light, both beds A and B offered exactly the same range of conditions. In the two months during which the experiments were

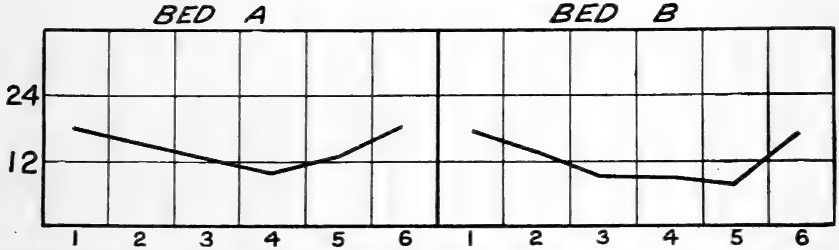


FIG. 6.—Diagrams showing the relative evaporation (in grams per day) from a porous cup for the entire period of the experiments.

conducted there was approximately 70 per cent of possible sunshine at the nearest station where observations were recorded.

The results show that a slight reduction in illumination is accompanied by increased growth. In the lighter shades the occurrence of dark days would reverse the conditions between such shades and full light by reducing the light of the shades below the optimum, thus overcoming to some extent the increase in growth of plants in these shades as compared with those in full light; but in the denser shades dark days would entirely stop growth, thus increasing the differences in growth between the denser shades and full light or the lighter shades. The illumination as shown by the recorded sunshine was fairly normal or, if anything, above the normal for this locality during the period of these experiments.

In bed A the use of the electric fan during the day to provide a current of air prevented entirely the changes in conditions of air temperature and humidity which otherwise result when shade is applied. In bed B all of the effects upon temperature and humidity resulting from altered light conditions were operative.

During the period of experimentation the rainfall was in excess of 21 inches and the problem of water supply was never of importance. Under all shades the soil was constantly in a moist condition, the samples taken for moisture determinations showing no differences of importance to plants. The soil was well drained.

In bed A the influence of the different shades was independent of their effects upon temperature and humidity, since these factors were neutralized by the use of the fan. Wind movement due to the fan was only slight, the movement having been less than 1 mile per hour in section 1 and entirely negligible in sections 3 to 6. In bed B the results under the different shades may have been influenced by the accompanying changes in temperature and humidity.

EFFECT OF DIFFERENT LIGHT INTENSITIES ON PLANTS.

MUSTARD.

In section 1 (n/93) the plants of mustard were unable to continue growth after the reserve food material in the seeds was exhausted. The light was too weak to enable the plant to elaborate carbohydrates. Growth ceased after about 25 days and the plants disappeared at the end of 30 days.

At the end of 30 days (Table IV), when the plants in section 1 (n/93) had died, no great reduction in growth was observable in the other sections with the exception of section 2 (n/15). In average height the plants (Table V) were comparatively uniform under the lighter shades at the end of 30 days. The diameter of stem (Table VI) varied considerably, being smallest in section 2 and much greater in the lighter shades. The stem diameter was not greatly increased in full light. In fact, while in bed A the stems in full light were slightly thicker than those under the shades, in bed B the stems showed considerably less diameter in the full light than in sections 4 and 5.

The general appearance of the plants at the end of 24 days is well illustrated in Plate II, figure 3. Growth in full light and in sections 3, 4, and 5 was approximately the same. In section 2 the plants were much dwarfed, while no plants were able to survive in section 1. No appreciable difference in the plants in beds A and B could be attributed to the air current of the fan and the resulting equalization of conditions of temperature and humidity under the different shades. Differences in light above one-seventh normal (n/7) seem to have had very little effect upon this plant.

At the end of the experiment, 51 days from the time of planting, the mustard plants showed the best growth between sections 4 and 5, or at light intensities between n/2 and n/5. When light was reduced to n/15 or below no plants were able to survive. The mustard plants suffered severely from parasitic fungi, and on this account final weighing and measurements were omitted.

LETTUCE.

Lettuce was unable to elaborate any food material in section 1 and the plants died as soon as the reserve food material in the seeds had been consumed. In section 2 growth was barely possible and the plants were thin and emaciated at the end of the experiment. Lettuce could not continue growth where the light was reduced to less than n/15. In this respect it showed somewhat less shade tolerance than the mustard. In light more intense than n/15 no great difference was noted in the weight, although the plants were uniformly heavier in sections 3 to 5 than in normal light. (Table VIII.) In height plants 30 days old (Table V), as well as those 50 days old (Table

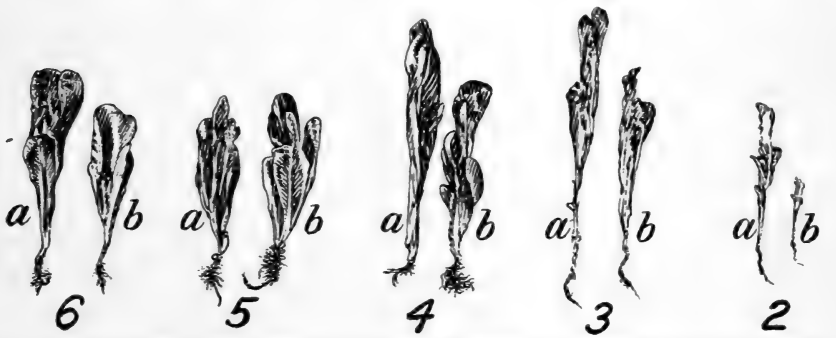


FIG. 7.—Relative sizes of lettuce plants 50 days after germination. The numbers correspond to those of the shades and the letters indicate the two beds in the experiment. (Traced from photograph.)

IX), were consistently taller in sections 3 and 4. The diameter of stem after 30 days (Table VI) and after 50 days (Table X) was not substantially increased in full light as compared with light reduced as little as to n/7. The stems in n/15 light were greatly reduced in diameter.

