Gast

INSOLATION AND SILVICULTURE

with reference to studies at the Harvard Forest.

Introduction[1]

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1 General Reference: Fernow, History of Forestry 1913.

The recognition of a relation between plant growth and insolation, the amount of exposure to the sun's radiation, is not new. In his "Natural History" (50 A.D.), a compilation of information from about two thousand authors, Pliny deals at length with agricultural husbandry, and discusses many aspects of the effect of climate on plants. The suitability of the Bosphorous for pomegranates and fig-trees, the suitability of the more northern regions for pines and firs and the difficulty of cultivating chestnuts and cherries near Rome are commented on. Nursery practice, the growing of trees from seed and transplanting, is treated. In transplanting trees he recommends that the orientation of the tree with respect to the compass be marked so that the northern side will not be placed in a southern aspect and so exposed to the unaccustomed heat of the sun. Pliny speaks of the water demands of the plant, and also of the relation between temperature and aspect. He notes that the shade of pines excludes vegetation, and compares the relative shade cast by pine, oak, sycamore, cypress, beech, elm, aspen, walnut, and apple trees. The lore assembled by Pliny indicates a deal of practical knowledge of plant cultivation and a high development of the art of plant production, though there was no extensive forest practice. But after the invasion of the Germanic tribes into the Roman territory, agricultural, and with it, arboricultural art declined.

Following the barbarian conquests there was little need for a high order of silvicultural knowledge, because not until the end of the Middle Ages in 1500 did the need of forest management to maintain wood resources become general. The necessity of forest management arises only when there are no unexploited forest resources left within the reach of economical transportation. Up to 1500, forest practice had been concerned chiefly with the rights of use and ownership, although there had been some reforestation by seeding and planting.

In the three centuries from 1500 to 1800 the need of establishing forest lands as permanent sources of wood became apparent. Regulations providing for the regeneration of the forests after cutting were established. Different cutting methods which attempted to insure reproduction were advised and subjected to practical test. These silvicultural practices were reduced to well-differentiated formal "systems" by the beginning of the nineteenth century. The development of natural science made possible the study of the fundamental physical and chemical factors whose variations are responsible for the success or the failure of these practices, but the complexity of the processes involved has not led to as rapid an advance as in the physical sciences.

The importance of "light",[2] better termed radiation, as a factor comprised in the silvicultural term "tolerance", is still a controversial subject although Pliny had observed the effect of the shade of trees in excluding vegetation.

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[2] "light" properly speaking, is only that radiation which is visible to the eye. Insolation is the amount of radiation originating in the sun and falling upon a surface on the earth. By definition, it comprises infra-red, visible, and ultra-violet radiation.

Radiant Energy and Photosynthesis

While Priestly[3] was the first to show that plants

3 Priestly, Experiments and Observations relating to various Branches of Natural Philosophy, with a continuation of the Observations of the Air. 1778

"meliorated" the atmosphere by the absorption of "fixed air" (CO_2) with the production of "dephlogisticated air" (O_2) his results were confusing in that the plants sometimes "injured" the air instead. Ingen-Housz conveys his contribution to the subject in the title of the volume by announcing the results of "Experiments Upon Vegetables discovering their great Power of Purifying the Common Air in the Sun-shine, and of Injuring it in the Shade and at Night."[4]

4 London, 1779

Spoehr[5] and Stiles[6] have organized the mass of information

5 Spoehr, Photosnythesis, New Yor. 1926

6 Stiles, Photosynthesis, London. 1925

tion which has been accumulated since the work of Priestly and Ingen-Housz. Out of the data (Spoehr quotes approximately 600 authors, Stiles gives a bibliography of about 900 papers) emerges the fact that radiation is but one of the factors affecting photosynthesis. The factors may be separated into external and internal factors. The variations of the external factors are due to alternations in the environment. The influences of the internal factors are due to variations which originate within the plant and are only remotely dependent on external factors. In order of importance they may be listed as:

External, (general)

1. Carbon dioxide supply
2. Irradiant intensity and wave length (frequency)
3. Temperature
4. Water supply
5. Supply of mineral nutrients
6. Supply of oxygen
7. Electrical conditions

Internal,

8. Chlorophyll content
9. Protoplasmic factor
10. Respiration
11. Accumulation of products of photosynthesis

An attempt to visualize the interactions of these variables in a sort of diagram is shown in Fig. I.). It is apparent that the solution of the complex physical-chemical system of the plant and environment here presented is a difficult one.

From the great mass of published work on the photosynthetic process may be culled the following information which represents our present knowledge of the facts.

