

INFLUENCE OF VARIOUS WAVE LENGTHS OF RADIANT ENERGY ON HEAT
RESISTANCE IN CROP PLANTS

by

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INTRODUCTION

Semiarid and arid regions comprise a major portion of the agricultural lands of the globe. Potential production is high in these regions but frequently falls far short of expectations due to the action of two major limiting factors; high temperature and drought. These factors may operate singly but far more frequently are found in combination, and the situation in the field is generally such as to make any distinction between them extremely difficult.

Numerous studies of drought resistance have been carried out and several competent investigators have turned their attention to heat resistance investigations. The anatomical adaptations of heat and drought resistant species have been described in detail as have the several growth habits which enable some plants to evade, escape, or endure these periods of stress. While these adaptations are of interest and some of them are possessed by many of the common crop plants, it is generally recognized that knowledge of the mechanisms which enable the plant to live through heat and drought in the vegetative condition is inadequate.

The suggestion has been made by Duggar (1936) that there may be a direct relationship between the photosynthetic process and heat resistance, since exposure of plants to light seems to induce increased heat resistance. Several workers, as reported by Franck and Loomis (1949, p. 249), have shown that photosynthesis occurs in all portions of the visible spectrum. The investigation herein

reported represents an attempt to determine by physical means whether induction of heat resistance by exposure to light also occurs in all regions of the spectrum or only in certain portions.

REVIEW OF LITERATURE

Morphological and Physiological Influences of Radiation

Probably the first investigations involving the influence of different spectral regions on the green plant were concerned with gross morphological characteristics. The work of Popp (1924) is an example of this type of research. It was found that plants grown under glass which screened out various portions of the spectrum showed marked morphological and physiological differences. Plants were grown under five different types of glass. Those plants receiving all light of wave lengths longer than 3880A were superior in dry weight over all others tested and bloomed earlier. Plants grown in 4710A were tall but did not produce as much total dry matter. Soy beans grown in this situation and also in light of wave lengths longer than 5410A became twiners. In both of these latter treatments storage organs failed to develop. It is unfortunate that this work included no comparison with direct sunlight.

Hibben (1924) found that constant regulated artificial light alone produces better growth than the changeable daylight of early spring when considering the natural development of the bulb

plants. He also reported that light from the incandescent electric lamp produces better growth than does the same light from which wave lengths below 5500A have been screened.

Working with lettuce seeds and seedlings, Flint and Moreland (1939) report that red light (7600A) inhibits germination and retards development of the seedlings. No greening was observed in these plants. The authors state that this does not seem to be associated with assimilation or temperature. These effects were not found under radiation of 6500A or of 8500A wave length.

Plants grown under continuous sodium vapor light (5893A) were used in experiments by Arthur and Harvill (1937). Such plants were found to grow well for a short time, after which slow degeneration occurred. When the sodium light was supplemented by a two-hour exposure each day to light from a mercury vapor lamp, the plants appeared to be rejuvenated, with excellent leaf color, and normal flowering occurring in some plants. The light of the mercury vapor lamp is rich in short wave length radiation, much of the energy lying within the ultra-violet region of the spectrum.

Using *Marchantia*, radish, and several other plants, Schappelle (1936) found that red and blue lights are of approximately equal effectiveness in producing reproductive growth response. In all cases it was found that either end of the visible spectrum, given in complete absence of the other, causes abnormal growth. Blue light appeared more injurious than red in this respect.

Arthur and Stewart (1935) found that when equal intensities

of light from Mazda bulbs, and from neon, sodium and mercury vapor lamps were used as illumination for the growth of buckwheat plants there was a difference in production of dry weight. The lamps in order of dry weight production ranged from neon through Mazda and sodium and down to mercury vapor. Efficiency of use of the various lights by plants was calculated. The sodium light was found to be most efficient with the neon lamp second and the mercury vapor lamp least efficient. No correlation could be detected between the efficiency of the lamp and the relationship of its energy spectrum to the absorption spectrum of chlorophyll. In a somewhat different type of study of light efficiency in photosynthesis, Warburg and Negelein (1923) using the green algae Chlorella reported a photosynthetic value of 33.8 for blue light (4360A) as compared with 53.5 for yellow light (5780A). Red light (6600A) was reported to be 1.13 times as effective as yellow.

In a study of comparative rates of photosynthesis in equal intensities of red and blue as compared with sunlight, Dastur and Mehta (1935) reported the rate to be highest in sunlight, intermediate in red light, and very low in the blue light. These authors concluded that the efficiency of photosynthesis decreases with decreasing wave lengths but that both red and blue light are necessary for normal photosynthesis. Hoover (1937) found that on a basis of equal incident energy determined as a function of the wave length of light, the entire visible spectrum is effective in the wheat plant. Plotted as a curve, photosynthesis against wave length, a principal maximum appears at 6550A in the red and a

secondary maximum at 4400A in the blue. Increased reflection and transmission of radiation in the green region are given as a possible explanation for the lower effectiveness of incident green rays. In general agreement with these investigations, Dutcher and Haley (1932, p. 280) found that carbohydrates may be synthesized in the absence of ultra-violet light and under the influence of any light of a definite wave length, but that some wave lengths are more efficient for photosynthesis than others. Duggar (1936, p. 632) reports the use of a different method in a similar investigation. Irradiated cells were tested with methylene blue and their permeability to the dye measured. Permeability was found to depend more on the wave length of irradiation than on the amount of energy applied. White light gave greatest permeability, followed by ultra-violet, blue, green, and red with no light the lowest. This author also states (p. 783) that as the wave length of incident radiation decreases, light transmission decreases and absorption of the light by the leaf increases.

In an attempt to duplicate results by other workers Fuller (1932) exposed tomato and bean plants to radiation from a quartz mercury vapor lamp. His results indicate that much of the injury which has been ascribed to the blue and violet region may actually be due to infra-red radiation. In order to obtain high intensities the plants were placed only 15 inches from the light source. It was found that these radiations were rich in both ultra-violet and infra-red rays and that considerable heat was produced. When the light was passed through a quartz water cell which screened

out all infra-red rays, injury to the plants was greatly reduced, indicating that this injury, formerly thought to be an effect of ultra-violet radiation, may be largely the result of infra-red influence.

In an investigation of the influence of wave length of light on quantum yield of photosynthesis by the green algae Chlorella, Emerson and Lewis (1943) report a maximum yield of 0.09 at about 6850A. This was reduced and became "vanishingly small" beyond wave lengths of 7300A. From 6850A to 5800A the level of yield was near 0.09, while below 5800A it declined to a minimum of 0.065 at 4850A before rising again to nearly 0.08 at 4200A. This would indicate that at least 12 quanta of red light are required per molecule of O₂ evolved by the plant in photosynthesis. Other workers as reported by Franck and Loomis (1949, p. 219, 239, 251 and 273) achieved substantially similar results. These results are contrary to those reported by Warburg and Negelein (1923) and by Baly (1940) in which the maximum quantum yield for the green algae Chlorella is reported to be near 0.25 at a wave length of 5780A.