In figure 7 the relative size of the plants at the end of 50 days is shown. No consistent differences attributable to the differences in temperature and humidity could be noted as between bed A and bed B. In the deepest shade the plants died more quickly in the bed with the fan than in the bed without, but aside from this no other differences were noted.

Lettuce could not endure a shade greater than n/15. The best growth was made under the lighter shades. In full light the plants were smaller than in n/2 and n/5 light. Growth was best along the line between these two shades. In flavor only a slight change could be noted between the plants receiving full light and those receiving n/2 light, but under n/5 illumination the strong taste had almost entirely disappeared. When the light was reduced to n/7 the flavor was even better, but the plants were by no means as desirable in habit of growth as in brighter light.

RADISH.

In n/93 light the radish continued for 30 days in bed B. In bed A all plants subjected to this reduction of light had died before this date. At the end of 50 days plants were still growing in n/15 light, although the growth was very slight. The shade tolerance of radishes is about the same as that of lettuce.

Growth was quite consistently better in n/2 and n/5 than in full light, the plants having been not only heavier (Table VIII) but taller (Table IX) and showing more nodes (Table XI). The plants in bed A seem to have been better than those in bed B according to measurements of height and weight, but observations at the end of the experiment failed to show any consistent difference.

General observations showed that the best growth of radishes took place in sections 4 and 5, and a decided reduction in section 3 and in full light. There was practically no production of roots below section 3. The effect of shade could not be noted in the flavor.

POTATO.

Because of the large amount of stored food material, potato plants were able to continue growth in the deepest shade for a period of 50 days. At the end of 30 days there was a noticeable difference in the height of the plants in the different shades (Table V), and by the end of 50 days the plants under shades which gave a light intensity varying from n/7 to n/2 became much taller than normal, especially those in bed A (Table IX). In diameter of stem there was little difference either after 30 days or after 50 days. (Tables VI and X.) In weight there was considerable variation after 30 days (Table IV), and even more after 50 days (Table VIII). The plants gained greatly in weight during this period in light n/2 to n/7, but in light n/15 the plants weighed less at the end of 50 days than at the end of 30 days. This loss is also indicated by the shrinkage of the diameter of the stem. The number of nodes developed was greater in light n/2 to n/7, and it is evident that the increased height was due to an increase in the number of nodes and not to greater length of the individual segments. The number of nodes developed did not differ greatly in full light and in light intensities of 1/15 normal or less. (Table XI.) The height of the plants was about the same in normal light as in a light intensity of n/15. (Tables V and IX.)

It should be noted that the plants in bed A (that in which the fan was operated) were much taller and heavier than those in bed B. (Tables IV, V, VIII, and IX.) Since the difference showed most markedly in shade 5, which was so far removed from the fan as to make it practically impossible to detect the air current, the writer is inclined to regard it as produced by some factor other than those especially considered in this paper.

The potato could elaborate no food material and in fact developed no leaves in the deepest shade. In n/15 light the leaves were very small, and no food material, or at least very little, was elaborated, since when once the plants had exhausted the reserve food supply there was no further increase in weight, the weights at the end of 50 days having been less than at the end of 30 days. With a light intensity varying from n/7 to n/2 growth was greater than in full light.

FIG. 8.—Relative sizes of potato plants 30 days after the beginning of growth. The numbers correspond to those of the shades and the letters indicate the two beds in the experiment. (Traced from photograph.)

The relative size of the plants after 30 days (fig. 8) and 50 days (fig. 9) shows the increased growths in light n/2 to n/7; also the limited growth in n/15 and n/93 light. As long as the food supply of the tuber was adequate to the needs of the plants they grew as well under the deeper shades as in the more intense light; but as soon as the food supply failed, it became evident that a light intensity of n/15 or less was insufficient for food manufacture. Small leaves, which were normally green developed in n/15 light, but apparently little or no starch formation could take place.

COTTON.

In some ways the results of shading cotton were more interesting than those obtained with any other plant. The weight of the cotton plants showed a considerable increase at the end of 30 days even in n/15 and n/93 light. In n/7 to normal light no great differences were noticed. After 50 days, however, the greatest growth was recorded in n/2 light. In the full light great reduction was noticed in the weight of the plant in each case. It is especially interesting that cotton, which is supposed to be a sun-loving plant, was the only plant able to remain alive and in a healthy condition in light as weak as n/93 for as long a period as 50 days. The plants continued in n/15 light in both beds until the end of the experiment, although no appreciable increase in weight resulted.

In height the best growths recorded were in light of an intensity equal to n/7 or stronger. (Tables V and IX.) In n/93 and n/15 the plants were not noticeably taller at the end of 50 days than at the end

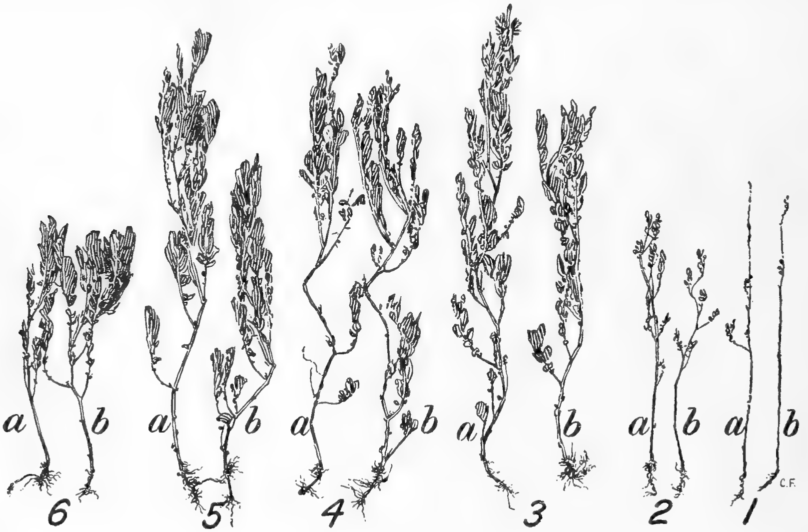


FIG. 9.—Relative sizes of potato plants 50 days after the beginning of growth. The numbers correspond to those of the shades and the letters indicate the two beds in the experiment. (Traced from photograph.)

of 30 days. In each case the height in normal light at the end of 50 days was less than in n/7 to n/5 light.