1. The carbon dioxide supply is the limiting factor under high irradiation intensities while under the minimal intensities, the light becomes the limiting factor.

2a. Photosynthesis follows irradiation with energy of wave lengths 0.7 to 0.4 μ inclusive. The relative efficiency of the process ranges, according to present evidence, from 0.53 in the red end of the spectrum to

0.33 in the blue (Warburg and Negelin, 1923).[7]

[7] Zeit. Phys. Chem. 106:191-218

2b. Plants and leaves growing in the sunlight and in the "shade" show a chromatic adaptation to their environment. Those grown in the "Shade" into which penetrates mostly diffuse sky-light with a relatively high content of blue show a higher efficiency in the blue than do specimens customarily irradiated with bright sunlight. (Engelmann[8], 1884,

[8] Engelmann. Bot Zeit. 42:81- 1884

Stahl[9], 1906, Harder[10], 1903).

[9] Stahl. Lanbfarbe und Hunnilslicht. Jena 1906

[10] Harder. Zeit. f. Bot. 15:305. 1903

3. Temperature increases of 10° C. in the region of 5° to 25° C. (41° to 77° F.) double the rate of photosynthesis. Above and below this region the relative increase with rising temperatures is not as great.

4, 5 and 6. Minimal water, mineral, and nutrient, and oxygen supplies are necessary for photosynthesis. The values of the optimum supply are not known at present.

7. In an ionized atmosphere photosynthesis proceeds faster than in an unionized.

8. Increased rates of photosynthesis are associated in an uncertain manner with larger chlorophyll contents. A more important relation is found, however, in the fact that leaves of the lower chlorophyll

content do not begin photosynthesis except at higher mimimal intensities, but at lower temperatures.

9. The "protoplasmic" factor is held to account for some of the effects of temperature upon photosynthesis.

10. The rate of respiration is found to be associated with the rate of photosynthesis.

11. The accumulation of the products of photosynthesis may slow down the reaction.

Irradiation Intensity and the Growth of Tree Species.

An extensive literature on the measurement of the radiation under the forest canopy can be cited.[11] The problems which have been studied are:

(1) The change in quality -(spectral energy distribution)- of light filtered thru canopy.

(2) The intensity of light under canopy compared with that in the open; and the relative ability of species to grow in the diminished intensities.

Spectral Distribution of Canopy Filtered Light.

Zederbauer[12] measured the spectral distribution of visible light with a hand spectroscope and monochromatic filter glasses. The method was defective in that he could not obtain pure monochromat filters and because of the difficulty of judging intensities near the extremities of the visual sensitivity curve. His evidence was to the effect that the light transmitted by the forest canopy is significantly different from filtered white light. The canopy abstracts the radiant energy between the Frauenhofer lines B and C, in the vicinity of the F line, and beyond the H line. The intolerant species do not use the blue and violet, the tolerant use the blue indigo and violet. These results are interesting in view of the fact of chromatic adaptation, but are scarcely conclusive because of the imperfections noted. The eye is not adapted for fine differentiations in the region of the B and C lines.

(11) Toumey, "Foundation of Silviculture Upon an Ecological Basis", Mimeographed Ann Arbor 1926 - Part III:325-343.

12 Centrabl. f. d. gesamte Forstwesen. 325-330. 1907

Knuchel[13] by spectroscopic methods determined the absorption of leaves, the forest canopy and individual tree crowns by measuring percentage composition of the light passed. He concluded that (1) the open grown leaves of beech were more efficient in absorption than the shadow grown leaves, especially in the red and green. (2) The shade leaves of nearly all deciduous arborescents transmit more "light" than the sun leaves. (3) The light passing thru hardwood canopies is the same as that passing thru the hardwood leaves, with slight additions of diffuse blue sky radiation. (4) Under softwood canopies the penetrating radiation is spectrally very close to that of the diffuse sky light.

[13] Mitteil d. Schweizer. Centralanstalt. f. d. Forst. Versuchswesen, 11. 1924

forest

Total Light Intensity under Canopies.

With the exception of the workers noted above, physiologists and ecologists have used varieties of printing-out-papers or "ordinary" plates and films for the measurement of light intensities under canopies[14].