Arthur and Stewart (1933) studied transpiration in tobacco plants exposed to both visible and infra-red radiation under controlled temperatures and humidities. It was found that, using a standard incandescent lamp, an increase of 2.3 times the energy doubled the rate of water loss. The relationship appeared to be independent of humidity over a range of 50 percent to 88 percent at a temperature of 73° to 78° Fahrenheit. At higher temperature

of 98° to 100° high humidity was reported to decrease transpiration slightly. At the lower temperature the rate of water loss under the lamp without a filter was about 2.5 times the loss under the same lamp with a heat-transmitting filter which passed infra-red rays only. At the higher temperatures the water loss under infra-red increased rapidly. It was concluded that transpiration makes it possible for leaves to exist under high radiation values at high temperatures. In all cases the stomata were found to be closed completely under infra-red radiation. Sayre (1929) had similar results. Using plants of the species Rumex patientia he reported no opening of the stomata in light of wave lengths longer than 6900A. Other regions of the visible spectrum were reported to be equally effective with the exception of the violet region, which was not investigated. Duggar (1936, p. 774) cites investigations by Iwanoff and Thielmann which indicated that blue-violet light seems to favor increased transpiration over red-yellow light.

Chemical Influences of Radiation

Some attempts have been made to determine the influence of various wave lengths of radiations on the chemical composition of the plant. Using the wheat plant, Lease and Tottingham (1935) found that elimination of the blue region from radiation resembling sunlight decreased nitrate assimilation and conserved carbohydrates in the young plant. The plant tissue was found to

be increased in chlorophyll and sulfhydryl content over that of the controls. Associated with an increase in nitrate assimilation was a depression of pentosan formation. Tottingham (1939, p. 214) reports that nitrates could not be absorbed and retained by the plant in darkness.

Using lights of equal total intensity Dastur, Kanitkar, and Rao (1938) found that water soluble nitrogen was formed in leaves in greatest amounts under a carbon arc lamp. A "daylight" lamp was next, followed in order by an ordinary electric lamp and daylight. With low light intensity using monochromatic light and daylight, organic nitrogen content of leaves was investigated. Water-soluble nitrogen formation was found to be greatest in daylight with red light equal to blue-violet at a lower level. It has been reported by Tottingham (1939, p. 212) that plants which have grown under light having wave lengths down to 2900A have a smaller percentage of xylan on a dry matter basis than do those which received no wave lengths shorter than 5200A. He reported that both the ultra-violet and the blue-violet regions appeared to favor the formation of uronic acid and that this condition is associated with a decline in the production of xylan and other pentosans. Gortner (1929) found that high pentosan content is characteristic of many desert plants and that these compounds are highly hydrophilic, apparently functioning as an aid in prevention of water loss. Tottingham and Lowsma (1928) found that increased absorption of nitrate by the young wheat plant when exposed to an increase in blue-violet and long ultra-violet radiation was as-

sociated with sugar consumption and synthesis of protein forms of nitrogen.

In early experiments with ultra-violet radiation on living bacteria, Burge (1917) found that exposure to radiation of sufficient intensity to kill the cells does not decrease the activity of intra-cellular enzymes to any appreciable extent. Death of the cells was described as being due to coagulation of the protoplasm.

Heat Resistance: Artificial Hardening and Reaction to Drought

Some comparatively recent investigations have been made concerning the influence of temperature or heat on the physiological activities of the living plant. Whitfield (1932), in an ecological study, reported that soil temperature below 40° F. has an important influence on transpiration but that at higher temperature the influence is not great.

In a similar study using Helianthus annuus, Clements and Martin (1934) observed little variation in transpiration when soil temperature varied between 55° F. and 100° F. and report that there was no indication that transpiration would be greatly affected at higher soil temperatures. In a detailed analysis of wheat plants during hardening for drought resistance, Vassiliev and Vassiliev (1936) determined the changes in carbohydrates in five varieties of wheat while growing normally, during stress for moisture which induced permanent wilting, and after recovery.

They reported that at the beginning of wilting there was an increased concentration of monosaccharides and sucrose and a decrease in hemicellulose. At the stage of permanent wilting sucrose had decreased, monosaccharides had increased, and there was a decided increase in hemicellulose to a level above that of the check plants. Twenty-four hours after the resumption of irrigation, monosaccharides and sucrose had decreased. No report was made on hemicellulose at this point. Eight days after the plants had recovered, the monosaccharide content was lower than the check plants. Sucrose and hemicellulose content had increased. The suggestion was made that in the wheat plant hemicelluloses take the place of starch as storage foods and act to bind water against loss.

Hardening of plants was found by Dexter (1933) to be favored by conditions which promote the accumulation or conservation of carbohydrates and other reserve foods. These conditions were reported to be any which further photosynthesis and reduce respiration and growth.

Whitman (1941) took weekly samples of the principle species of four representative grassland types in western North Dakota. Tests were made for total water, osmotic value of expressed sap, and relative proportions of bound and free water. It was found that the increase in bound water expressed as percentage of total water was the result of losses of free water due to progressive drying of the plant tissues and not from increases in the water-retaining capacity of the leaves. He considered bound water per-

centage to be a reflection of the relative degree of dryness of the habitat and not a measure of the inherent adaptation of that species to a dry habitat.

Investigations by Bartel (1947), using four varieties of spring wheat, indicated that drought conditions cause a decrease in total moisture content of the leaves and an increase in osmotic pressure and percentage of total solids in the expressed juices. He also reported the reduction in moisture content to be about the same for all varieties, but that the increase in osmotic pressure and in percentage of total solids was greatest in the variety which had been observed to be most drought resistant and least in the variety which had been observed to be least drought resistant.

Laboratory methods and testing procedures have been devised for determining relative heat and drought resistance of the living plant. Hunter, Laude and Brunson (1936) tested 14-day-old corn seedlings of several varieties under controlled temperature and found that an exposure of 6.5 hours to a temperature of 140° F. and a relative humidity of about 30 percent resulted in differential injury to the varieties. This injury was in the same order as the drought injury which had been noted in the field. Heyne and Laude (1940) reported similar results and also noted an increase in heat resistance when the plants were exposed to as little as 1 hour of light following 12 hours of darkness.

Evidence now available indicates a definite close relationship between increased heat and drought resistance and exposure to

light. Duggar (1936, p. 727-762) reported a quick response to light in this respect and suggested that the response might be directly related to the photosynthetic process. Laude (1939) and Kenway, Peto, and Neatby (1942) found a rapid increase in survival of plants exposed to heat and drought, this increase correlating with increase in the length of time during which the plants were exposed to light prior to treatment. It was determined that the lowest survival rate was among plants which had been held in total darkness and that at the end of a two-hour light period the greatest gain in survival was noted although small additional gains were reported for longer exposures.