The relative diameter of stem is shown in Tables VI and X, and was usually greater in the weaker shades than in full light. A noticeable difference also occurred in the number of nodes developed at the end of 50 days, an increase in number having been observed in the weaker shades. (Table XI.)

A good idea of the appearance of the plants at the end of 30 days in the bed with the fan is given in Plate II, figure 1, and in the bed without the fan in Plate II, figure 2. No appreciable reduction in growth took place until the light was reduced below n/7. The relative size of the plants at the end of the experiment (after 50 days) is shown in figure 10.

At the end of the experiment no consistent effect could be noted which could be ascribed to the use of the fan. The best growth was found between n/5 and n/2 light, a marked decrease being noticeable in full light. In the shades no great reduction in growth occurred until the light was reduced to n/15, and even at the end of the experiment plants were alive and in good condition in n/93, although they had produced no leaves aside from the cotyledons. Cotton, therefore, showed more tolerance of shade than any of the other plants used in these experiments.

CORN.

Corn showed considerably more tolerance of shade during the early portion of the experiment than either mustard, lettuce, or radish,

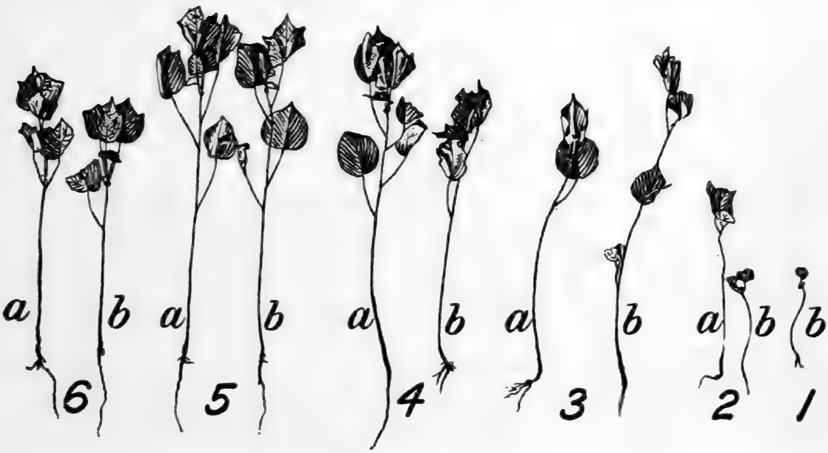


Fig. 10.—Relative sizes of cotton plants 50 days after germination. The numbers correspond to those of the shades and the letters indicate the two beds in the experiment. (Traced from photograph.)

probably as a result of the larger seed and consequent greater food supply. At the end of 30 days plants were still living in n/93 light, and in bed A plants remained alive in n/15 until the end of the experiment, or 50 days. On the whole, however, the best plants were produced in the strongest light (Table VII), and in this respect the results with corn differ from those with cotton, potato, radish, lettuce, and mustard. While the plants were tallest in n/7 to n/2 light, the stems had the greatest diameter in the strongest light. The most interesting fact brought out in the case of corn was that although the plants grew fairly well with as slight illumination as n/15, and although with a light intensity of n/93 plants maintained themselves in the bed with the fan for 30 days, all plants had disappeared from the portion of the beds receiving this intensity of light before the end of the experiment, and in the bed without the fan they had also disappeared in n/15 light.

At the end of the experiment it was evident that corn was the least tolerant of shade of any of the plants used, and a reduction of light to n/2 caused a decided reduction in growth. Figure 11 shows the relative size of the corn at the end of the experiment.

In corn, as in the other plants, the differences due to differences in light intensity were much greater than those produced by the variations in other factors.

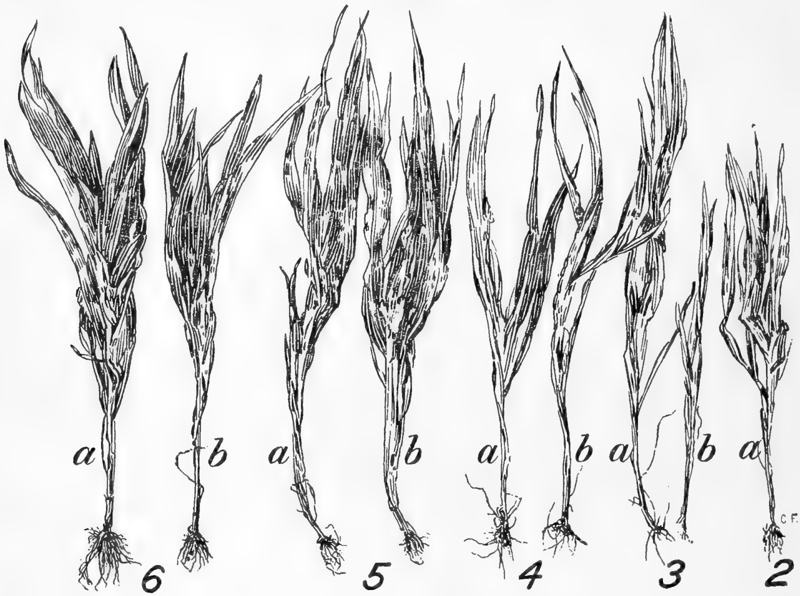


FIG. 11.—Relative sizes of corn plants 50 days after germination. The numbers correspond to those of the shades and the letters indicate the two beds in the experiment. (Traced from photograph.)