14
Wiesner. Sitz. d. k. Akad. d. Wiss. Wien. 104:605-711 1895
Der Lichtgenuss der Pflanzen. 1907
Clements. Research Methods in Ecology 1905
Pearson. U. S. Forest Service Circ. #174 1910
Gordon. Trans. Roy. Scot. Arbo. Soc. 26:147-155 1912
Vonk. Zeit. Biol. Technik. u. Methodik. 3:90-93 1915
Grafe. Ernahrungsphsiologisches Practicum der Höherer Pflanzen, p. 114- 1914
Salisbury. Journ. Ecology (Brit.) 4:82-117 1916
McLean Jour. Ecology (Brit.) 7:122-172 1919
Loftfield Carn. Ins. Wash. Pub. 314 p. 1921
Tansley Practical Plant Ecology p. 1923
Plitt & Pessin. Bul. Torr. Bot. Club. 51:203-210 1924
Pessin. Ecology 6:203-237 1925
Klugh. Ecology 6:203-237 1925
Lundegardh Biol. Zentral 42:404-431 (Reviewed Ecology 6:82, 1925) 1923

The criticism of all these methods with the exception of Klugh's panchromatic plates is directed against the poor sensitivity distribution curve. In his case we are not sure that this spectral energy sensitivity curve[15] of the source used has the same energy distribution

[15] Fig. 5. Loc. cit. p. 218

as sunlight. It is improbable that the chromatic bands of equal breadth on a normal spectrum should be of equal energy content in the source used for obtaining this picture.

Certain investigators have advocated or are using the MacBeth Illuminometer[16]. In criticism of this use of this instrument

[16]

Klugh	Ecology 6:208	1925
Popp.	Bot Gaz. 82:306-319	1926

Grasovsky. Yale Forestry School, private communications.

~~it may be remarked that as~~ Table 1 shows, in the region of λ 660 $\mu\mu$, where Warburg and Negelein show the photosynthetic efficiency to be 59%, the eye rates the energy as 0.061 of what it does in the region of maximum visual sensitivity at about λ 550-660 $\mu\mu$.

Aldrich[17] used a pyronometer for the only physically

[17] Ann. Smithson. Astrophys. Obs. 4:267-268. 1922

sound observations of irradiation intensities penetrating tree canopies of which the writer knows. Table 2[18] gives his results. The localities

[18] Table 91 Loc. cit. p. 268

are:

"(a) In the shade of two large trees, no undergrowth within several feet.

"(b) Under some rather thick saplings, partly shaded by higher trees, thin undergrowth.

"(c) In a bed of ferns which covered the instrument, but with an open space directly above.

"(d) In open space; trees all around; ferns and other vegetation on ground.

"(e) Thick growth of saplings, considerable small vegetation on ground."

Commenting on the observations of the different days he remarks:

"Sept. 7. The sky on this day was cloudy and very variable. Observations had been taken on the whole sky and sun two hours before the instrument was moved to the grove, but after that the sky became nearly overcast. At the close, observations on the whole sky were taken, but there was so much variation that the readings were of little value.

Sept. 12. The observations were repeated with a cloudless sky. With better conditions the readings showed far less variation among themselves than on the preceding days.

On October 2 a third set of observations was taken. The instrument was placed in the same five positions as before. This time the leaves were beginning to fall, and many that remained on the trees had turned yellow. The sky was cloudless and very clear."

Further he remarks:

"Readings were taken mostly in groups of four or five. In the table are the times for the middle of each group, the average calories for the group, an estimation of the total sky and sun radiation, and the ration of the observed radiation under the trees to the estimated radiation above them. The estimated whole sky radiation is based, for September 7, on the observations taken on the tower, following those in the grove; for September 12, on solar observations by the pyrheliometer and total sky observations taken before the pyranometer was moved to the grove; for October 2, on pyrheliometer measurements taken at different air masses during the afternoon and total sky observations taken in the morning with the pyrheliometer , the sum of the values at corresponding sun altitudes being used.

"Referring to the column of ratios in Table (   ) there is a slight increase at a between September 12 and October 2. This is to be expected, for in this place the light was obstructed by high leaves, and many of those had fallen. For place b we find approximately the same ratio for both days, perhaps because the foliage of the saplings and undergrowth did not fall so early as that of the larger trees. The decrease in the ration at c would follow an increase in the thickness of the ferns. At e, under saplings similar to those of b a noticeable increase in the ratio occurred. This was very likely due to the absence of any shadings by higher trees. The results of these foliage observations are meager, and of small reliability. Nevertheless, they suggest a field for wide and important research concerning the necessary amount of light for various types of plants and at various stages in their development. The pyranometer, supplied perhaps with special colored screens for measuring different kinds of light, seems remarkably well suited to this purpose. It is hoped that a much more extensive investigation along this line may be undertaken."

It must be remarked that all these observations consider the radiation on a flat horizontal surface, and that none of them are continuous for long periods of time.