A close relationship between heat resistance and hardening due to drought has been reported by several workers. Julander (1945), working with several species of grasses, reported that heat resistance is a measure of drought resistance and that hardening by drought under conditions favoring the accumulation of reserves produced highly significant differences in the ability of the plants to resist heat. In the species tested, this ability corresponds closely with the aridity of the natural habitat.

MATERIALS AND METHODS

The Plants

Plants used in this series of experiments were Zea mays and Triticum vulgare. The varieties selected were chosen on the

basis of availability of seed and uniformity of growth. Of the wheats the variety Pawnee was selected and for corn, the single cross WF9x38-11. The plants were grown under normal greenhouse conditions in 4-inch unglazed pots.

The soil used was a dark fertile loam, taken from the Agronomy farm. In experiments 1 to 13 the soil was used without admixture, but in subsequent experiments clean sand was added at the rate of 5 parts of soil to 2 parts of sand in an attempt to obtain uniform pot drainage. No nutrients were added in any of the experiments, the plants being irrigated with tap water only.

Five seeds were planted in each pot and the seedlings thinned to three. The plants were tested from 28 to 35 days after planting to insure that endosperm reserves were depleted. Heyne and Laude (1940) found that corn endosperm reserves are essentially exhausted at 21 days after planting.

Light Treatments

Pertinent information about the light treatments used in this series of experiments is given in the chart in Plate I.

Because of space limitations it was not possible to include all of these treatments in any one experiment. However, every experiment included a "sunlight" treatment and a "total darkness" treatment, the latter serving as a check. The "sunlight" treatment consisted of exposure to the direct rays of the sun in the greenhouse for the period of the treatment. The intensity of this

illumination varied greatly from over 4000 foot-candles on bright days to less than 200 foot-candles on dark, cloudy days. In the "total darkness" treatment a group of plants, similar in every way to those being exposed to light, were held in complete darkness during the treatment period. These were then exposed to high temperatures as were the plants which had received light treatments. It was expected that exposure to bright sunlight would induce the maximum amount of heat resistance which could be produced by light exposure and that the "total darkness" treatment would in all cases represent the daily minimum heat resistance and any increase above this minimum could be ascribed to the influence of light treatments. Periods of exposure to the light were 1, 3 and 6 hours. The temperature within the light compartment was partially regulated by ventilation during treatment, and the difference between the highest and lowest treatment temperature during one experiment was seldom more than 7° F. Light intensity was measured by means of a Weston Photronic cell using a quartz screen which records radiant energy over a range of wave lights from 2900 Angstrom units to well into the infra-red region of the spectrum. An effort was made to equalize the light intensity of the treatments by regulating the distance of the plants from the light source and by changing the number of tubes used. This was partially successful in all cases except that of the sodium vapor lamp and, of course, in the case of sunlight.

The light treatments were carried out in specially constructed compartments (Fig. 1) in which was located a shelf adjustable

EXPLANATION OF PLATE I

The portion of the spectrum included in these investigations is plotted on the horizontal axis. It will be noted that this does not correspond exactly to the so-called "visible spectrum" which is generally considered to extend from 3900 to 7600A. The curves for the various light treatments are all plotted to peak at 100 on a relative scale and do not indicate the comparative amounts of visible light emitted by the various sources.

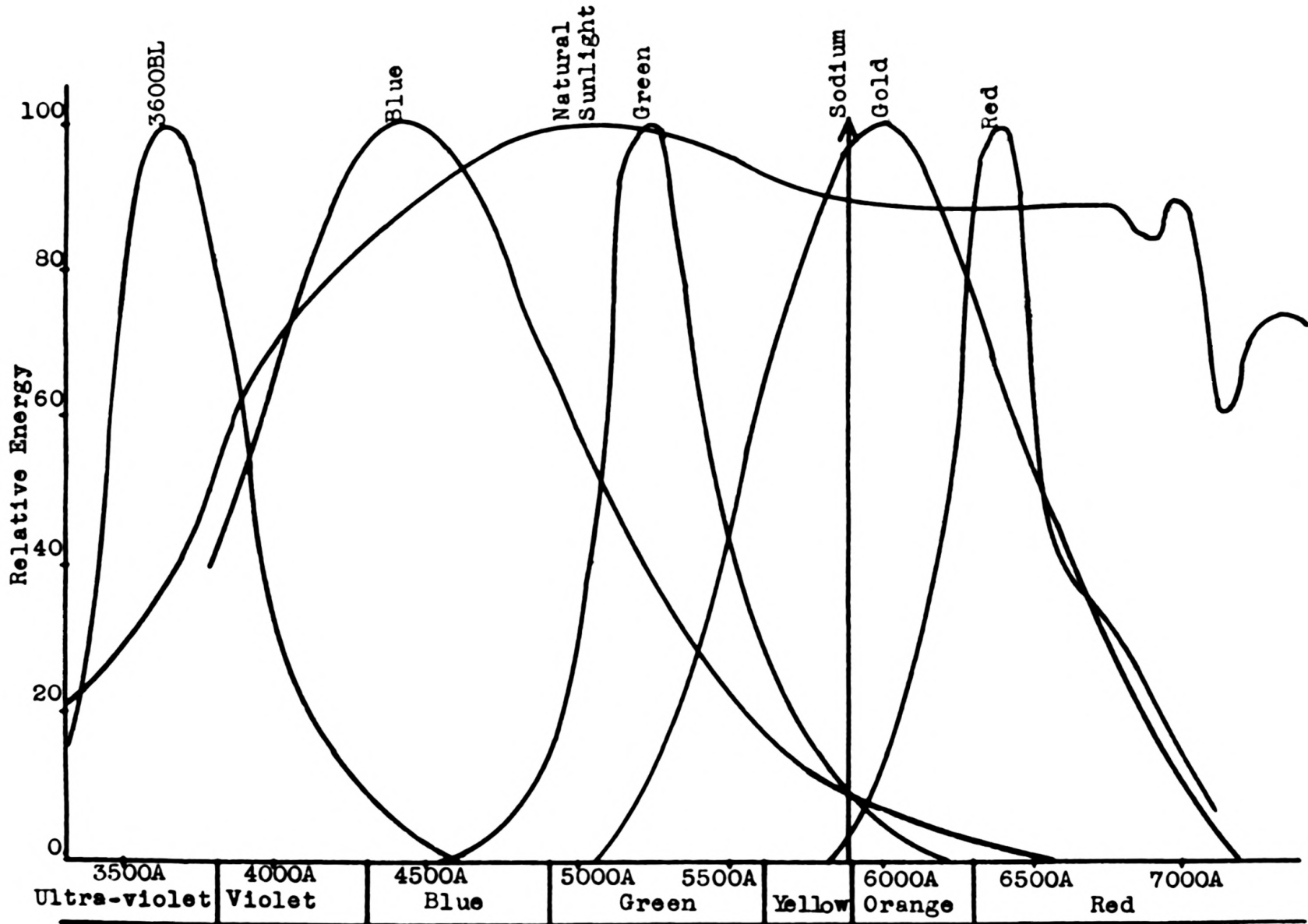


PLATE I

Table 1. Light sources used and portion of spectrum covered by each.