GENERAL CONDITION OF THE PLANTS AT THE END OF 30 DAYS.

The relative green weights based upon the average weight per plant at the end of 30 days under the different light intensities is shown in Table IV. The results for beds A and B show clearly that the growth was uniformly better in full light at this early period of the experiments. While the weights of some of the plants grown in the shades were above the weights of those grown in normal light, this was the exception rather than the rule. At the end of 30 days many of the plants were still growing even in the deeper shades, and at this time the green weights of the plants in most cases showed a gradual decrease from those in full light to those in n/93 light.

TABLE IV.—*Average green weight per plant at the end of 30 days, in percentages of weight in normal light.*

Bed and plants.	Section number and light intensity.					
	1, n/93.	2, n/15.	3, n/7.	4, n/5.	5, n/2.	6, n.
Bed A (with fan):						
Corn	2	8	30	55	77	100
Potato	34	65	168	130	129	100
Cotton	12	23	114	68	60	100
Radish	0	50	63	79	108	100
Mustard	0	16	69	72	70	100
Bed B (without fan):						
Corn	0	5	32	45	94	100
Potato	33	26	33	54	57	100
Cotton	12	31	49	123	92	100
Radish	0	88	48	77	68	100
Mustard	0	16	77	123	99	100

Table V shows the comparative height of the plants at the end of 30 days. The average height of the plants in the corresponding sections of beds A and B shows no significant differences. Both beds show clearly an increase in height in light n/7, n/5, and n/2 and a decided decrease in n/15 and n/93 light. In general the heights recorded in n/7, n/5, and n/2 light exceed those in normal light.

While the diameter of the stems (Table VI) of many plants is greater in shade than in full light, the averages show that, as a rule, the stem diameter was smaller in reduced light.

In general the plants showed a more or less gradual decrease in weight and in stem diameter in passing from normal to n/93 light. In height most of the plants in light n/7 to n/2 greatly exceeded those in normal light, and also those in n/15 to n/93 light. Plants of mustard and lettuce died in n/93 light, radish in n/93 light in the bed with the fan, and corn in n/93 light in the bed without the fan.

TABLE V.—*Average height of plants at the end of 30 days, in percentages of height in normal light.*

Bed and plants.	Section number and light intensity.					
	1, n/93.	2, n/15.	3, n/7.	4, n/5.	5, n/2.	6, n.
Bed A (with fan):						
Corn	38	48	86	113	104	100
Potato	120	149	149	160	131	100
Cotton	47	63	105	103	89	100
Radish	0	51	129	108	126	100
Lettuce	0	109	148	174	100	100
Mustard	0	57	102	108	102	100
Bed B (without fan):						
Corn	0	46	92	110	120	100
Potato	102	95	95	102	102	100
Cotton	47	68	105	100	111	100
Radish	36	54	88	125	123	100
Lettuce	0	96	169	169	130	100
Mustard	0	64	115	102	102	100

TABLE VI.—*Average diameter of stem at the end of 30 days, in percentages of diameter in normal light.*

Bed and plants.	Section number and light intensity.					
	1, n/93.	2, n/15.	3, n/7.	4, n/5.	5, n/2.	6, n.
Bed A (with fan):						
Corn	17	28	59	69	86	100
Potato	71	82	100	82	82	100
Cotton	72	91	127	109	109	100
Radish (diameter of root)	0	17	33	33	117	100
Lettuce	0	60	110	130	125	100
Mustard	0	33	73	62	73	100
Bed B (without fan):						
Corn	0	32	59	62	90	100
Potato	71	82	71	71	82	100
Cotton	73	91	145	73	100	100
Radish (diameter of root)	20	17	20	50	42	100
Lettuce	0	60	110	60	115	100
Mustard	0	33	91	127	127	100

GENERAL CONDITION OF THE PLANTS AT THE END OF 50 DAYS.

CORN.

During the later stage of the experiment corn behaved so differently from the other plants that it had best be discussed separately. In Table VII are shown the average green weight, the height, and the diameter of stem at the end of 50 days. These measurements indicate a reduction in the growth of corn even in the weakest shade. With a further reduction in light, marked reduction in growth is noted until in light n/93 none of the plants survived. Corn plants were barely able to survive in light n/15 and in bed B failed even under this illumination.

TABLE VII.—*Growth of corn at the end of 50 days, in percentages of growth in normal light.*

Bed and growth.	Section number and light intensity.					
	1, n/93.	2, n/15.	3, n/7.	4, n/5.	5, n/2.	6, n.
Bed A (with fan):						
Average green weight	0	35	47	84	62	100
Average height	0	87	111	87	108	100
Average diameter of stems	0	65	111	71	94	100
Bed B (without fan):						
Average green weight	0	0	7	46	94	100
Average height	0	0	72	96	103	100
Average diameter of stem	0	0	41	65	118	100

OTHER PLANTS.

In Table VIII the green weights at the end of 50 days are shown. An increase in weight is shown in five out of eight cases in n/7 light, as compared with that in normal light. The increase is considerably greater in n/5 light and still greater in n/2 light. A reduction of light to n/15 reduced the weight many times, and at n/93 only potatoes and cotton remained alive. In general, no growth was made in light of an intensity equal to n/15 or less after the food supply in the seeds had been exhausted. As a rule, light intensities ranging from n/7 to n/2 produced heavier plants than normal light.