For the purpose of this paper the work relating to the study of insolation and forest tree growth may be summarized under three heads:

(1) Radiant energy and photosynthesis

(2) Irradiation intensity and growth of tree species

(3) Meteorological records of solar energy.

Scale of Tolerance

Foundations of Silviculture, 1926
Toumey. Part III

The measurements of light under the forest canopy have been described in the preceding paragraphs. They serve as a check on the empirical observations of the tolerance scale. The earliest and the still most practical guide to the relative ability of trees to endure shade has been the arbitrary arrangement of the trees according to the comparative thriftiness of the different species in identical habitats.

Toumey[19] lists a number of growth characteristics

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19. Loc. cit. P. 338

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which can be used in the arrangement of the tolerance lists: They are the relative values of

1. Height growth.
2. Amount of seedling reproduction.
3. Crown density.
4. Vigor of dominated trees.
5. Rates of natural thinning.
6. Rates of self pruning.
7. Number of branch order.
8. Order of appearance of tree dominants.

Of these, he classes as the most important criteria for New England studies the relative vigor of dominated trees and the relative amounts of seedling reproduction. Burns varied the distance of potted specimens of trees from a source of energy in an effort to determine the radiation intensity of the compensation point. He then checked the radiation intensity by the use of a thermocouple. In this way the varying distance from the source, and the corresponding radiation intensity gave an absolute measure of the tolerance scale, and not merely a "greater than" or "less than" value. His work is open to the criticism that the influence of temperature on the respiration point, and the influence of the previous irradiation history are unknown. These factors have been shown by Harder[20] to be very

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20.
Jahrb. Wis. Bot. 56:254-298 (specifically p.281) 1915
60:531-571 1921
Ber. Deut. Bot. Ges. 41:194 1923

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important. For this reason, while the relative positions in the tolerance scale are undoubtedly correct, check observations on the absolute values made with these factors in mind are desirable.

Meteorological Records of Solar Energy

A large fund of information exists on the causes of variation in the amount of solar energy reaching the earth's surface. These variations may be due to

(1) Variations in the solar constant.

(2) Variations in the distance from earth to sun. Since the radiation intensity varies inversely as the square of this distance, we should expect it to be 7% more intense with the earth in perihelion early in January than with the earth in aphelion early in July[21].

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21. See also Humphreys "Physics of the Air" pp. 76-78 1920

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(3) Variations in solar altitude with time of day and of year resulting from (a) the effect of the cosine law of angle of incidence and from (b) the absorption of the varying masses thru which the radiation passes in reaching the earth's surface.

(4) Variations in the transmission of the atmosphere which change the absorptions of the air mass in (3).

Variations in the Transmission of the Atmosphere

Pulling lists seven ways in which the solar radiation incident upon the outer extremity of the earth's atmosphere may be changed in amount and spectral distribution before it reaches the earth's surface.[22]

[22] An extensive bibliography is to be found in Pulling, loc. cit. Plant World 22:157-191. 1919

"(1) General scattering by the permanent gases of the atmosphere.

(2) General scattering by water vapor.

(3) Selective (banded) absorption by the permanent gases.

(4) Selective (banded) absorption by water vapor.

(5) Absorption and reflection by clouds.

(6) Absorption and reflection by dust.

(7) Absorption in chemical reactions".

Fig. 2[23] shows the averaged effect of the earth's atmosphere on the spectral distribution of energy. The ordinates represent the relative energies, the abscissae, the wave lengths spaced on the normal spectrum. The various degree lines represent the altitude of the sun from the horizon, which is the complement, in degrees, of the zenith degree angles of the sun.

[23] Fig. 4 Pulling, Plant World 22:171. 1919

Fig. 3[24] is drawn from Kimball's data on probable radiation intensities at normal incidence for the Southern New England States (Lat. 42° N.) The ordinates are gram-calories per square centimeter per minute, the values are given for the 21st of each month, and each of the family of curves represents the designated number of hours before or after noon, solar time. Fig. 5

[24] 5a. Lat. 42° N. Northeastern States. loc. cit. p. 773

is a similar diagram for illumination intensity. These data was obtained by the calculation of the constant ratio between the energy recorded by the photometric measurements with a Sharp-Millar photometer.[25] It may be well to stress that these are calculated values. They are based upon the experimental determination of but a single experimental factor: the average vapor pressure for a number of years. From the values of this factor the absorptions of the various air masses are calculated.

[25] Kimball. Monthly Weather Rev. 52:478. 1924

Ecological Spherical Hot-Junction Thermopile.