| Treatment: | Light source | Manufactured by | Size | No. of bulbs: | Light intensity at plant height Foot candles | Portion of Spectrum covered | Peak at |
|------------|-------------------|------------------|----------|---------------|--|-----------------------------|---------|
| A | Sunlight | | | | | 2900-35,000A | 5000A |
| B | Total Darkness | | | | | | |
| C | North Light | | | | | 2900-35,000A | |
| D | Red Fluorescent | General Electric | 40 Watt | 4 | 70 | 6000-7200A | 6400A |
| E | Blue Fluorescent | General Electric | 40 Watt | 2 | 110 | 3700-5800A | 4400A |
| F | Green Fluorescent | General Electric | 40 Watt | 2 | 100 | 4800-6000A | 5300A |
| G | Sodium Vapor | General Electric | 180 Watt | 1 | 200 | 5500-6500A | 5893A |
| J | 360BL Fluorescent | General Electric | 40 Watt | 2 | 100 | 3200-4500A | 3600A |
| K | Gold Fluorescent | Westinghouse | 40 Watt | 2 | 110 | 5200-6900A | 6000A |

for height. The covering of the compartment was Sisal-Kraft building paper and was essentially light proof. The inner surface of the covering was sprayed with a white water-mix type of paint to reduce light loss.

The Heat Chamber

The heat chamber used in these experiments (Fig. 2) was a room 6 x 6 x 8 feet. In the center of this room a turntable 5 feet in diameter was located, operating at a constant speed of about 2 RPM. The room is heated by a steam radiator to a temperature of about 135° F. There was no automatic control and this temperature was found to vary depending on the number of pots placed in the room. Temperature and humidity were recorded by a hygro-thermograph and were found to remain quite constant within any one experiment. The length of exposure in the heat chamber was determined by the time required to produce differential injury to the plants. Injury was determined by visual examination of the plants during exposure.

Experimental Procedure

The general procedure used in these experiments was as follows: Plants which had grown under uniform conditions in the greenhouse were placed in a dark room (Fig. 3) in the evening. The following morning, units of four pots each were exposed to

EXPLANATION OF PLATE II

Fig. 1. Close-up of light compartments.

Fig. 2. Heat chamber with plants under treatment. Note the hygro-thermograph in operation on the turntable.

Fig. 3. Interior of dark room.

PLATE II



Fig. 1

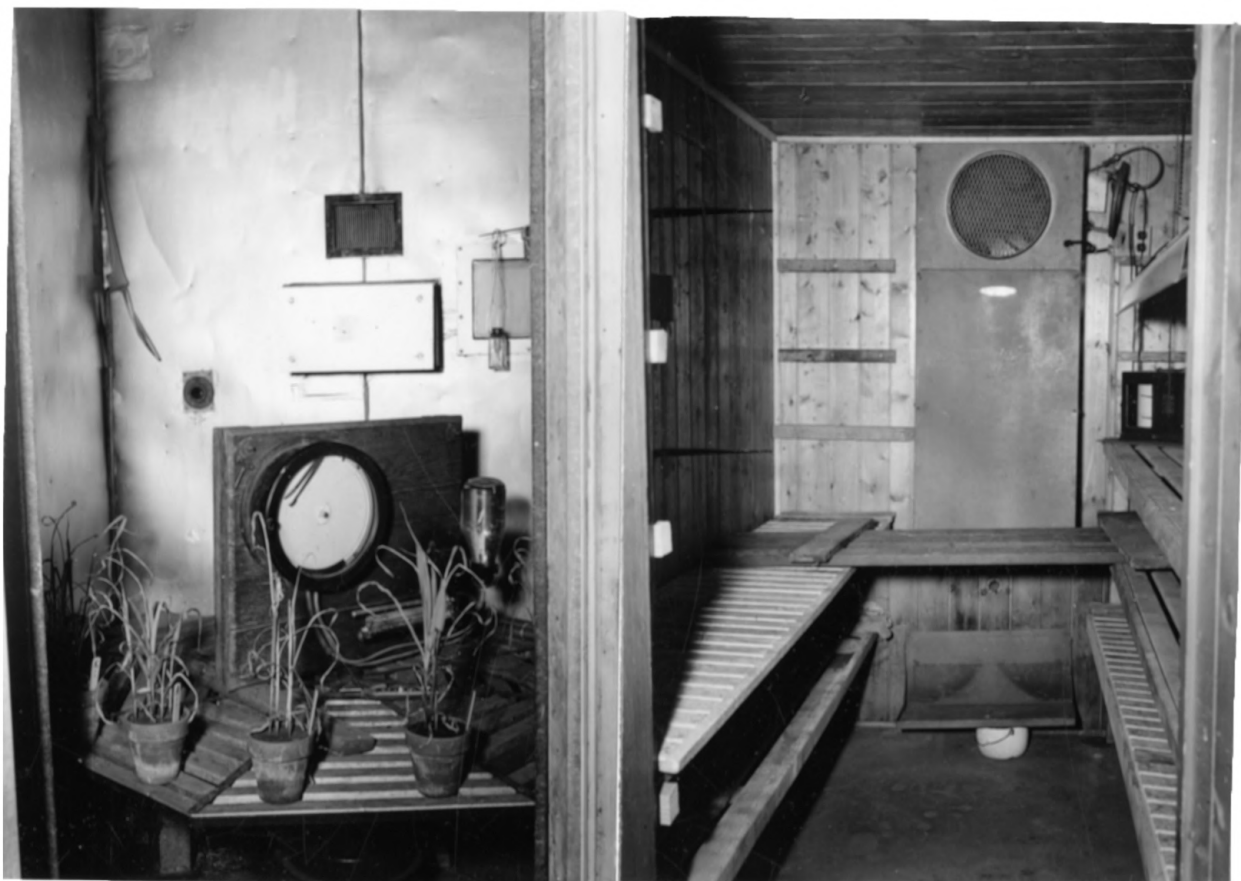


Fig. 2

Fig. 3

EXPLANATION OF PLATE III

- Fig. 4. Plants recovering in the greenhouse after treatment and before results are read.
- Fig. 5. Close-up of injured plants, showing the appearance of severe leaf injury which is not fatal to the plant.