TABLE VIII.—*Average green weight of plants at the end of 50 days, in percentages of weight of plants in normal light.*

Bed and plants.	Section number and light intensity.					
	1, n/93.	2, n/15.	3, n/7.	4, n/5.	5, n/2.	6, n.
Bed A (with fan):						
Potato	28	44	282	139	238	100
Cotton	0	18	63	91	223	100
Radish	0	3	103	157	228	100
Lettuce	0	4	106	124	129	100
Bed B (without fan):						
Potato	23	27	160	250	146	100
Cotton	8	10	31	177	178	100
Radish	0	1	55	119	107	100
Lettuce	0	9	147	107	107	100

The tallest plants (Table IX) were produced under light intensities ranging from n/7 to n/2, while those in n/93 to n/15 were generally much shorter than in full light. The ratios between height in the various shades in which an increase was observed and height in normal light were not as great as were the ratios between weight in the shades in which an increase took place and that in normal light, which indicates that the plants under the weaker shades were heavier in proportion to their height than plants grown in normal light.

TABLE IX.—*Average height of plants at the end of 50 days, in percentages of height in normal light.*

Bed and plants.	Section number and light intensity.					
	1, n/93.	2, n/15.	3, n/7.	4, n/5.	5, n/2.	6, n.
Bed A (with fan):						
Potato	112	100	179	171	175	100
Cotton	0	66	108	130	133	100
Radish	0	52	165	178	126	100
Lettuce	0	91	145	136	97	100
Bed B (without fan):						
Potato	108	88	142	165	125	100
Cotton	32	38	122	108	130	100
Radish	0	26	96	117	117	100

The greatest diameter of the stem (Table X) was found in plants grown in the weaker shades, with one exception. With a reduction to n/5 or less, most of the plants showed a decided reduction in stem diameter.

TABLE X.—*Diameter of stem at end of 50 days, in percentages of diameter of stem in normal light.*

Bed and plants.	Section number and light intensity.					
	1, n/93.	2, n/15.	3, n/7.	4, n/5.	5, n/2.	6, n.
Bed A (with fan):						
Potato	53	67	93	80	107	100
Cotton	0	86	143	171	143	100
Lettuce	0	32	84	105	95	100
Bed B (without fan):						
Potato	80	67	80	93	80	100
Cotton	71	71	86	86	143	100
Lettuce	0	32	84	84	105	100

In number of nodes (Table XI) the plants grown in n/2 to n/7 light usually exceed those grown in normal light except for cotton in n/7 light. With a light reduction of n/15 or more the number of nodes produced was greatly reduced except in the case of potatoes.

TABLE XI.—*Average number of nodes per stem at the end of 50 days, in percentages of number developed in normal light.*

Bed and plants.	Section number and light intensity.					
	1, n/93.	2, n/15.	3, n/7.	4, n/5.	5, n/2.	6, n.
Bed A (with fan):						
Potato	84	103	168	161	136	100
Cotton	0	55	91	127	146	100
Radish	0	67	107	133	120	100
Bed B (without fan):						
Potato	97	91	116	148	123	100
Cotton	18	18	91	109	127	100
Radish	0	40	107	133	107	100

EFFECT OF SHADE ON THE THICKNESS OF LEAVES.

Leaf prints made by exposing a series of selected leaves for a sufficient length of time to produce a print on a photographic "printing-out" paper, give a very good idea of the relative absorption of light by the different leaves. Leaves which have developed in full light are thicker and give lighter colored or whiter prints than the thinner leaves which have been grown under shades.

In corn (Pl. III, fig. 2), though a slight difference can be noted as between normal (No. 6) and n/2 (No. 5) light, and a more marked difference as between n/2 and n/5 (No. 4), practically no difference can be noted in the shades of the prints from leaves produced under a light intensity of less than n/5. Only a comparatively slight difference is shown in this series of prints, which indicates that in corn there was only a slight modification in thickness of the leaf and density of the chlorophyll as a result of this variation in the physical environment.

FIG. 1.—LEAF PRINTS OF POTATO FROM ALL SECTIONS OF BEDS A AND B AT THE END OF 30 DAYS. SHADES AS NUMBERED; 1 INDICATES LEAST ILLUMINATION AND 6 NORMAL LIGHT.

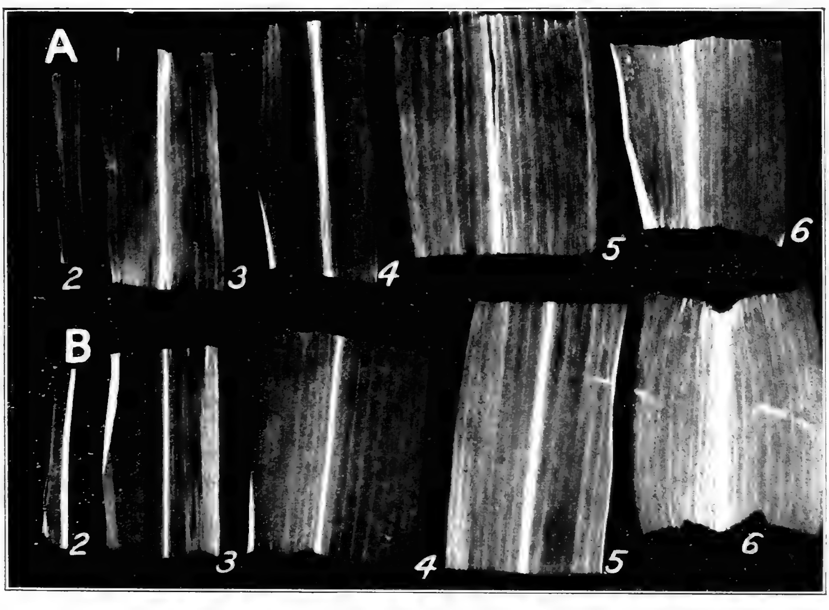


FIG. 2.—LEAF PRINTS OF CORN FROM BEDS A AND B AT THE END OF 30 DAYS. SHADES AS NUMBERED, RANGING FROM 2 (N 15 LIGHT) TO 6 (NORMAL).