PLATE III



Fig. 4



Fig. 5

various controlled light treatments for a definite length of time. After this exposure all of the pots were placed randomly in the heat chamber and exposed to a temperature high enough to cause differential injury to the plants. The pots were well watered prior to the light treatment and again after they had cooled upon removal from the high temperature treatment. They were then returned to the greenhouse bench (Fig. 4) and allowed to recover for about one week before survival determinations were made.

EXPERIMENTAL RESULTS

An attempt was made to record results as percent injury of tissue of the plants in each pot. This was found to be an unreliable method as there was considerable difficulty in determining the limits of the living and dead parts. It was observed that in some cases plants which a few days after treatment gave every evidence of life later succumbed. It was consequently decided to record results as percentage surviving plants per pot. Determination of the percentage of survival was made one week or more after treatment, at which time the living plants or plant parts showed up in sharp contrast to the dead tissue (Fig. 5).

Since in most cases there were only three plants per pot and this did not appear to constitute an adequate sampling unit, the four pots used in any one experiment were treated as a unit by reading the pots individually and then totaling the resultant percentages.

EXPLANATION OF PLATE IV

- Fig. 6. Wheat exposed to three hours and to six hours of light. The pot on the extreme left contains normal plants.
- Fig. 7. Corn exposed to three hours and to six hours of light.
- Fig. 8. Corn plants which have been exposed to treatments as labeled for three hours. The pot on the left contains normal plants.

The pots are arranged from left to right in order of increasing injury. Subscripts on the labels indicate length of light exposure.

PLATE IV

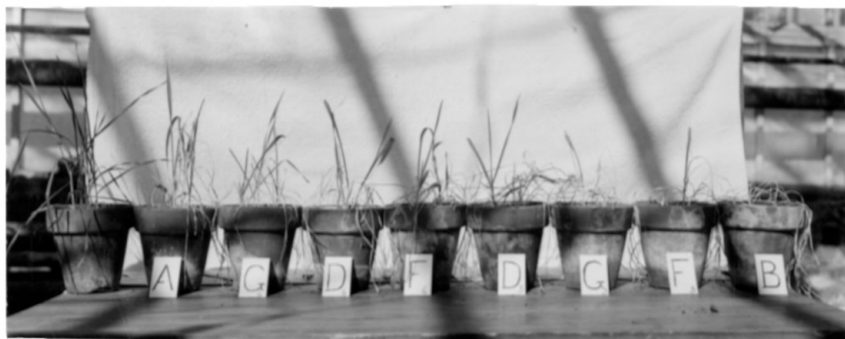


Fig. 6



Fig. 7



Fig. 8

EXPLANATION OF PLATE V

- Fig. 9. Wheat plants which have been treated as labeled for three hours. The pot on the left contains normal plants.
- Fig. 10. Corn plants which have been treated as labeled. Compare to the wheat plants in Fig. 9.
- Fig. 11. Corn plants from the last series of experiments compared to the normal plants on the left.

PLATE V



Fig. 9



Fig. 10

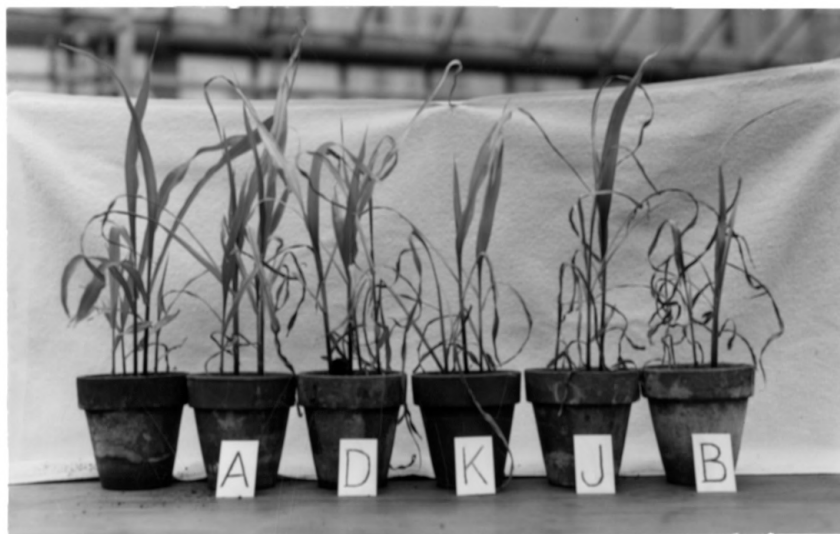


Fig. 11

A three-hour period of exposure to light was selected since Heyne and Laude (1940) reported that the greatest increase in heat resistance due to light occurs during the first two hours of exposure. Preliminary tests using both wheat and corn tended to corroborate these findings to the extent that an exposure to light of six hours as compared to one of three hours did not produce a significant increase in heat resistance in any of the spectral regions investigated. There appeared to be a difference in reaction to length of exposure due to the species being used. Wheat (Fig. 6) showed greatest increases under a six-hour exposure while corn (Fig. 7) appeared to be favored by the shorter three-hour period. These differences, if real, were not great and could not be shown to be significant.

Due to space limitations, only three artificial light treatments could be included in any one experiment, so the various light treatments were compared best by reference to their standings with relation to the two treatments, A (sunlight) and B (darkness), common to all of the experiments. Of most importance was the comparison with total darkness. Since the intensity of sunlight varied greatly its influence could be expected to vary. However, as the "darkness" did not vary in quality, all light being excluded and the temperature accurately regulated, the B treatment could be regarded as a base or minimum and any increase in heat resistance above this minimum could be considered as due to the influence of that particular light to which the plants were exposed.

In a comparison of each light treatment with the "darkness" treatment it was found that treatments A, C, D, F, G, J, and K all gave significant increases in heat resistance over the B (darkness) treatment. Treatment E did not show a significant increase over treatment B; but, as treatment E was used only in a small number of experiments it was felt that this lack of a significant increase was due to chance variations rather than to a lesser effectiveness of the blue light in inducing heat resistance. Additional tests are needed to determine this point.

Sample data are given (Tables 2 and 3) indicating the method of summarization and analysis used. A total of 56 experiments was run using various combinations of light treatments. These were later grouped for summary and the treatments compared in pairs using data from all experiments in which the pair of treatments under consideration appeared. This made possible a greater number of comparisons and increased the accuracy obtained. For an example, from Tables 2 and 3 data can be had on 6 experiments including treatments C, F, and G and 14 experiments including treatments J and K. But by combining data from the two tables it is possible to deal with a total of 20 experiments which include treatments A, B, and D. This method was used in all analyses of the data obtained from these experiments.

Treatment A (sunlight) was found to induce significantly higher heat resistance than did treatment B (darkness) or any other light treatment except C (north light). There was an apparent difference between treatments A and C in favor of A but

Table 2. Survival data from experiments 8 through 13.

| Experiment No. | Treatment | | | | | | Total |
|-------------------|-----------|-----|------|-----|-----|-----|-------|
| | A | B | C | D | F | G | |
| 8 | 233 | 33 | 367 | 67 | 233 | 99 | 1032 |
| 9 | 334 | 33 | 133 | 100 | 233 | 127 | 960 |
| 10 | 400 | 167 | 267 | 167 | 133 | 267 | 1401 |
| 11 | 33 | 0 | 33 | 0 | 66 | 33 | 165 |
| 12 | 400 | 0 | 0 | 0 | 66 | 0 | 466 |
| 13 | 367 | 0 | 300 | 100 | 199 | 67 | 1033 |
| Total | 1767 | 233 | 1100 | 434 | 930 | 593 | 5057 |
| Mean | 295 | 39 | 183 | 72 | 155 | 99 | |

Least significant difference = 96, P = .05

Table 3. Survival data from experiments 43 through 56.

| Experiment No. | Treatment | | | | | Total |
|-------------------|-----------|------|------|------|------|-------|
| | A | B | D | J | K | |
| 43 | 350 | 275 | 260 | 250 | 250 | 1385 |
| 44 | 375 | 180 | 235 | 175 | 200 | 1165 |
| 45 | 400 | 270 | 300 | 275 | 192 | 1437 |
| 46 | 400 | 100 | 225 | 150 | 225 | 1100 |
| 47 | 400 | 250 | 355 | 375 | 375 | 1755 |
| 48 | 375 | 275 | 350 | 350 | 250 | 1600 |
| 49 | 240 | 148 | 180 | 160 | 117 | 845 |
| 50 | 300 | 215 | 333 | 325 | 300 | 1473 |
| 51 | 380 | 300 | 340 | 250 | 290 | 1560 |
| 52 | 222 | 140 | 335 | 267 | 293 | 1257 |
| 53 | 400 | 100 | 302 | 95 | 165 | 1062 |
| 54 | 400 | 245 | 250 | 230 | 250 | 1375 |
| 55 | 300 | 100 | 141 | 157 | 335 | 1033 |
| 56 | 400 | 248 | 360 | 350 | 340 | 1698 |
| Total | 4942 | 2846 | 3966 | 3409 | 3582 | 18745 |
| Mean | 353 | 203 | 283 | 245 | 256 | |

Least significant difference = 42, P = .05

the difference, if real, was not great enough to be significant. No method could be devised by which to control the intensity of sunlight without altering its quality; and since this intensity varied from 150 to 4000 or more foot-candles in the greenhouse while that of the artificial light sources ranged from 70 to 200 foot-candles, it is not unlikely that the superiority of sunlight in inducing heat resistance in these experiments is an expression of this higher intensity.

No significant differences could be detected between the various artificial light treatments and all except treatment E (blue fluorescent tube) induced a significant increase in heat resistance over darkness. The differences described above may be seen readily in Fig. 12 and are present, though not apparent, in Fig. 13. The apparently smaller differences indicated in Fig. 13 are due probably to less severe total injury to the plants used in that series of experiments. This was caused by mechanical difficulties which developed in the temperature control mechanism necessitating the use of higher temperatures (about 135° F.). Under this high temperature a shorter exposure period was essential to avoid killing all of the plants and the differential injury obtained was not so marked as at the lower temperatures previously used.

DISCUSSION

The data presented are from experiments selected to include all light treatments in a sufficient number of replications to

EXPLANATION OF PLATE VI

- Fig. 12. Average percent survival per pot for each light treatment in the first 42 experiments.
- Fig. 13. Average percent survival per pot for each light treatment in the last 14 experiments.