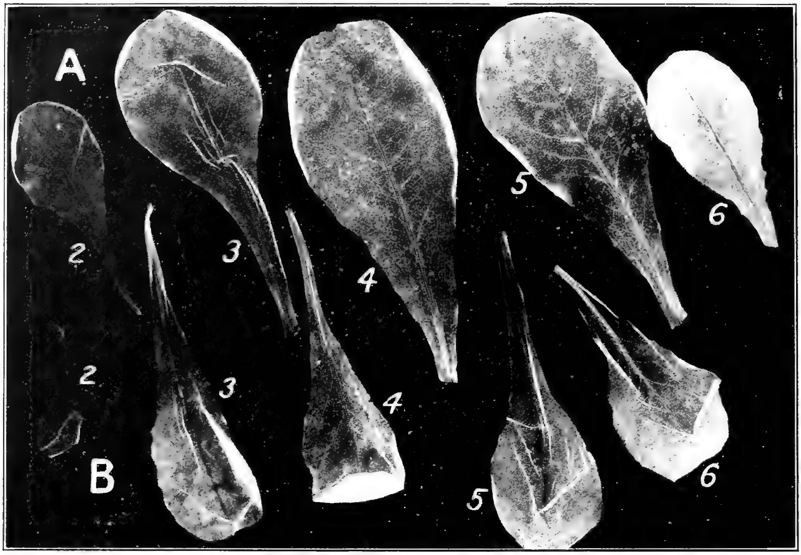


FIG. 1.—LEAF PRINTS OF LETTUCE FROM BEDS A AND B AT THE END OF 30 DAYS. SHADES AS NUMBERED, RANGING FROM 2 (N/15 LIGHT) TO 6 (NORMAL).

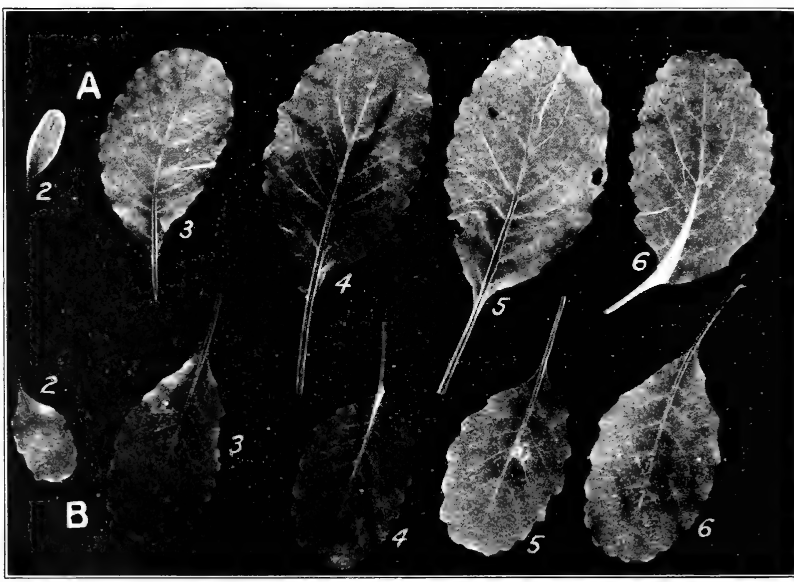


FIG. 2.—LEAF PRINTS OF MUSTARD FROM BEDS A AND B AT THE END OF 30 DAYS. SHADES AS NUMBERED, RANGING FROM 2 (N/15 LIGHT) TO 6 (NORMAL).

The potato leaf prints present a very uniform gradation, being lightest in the case of leaves produced under full light and darkest in those produced under the deepest shade. (Pl. III, fig. 1.) In the older leaves a marked difference was noted between those produced under light intensities of n/2 and n/5. The prints from leaves under n/2 were almost as white as those grown under full light, while those in n/5 were almost as dark as from the leaves grown in n/7 or below, which shows a comparatively great morphological variation as a result of changed conditions.

In cotton (Pl. V, fig. 1) there was a rather uniform gradation in darkness of the print, passing from full light to the deeper shades. The most marked difference occurred between normal (section 6) and n/2 (section 5) light. In the cotyledons this difference is not so marked as in the later leaves, but there is a great although gradual variation from n/93 to normal illumination. Cotton showed considerable morphological differences in both the cotyledons and the foliage leaves.

Mustard shows a very gradual although slight difference in the leaves in passing from n/93 to normal light. (Pl. IV, fig. 2.) This indicates but little ability to modify the leaf morphology to meet changed conditions.

Radish shows a marked difference in the leaves produced under normal light as compared with those developed under n/2 and corresponding differences under each deeper shade. (Pl. V, fig. 2.) The same is true of lettuce. (Pl. IV, fig. 1.) In each case profound morphological changes resulted from altered environmental conditions.

It is especially interesting to note that the leaf prints for a number of these plants indicate marked morphological differences such as have been noted in comparing sun and shade leaves of the same species (Stahl, 1883). Two of the plants used, corn and mustard, show little variation, and these plants are the ones which have proved the least productive in shade. All of the others—cotton, potato, radish, and lettuce—show pronounced variations or morphological adaptations, and these are the plants which have shown increased production when grown in shade.

GENERAL DISCUSSION.

Lubimenko (1908) showed clearly that in France a slight reduction of illumination produced an increase in the production of dry matter in the great majority of the plants tested. Shades giving only a slight reduction of light intensity were employed, and no attempt was made to equalize other conditions. The work of Combes (1910) is far more exhaustive and brings out the fact that some of the plants were immediately retarded in growth by the application of shade. This was not true for the ordinary mesophytic plants but for such plants as *Salsola tragus*, *Amaranthus blitoides*, and *Atriplex canescens*, which are all xerophytic, sun-loving plants.