PLATE VI

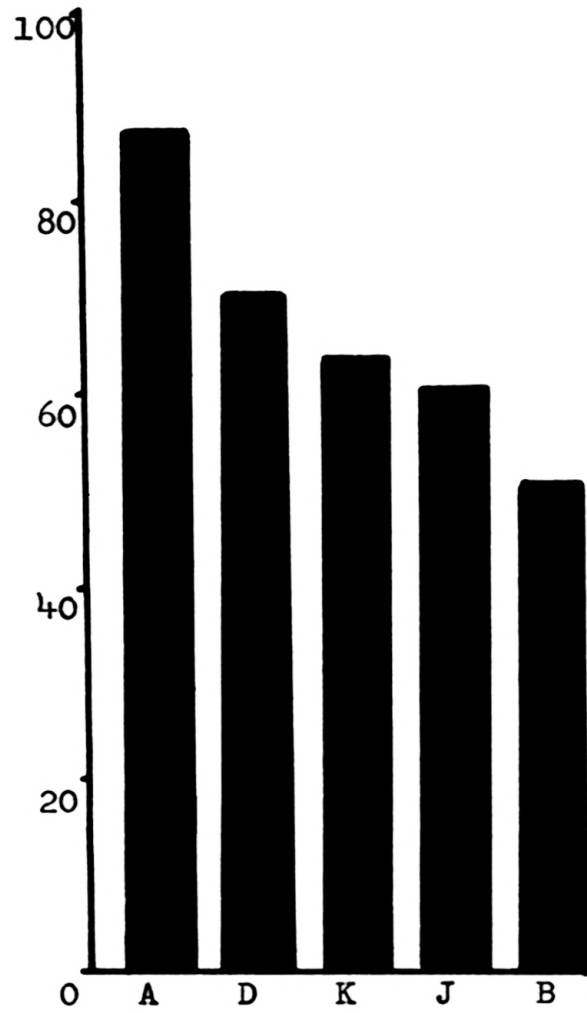


Fig. 12

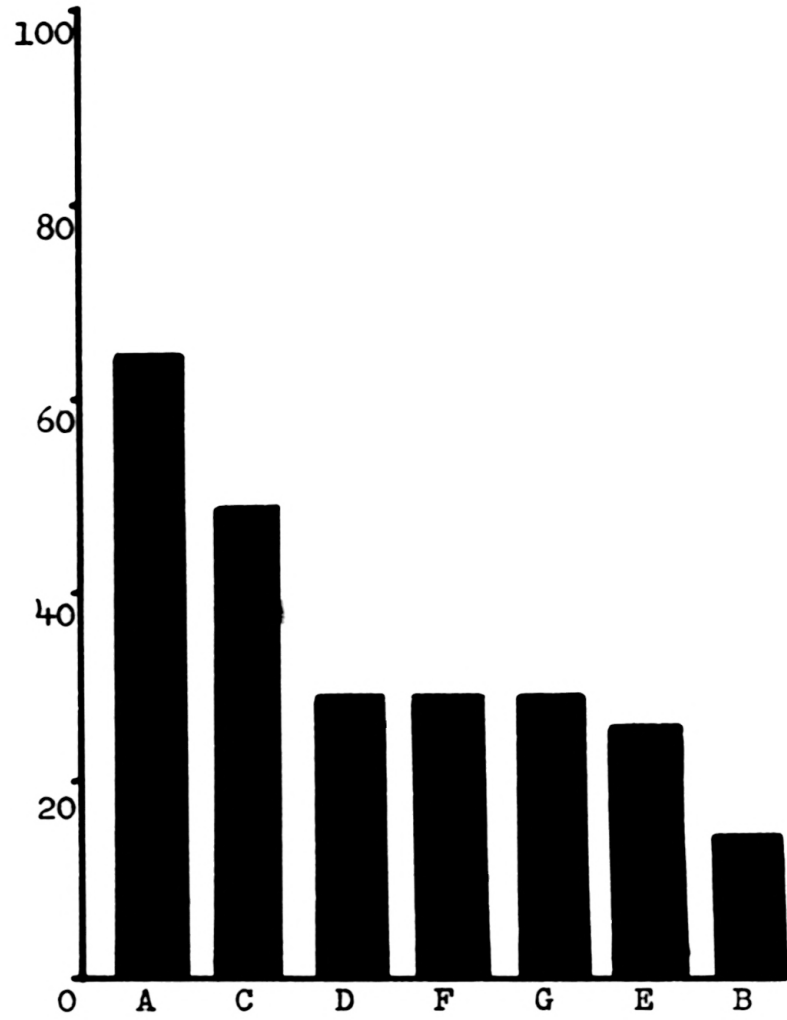


Fig. 13

give adequate comparisons. Where it was felt that uncontrollable factors, such as fluctuating sunlight intensity due to cloud cover, had an undue influence, the data from the experiment were discarded. No comparison of the two species used was attempted since both wheat and corn gave quite similar results. Better differential survival was apparent in the experiments using corn but this may be due to the greater difficulty encountered in determining the severity of injury to wheat while it was in the heat chamber.

Relative humidity in the heat chamber could not be controlled but ranged from 30 percent to 35 percent in all experiments. The rate of water loss from the plants was high, and some of the injury obtained may have been due to physiologic drought. However, since the pots were uniformly saturated before treatment and the plants were of uniform size, any injury due to physiologic drought should have been uniformly distributed among the pots. The soil in the pots appeared moist at the time of removal from the heat chamber, and at no time were the plants under stress from an actual shortage of soil moisture.

Regulation of light intensity in the treatments was only partially successful. By using more or fewer fluorescent tubes and by changing the distance of the plants from the light source some equalization of intensity could be effected. This did not permit raising the intensity of the red (D) light to a point of equality with the others, nor was it possible to reduce the intensity of the sodium (G) light to that of the others. As has

been reported previously, no regulation of sunlight intensity was achieved. The intensities arrived at by these adjustments and used in the experiments are recorded in Table 1. Light intensity was measured by a Weston Photronic cell using a quartz screen and highly sensitive to all visible radiations. This range of sensitivity extends into the ultra-violet region as low as 2900A, and far into the infra-red. As all of the light sources used had their peak energy output within a range of 3200 to 6400A, the intensities could be measured with good accuracy.

Since results were recorded simply as "living" and "dead" plants and these readings were made after the live plants had recovered sufficiently to be in sharp contrast with the dead ones, there could be no appreciable error at this point. However, considerable variation between pots subjected to the same treatment was noted frequently. This may have been the result of heat injury to the root system since the soil temperature in the pots got much higher than it would have under comparable field conditions. No practical method for maintaining a lower temperature in the soil could be devised.

All artificial light treatments produced significant increases in heat resistance over that observed under the "total darkness" treatment with the single exception of the blue light treatment. This exception appeared to be due to experimental error rather than to a real difference in induced heat resistance. Had the E (blue light) treatment been included in a larger number of experiments, it is probable that the error term would have been

reduced and that there would have been a significant increase in heat resistance over darkness. Since photosynthesis is known to occur at comparable rates throughout the visible spectrum, as has been reported previously, there would appear to be a very close relationship between the photosynthetic process and heat resistance as induced by exposure to isolated segments of the visible spectrum as represented by sunlight.

CONCLUSIONS

Young corn and wheat plants were held in darkness for 12 hours and then treated by exposure in groups to various portions of the spectrum, with one group of plants being kept in darkness during the treatment period. All were then placed in a heat chamber until differential injury was obtained. From analyses of the results, based on the percentage of the plants which survived, it is concluded that:

1. Exposure of plants to visible radiation for a period of three hours induced a significant increase in heat resistance over plants which had no light.
2. A six-hour exposure to light was not significantly better than a three-hour exposure when measured by the induced heat resistance.
3. Under the conditions of this investigation sunlight induced significantly higher heat resistance than did any artificial light treatment.

4. Exposure to artificial light in various segments of the spectrum including violet, green, gold, orange (sodium vapor), and red produced significant increases in heat resistance over that possessed by plants which had received no light. Exposure to blue light caused no significant increase but this may have been due to the fact that this experiment was repeated only a few times.

5. Nonsignificant differences between artificial light treatments possibly were the result of different amounts of light being supplied to the plants in the several treatment groups. Another possible reason might be that the amount of light or the time of exposure did not develop the maximum influence in each case.

6. All regions of the visible spectrum included in this study were effective in inducing heat resistance in plants which previously had been held in darkness.

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LITERATURE CITED

- Arthur, J. M.
Work to date at Boyce Thompson Institute for Plant Research on effect of light on plant growth. Illum. Engin. Soc. Trans. 19: 995-997. 1924.
- Arthur, J. M. and E. K. Harvill.
Plant growth under continuous illumination from sodium vapor lamps supplemented by mercury arc lamps. Boyce Thompson Inst. Contrib. 8: 433-443. 1937.
- Arthur, J. M. and W. D. Stewart.
Transpiration of tobacco plants in relation to radiant energy in the visible and infra-red. Boyce Thompson Inst. Contrib. 5: 483-501. 1933.
- Arthur, J. M. and W. D. Stewart.
Relative growth and dry weight production of plant tissue under Mazda, neon, sodium, and mercury vapor lamps. Boyce Thompson Inst. Contrib. 7: 119-130. 1935.
- Baly, E. C. C.
Photosynthesis. New York: D. van Nostrand Co. Inc., 1940, 243p.
- Bartel, A. T.
Some physiological characteristics of four varieties of spring wheat presumably differing in drought resistance. Jour. Agr. Res. 74: 97-112. 1947.
- Burge, W. E.
The action of ultra-violet radiation in killing living cells such as bacteria. Amer. Jour. Physiol. 43: 429-432. 1917.
- Clements, F. E. and E. V. Martin.
Effect of soil temperature on transpiration in Helianthus annuus. Plant Physiol. 9: 619-630. 1934.
- Clum, H. H.
Effect of transpiration and environmental factors on leaf temperatures. Amer. Jour. Bot. 13: 217-230. 1926.
- Dastur, R. H., U. K. Kanitkar, and M. S. Rao.
The formation of proteins in leaves in light of different quality. Ann. Bot. (London) 2: 943-953. 1938.
- Dastur, R. H. and R. J. Mehta.
Study of the effects of blue-violet rays on photosynthesis. Ann. Bot. (London) 49: 809-821. 1935.

- Dastur, R. H. and S. Solomon.
Study of the effect of blue-violet rays on the formation of carbohydrates in leaves. *Ann. Bot. (London)* 1: 147-152. 1937.
- Dexter, S. T.
Effect of several environmental factors on the hardening of plants. *Plant Physiol.* 8: 123-129. 1933.
- Duggar, B. M., editor.
Biological effects of radiation. Two volumes. New York: McGraw-Hill Book Company, Inc., 1936. 1341p.
- Dutcher, R. A. and D. E. Haley.
Introduction to agricultural biochemistry. New York: John Wiley & Sons, 1932. 280p.
- Eaton, F. M. and D. R. Egle.
Carbohydrate accumulation in the cotton plant at low moisture levels. *Plant Physiol.* 23: 169-187. 1948.
- Emerson, R. and C. M. Lewis.
Dependence of the quantum yield of Chlorella photosynthesis on wave length of light. *Amer. Jour. Bot.* 30: 165-178. 1943.
- Flint, L. H. and C. F. Moreland.
Response of lettuce seedlings to 7600A radiation. *Amer. Jour. Bot.* 26: 231-233. 1939.
- Franck, J. and W. E. Loomis, editors.
Photosynthesis in plants. Ames: The Iowa State College Press. 1949. 500p.
- Fuller, H. J.
The injurious effects of ultra-violet and infra-red radiations on plants. *Ann. Missouri Bot. Grad.* 19: 79-86. 1932.
- Gortner, R. A.
Outlines of biochemistry. New York: John Wiley & Sons, 1929. 538p.
- Heyne, E. G. and H. H. Laude.
Resistance of corn seedlings to high temperatures in laboratory tests. *Amer. Soc. Agron. Jour.* 32: 116-126. 1940.
- Hibben, S. G.
Influence of colored light on plant growth. *Illum. Engin. Soc. Trans.* 19: 1000-1010. 1924.
- Hoover, W. H.
Dependence of carbon dioxide assimilation in a higher plant on wave length of radiation. *Smithsn. Inst. Misc. Collect.* 95(21). 1937.

- Hunter, J. W., H. H. Laude, and A. M. Brunson.
A method for studying resistance to drought injury in inbred lines of maize. *Amer. Soc. Agron. Jour.* 28: 694-698. 1936.
- Jenkins, M. T.
Differential resistance of inbred and crossbred strains of corn to drought and heat injury. *Amer. Soc. Agron. Jour.* 24: 504-506. 1932.
- Julander, O.
Drought resistance in range and pasture grasses. *Plant Physiol.* 20: 573-599. 1945.
- Kenway, C. B., H. B. Peto and K. W. Neatby.
Researches on drought resistance in spring wheat. *Canad. Jour. Res. Sect. C, Bot. Sci.* 20: 397-402. 1942.
- Kenway, C. B. and H. B. Peto.
Researches on drought resistance in spring wheat. *Canad. Jour. Res. Sect. C, Bot. Sci.* 17: 294-296. 1939.
- Kramer, P. J.
Effects of soil temperature on the absorption of water by plants. *Science.* 79: 371-372. 1934.
- Krotkov, G.
Diurnal changes in the carbohydrates of wheat leaves. *Canad. Jour. Res. Sect. C, Bot. Sci.* 21: 26-40. 1943.
- Laude, H. H.
Diurnal cycle of heat resistance. *Science.* 89: 556-557. 1939.
- Lease, E. J. and W. E. Tottingham.
Photochemical responses of the wheat plant to spectral regions. *Amer. Chem. Soc. Jour.* 57: 2613-2616. 1935.
- Lepeschkin, W.
Influence of temperature and light upon exosmosis and accumulation of salts in leaves. *Amer. Jour. Bot.* 35: 254-259. 1948.
- Meier, F. E.
Growth of a green algae in isolated wave length regions. *Smithson. Inst. Misc. Collect.* 94(17). 1936.
- Miller, E. C.
Plant physiology. Second Edition. New York: McGraw-Hill Book Company. 1938. 1201p.
- Pfeiffer, N. E.
Anatomical study of plants grown under glasses transmitting light of various ranges of wave lengths. *Bot. Gaz.* 85: 427-436. 1928.

- Popp, H. W.
Summary of literature of some phases of the effect of light on plant growth. *Illum. Engin. Soc. Trans.* 19: 981-984. 1924.
- Roodenburg, J. W. M. and G. Zecher.
Irradiation of plants with neon light. *Nature (London)* 139: 725. 1937.
- Sayre, J. D.
Opening of stomata in different ranges of wave lengths of light. *Plant Physiol.* 4: 323-328. 1929.
- Schappelle, N. A.
Effect of narrow ranges of wave lengths of radiant energy and other factors on the reproductive growth of long day and short day plants. New York (Cornell) Agr. Expt. Sta. Memoir no. 185: 1-33. 1936.
- Shirley, H. L.
Light as an ecological factor and its measurement. *Bot. Rev.* 11: 497-532. 1945.
- Tottingham, W. E.
Plant Biochemistry. Minneapolis, Minn.: Burgess Publishing Co. 1939. 249p.
- Tottingham, W. E. and H. Lowsma.
Effects of light upon nitrate assimilation in wheat. *Amer. Chem. Soc. Jour.* 50: 2436-2445. 1928.
- Vassiliev, I. M. and M. G. Vassiliev.
Changes in carbohydrates content of wheat plants during the process of hardening for drought resistance. *Plant Physiol.* 11: 115-125. 1936.
- Volz, E. C.
Present status of light research. *Iowa State Hort. Soc. Proc.* 1937: 160-240.
- Warburg, O. and E. Negelein.
Über den einfluss der wellenlänge auf den energieumsatz bei der kohlen säureassimilation. *Zeitsch. Physik. Chem.* 106: 191-218. 1923.
- Weitz, C. E.
General Electric lamps. Lamp Department, General Electric Bul. LD-1 1946.
- Whitfield, C. J.
Ecological aspects of transpiration: II Pike's Peak and Santa Barbara regions: edaphic and climatic aspects. *Bot. Gaz.* 94: 183-196. 1932.

Whitman, W. C.

Seasonal changes in bound water content of some prairie grasses. Bot. Gaz. 103: 38-63. 1941.