Most of the species used showed increased growth in shade. Combes (1910) concludes from his experiments that seedlings are more tolerant of shade than are adult plants. From the data obtained both by Combes and by the writer it appears likely that tolerance of shade is largely determined by the ability of the plant to manufacture food. If this be the case, seedlings, because of the food stored in the seed, would be expected to show much greater tolerance than adult plants, which are entirely dependent upon photosynthesis to support further growth.

The results of the experiments described in this paper make it seem probable that only during the periods of most intense illumination was a light intensity of n/15 sufficient to permit the elaboration of starches in any of the plants grown. (Pl. VI.) Moreover, none of the native plants which grew as weeds at the edge of the beds under the different shades were able to manufacture starch when the light intensity was below n/15.

It was also evident that where the illumination exceeded n/15 cotton, lettuce, potato, and radish were able to elaborate organic matter as readily as under full light.

Careful observation of the growth of these plants for the period during which the experiment was continued showed in practically all cases an increased growth where there was a slight reduction of the light intensity. A decided increase in growth could be noted in passing from normal to one-half normal light in all cases with the exception of corn.

In general no reduction in growth occurred when light was reduced to n/5, and usually none took place at n/7. But when the light was reduced to n/15 a very marked falling off in growth occurred (Pl. VI) and in most species the plants disappeared entirely under the shade, giving an illumination of n/93. Mustard made its best growth in light of an intensity between n/5 and n/2, and radish between n/7 and n/5, with a decided reduction of growth in full light. Lettuce grew best where the light was between n/2 and n/7, the plants under full light being smaller by comparison. Cotton produced the largest and most vigorous plants between the shades corresponding to n/5 and n/2 light intensity, the plants in full light having been much smaller. In n/15 growth was almost checked, while in n/93 the plants continued alive but were unable to elaborate any food material. Full light seemed unfavorable to maximum growth in the potato but not in corn. While the potato and corn were able to maintain

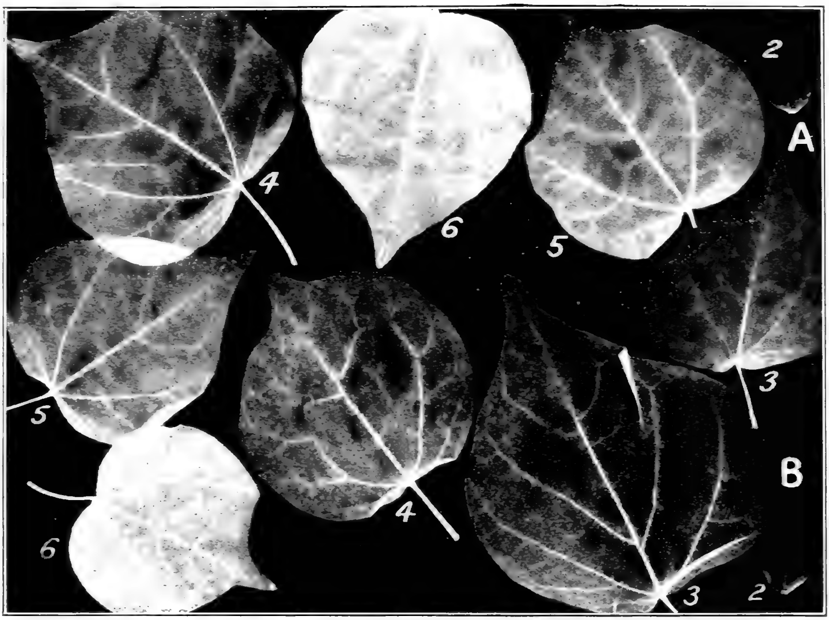
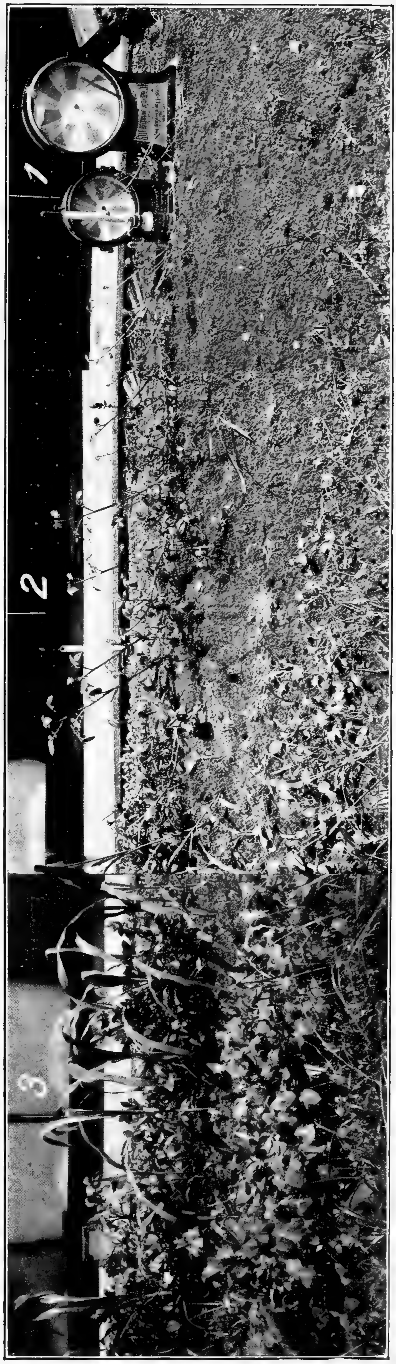


FIG. 1.—LEAF PRINTS OF COTTON FROM BEDS A AND B AT THE END OF 30 DAYS. SHADES AS NUMBERED, RANGING FROM 2 (N 15 LIGHT) TO 6 (NORMAL).

FIG. 2.—LEAF PRINTS OF RADISH FROM BED B AT THE END OF 30 DAYS. LEAF PRINTS OF BED A EXHIBIT NO ESSENTIAL DIFFERENCES FROM THOSE HERE SHOWN. SHADES AS NUMBERED, RANGING FROM 2 (N 15 LIGHT) TO 6 (NORMAL).



GENERAL APPEARANCE OF BED A, SECTIONS 3, 2, AND 1 (N/7, N/15, AND N/93 LIGHTS), AT THE END OF 50 DAYS.

themselves in the deepest shade in the early part of the experiments, they made practically no growth in a light intensity of n/15 or less.

The effect of the reduction of light upon the flavor of lettuce was very marked. With a reduction to n/5 the flavor of lettuce was noticeably improved and the growth was still somewhat better than in full light. The flavor of radish was not perceptibly changed by shading.

The effect of the equalization of temperature, due to the introduction of the fan in one of the beds, was in most cases very slight. In the case of the potato the growth in the bed with the fan seemed to be considerably better than in the other. In all probability this was not due to the action of the fan itself, for the reason that in sections 4 and 5, far removed from the fan, the differences were greater than in sections 2 and 3, which were nearer to the fan. In fact, careful observations of the beds at the end of the experiment led to the conclusion that the effects resulting from changes in temperature, humidity, and even wind movement, were negligible as compared with those resulting from differences in illumination. As far as the evidence from these experiments go, the effects noted in shade experiments are attributable to reduction of the light intensity and not to any appreciable extent to the resulting differences in other factors.

In general, we may say that the growth of the plants with which experiments were made was not as good, measured by the general appearance of the plants, height, green weight, and number of nodes, in full light as it was in the light from n/2 to n/5. Some of these plants were able to grow in a light reduced to n/7 almost as well as in full sunlight. A reduction of the light to n/15 cut down the growth very perceptibly, although all of the plants, with the exception of corn in bed B, were able to keep alive even under this condition. When the light was reduced to n/93 the only plants which survived were cotton and potato. The potato plants were in a dying condition at the end of the experiment, and the cotton had made no growth, but was able to keep alive and in good condition even with this degree of shading. The probable reason for the failure of these plants to grow in light less than n/15 was their inability to manufacture carbohydrates. The plants were green colored and had developed chlorophyll, but were unable to increase in size after the reserve material of the seed or the tuber was exhausted. Corn showed very little ability to continue growth even with n/15 light. This amount of light reduction apparently marked almost the limit for carbon assimilation in all of the plants used.

The amount of solar energy utilized directly in the process of photosnythesis has been accurately calculated by Brown and Escomb (1905), and is a surprisingly small proportion of the amount of light which in the present experiments proved to be necessary in order that growth could take place. They have also shown that of the incident light the greater portion is dissipated by emissivity from the leaves and through transpiration. A limit to the amount consumed in photosynthesis is therefore established by the limited supply of CO_2 in the atmosphere. Although only a fraction of 1 per cent of normal light is usually required for photosynthesis, it does not follow that photosynthesis will continue when the light intensity is reduced to this amount.

The actual amount of solar energy received by the plants under the different shades in the experiments here described necessarily varied greatly at different periods of the day. The maximum daily illumination would probably be the most important factor in fixing the lower limits for growth under the shades. By comparing the data given by Abbot (1911, pp. 358 and 385, fig. 72) it will be seen that the rate at which solar energy is received at Baton Rouge during the months of April and May during the brighter part of the day is approximately 150 calories per square meter per second, this value including both direct sunlight and the additional radiation from the sky (Abbot, 1911, p. 307).

Since the relative shading produced by the different cloths used in these experiments was measured by means of Abbot's pyrheliometer, it is possible roughly to express the results in terms of total solar energy received by the plants under different shades. In these experiments growth was best when the solar energy during the brighter part of the day was so reduced as to range from n/2 to n/7, or to range from 75 to 21 calories per square meter per second. On the other hand the lower limit of growth was somewhat below 10 calories per square meter per second (n/15). Previous measurements by Brown (1905, p. 525) show that photosynthesis was not retarded in some cases when the illumination was reduced to 7 calories per square meter per second. This accords very well with the results obtained in the experiments here recorded.

SUMMARY.

(1) When the illumination was so decreased as to range from n/2 to n/7 a general increase in growth resulted in potato, cotton, lettuce, and radish, which was expressed in increased green weight, height, and number of nodes.

(2) Corn made its best growth in full light.

(3) When the light was reduced to n/15 or less none of the plants tested were able to elaborate food material sufficient to produce growth after the seedling stage was passed.

(4) From Abbot's measurements, the total maximum rate at which solar energy was received during any considerable period while the experiment lasted was probably approximately 150 calories per square meter per second. In terms of solar energy, growth was best when the energy received varied from 21 to 75 calories per square meter per second. Photosynthesis and consequently growth practically ceased when the energy was reduced to 10 calories per square meter per second or less.

(5) The apparent tolerance of shade exhibited by the younger plants was probably the result of the food supply still remaining in the seed and not of any special ability of seedlings to carry on photosynthesis in weak light.

(6) The effects of variations in temperature and humidity incident to shading were so slight in this experiment that they could not be detected by a comparison of the plants in the bed in which these conditions were equalized by the use of an electric fan with the plants in the bed in which no attempt was made to equalize conditions by this means. Differences in shade produced such marked effects on plant growth that the effects due to shading were entirely predominant, and compared with these the resulting effects of change in humidity and temperature were practically negligible.

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