From an ecological viewpoint, the types of pyrheliometers and radiometers available have the disadvantage that the receiving surfaces heated by the radiation are plane. For following the diurnal changes in direct solar radiation (sky radiation eliminated by diaphragms) some pyrheliometers are mounted in a clock-driven equatorial transit. In all other cases the radiation measurements obtained on a horizontal plane are subject to Lambert's cosine law relating intensity to angular incidence.

The issue of the cosine law of incidence may be evaded by the adoption of spherical hot-junctions. Fig. 6. shows the instrument constructed with spherical hot-junction and Fig. 7. is a detailed sketch.

The spherical hot-junctions, five in number, are German Silver beads 0.1 inch (2.5 mm.) in diameter to which the constantin and iron wires, 0.005 inch (0.13 mm.) in diameter, are spot welded. The cold junctions are cold-rolled pieces of pure nickel 0.2 inch long x 0.1 inch wide x 0.02 inch thick (5 x 2.5 x .5 mm.). To these also the thermo-element wires are spot welded. The cold junctions in addition to being bright are shielded by the silvered annular ring of mica which also serves to hold the thermo-element wires rigidly separated. The "anchors" of the electric-light bulb stem support the spherical hot-junctions and the annular ring. After mounting on the electric-light bulb base, the hot-junctions are coated with lamp-black mixed with a minimum of Bakelite varnish. The whole is then baked in an electric oven in which the temperature is gradually raised to 170° C

The Problem. No P

No satisfactory physical device for the measurement of radiation in ecological studies existed [redacted] when this study was initiated. It was first necessary to elaborate and adapt the instruments.

For the designing of satisfactory apparatus for silvical work the following criteria may be established: it must be

(1) Capable of calibration in absolute units
(2) Recording, with a minimum of field equipment
(3) Easily and safely transportable
(4) Sensitive
(5) Ultimately capable of measurement of the spectral distribution of energy.

The thermopile type of instrument, which measures the irradiant energy by its heating effect best meets these requirements. The instrument last used was the so-called "Spherical Hot-Junction Thermopile."

In the course of the evolution of the last instrument the so-called Massive Base Thermopile was built. The records taken in the summer of 1925 were made with this device.

In the course of the field work in the summers of 1925 and 1926 a battery of thermopiles and a recording galvanometer were used in the comparison of radiation intensities in the open and under forest canopies. As companion studies a uranium sulfate-oxalic acid photosensitive solution was used for the determination of the ultra-violet radiation in seven hours. The bases are then put into the regular electric-light automatic machine, which unites the base and globe, evacuates the bulb, seals off the evacuation tube, mounts, bakes on the threaded brass base, and solders the leads to the contacts of the base.

Three of these five-junction bulbs are mounted in series giving a total resistance of about six ohms. Approximately 3.4 millivolts per gr. cal. per sq. cm. or 0.29 gram cal. per millivolt are developed by the pile.

The possible sources of error in this device - the amount of polarization and the over-run or under-run or the change in the angle of incidence of the radiation remain to be investigated.

Unless the diameter of the bulb is more than double the diameter of the circle passing thru the centers of the hot-junctions and the center of the annulus, the caustic curve caused by the reflection of the light from its internal surface may fall in the junctions and the annulus and create an error[29].

29. Kimball & Hobbs. Month. Weather Rev. 51:239-242, 1923
Miller, Month. Weather Rev. 43:264-266, 1915

This source of error does not exist in the device. However, the bulb is not absolutely free from optical irregularities.

The use of the exhausted electric light bulb inhibits the effect of leaks, as glass seals are used thruout.

Wave Length Sensitivity Curve of the Ecological Thermopile.

Due to the presence of the glass envelope and from the data on the absorption of lampblack[30] it may be stated that the

30. Coblentz, Fur. Standards Sci. Bull. (#196) 9:283-325 1913

probable sensitivity curve of the apparatus is non-selective within the regions of wave lengths 2.0 to 0.31 . Irradiant energy not lying within this region does not, it is believed, affect the registration of the apparatus. A systematic investigation of the sensitivity is in order, but has not yet been made.

Concerning the relations of these wave lengths to photosynthesis certain statements are justified. Criticism has been made against the use of apparatus which depends upon the heating effect of radiation as an instrument for measuring the total radiation affecting plants. Toumey[31] following Klugh[32] emphasizes "the measurement of light

31. Foundations of Silviculture. 1926 p.326.

32. Klugh. Ecology 6:205. 1925

that a plant is subjected to in a given habitat is an entirely different thing from the measurement of the heating effect of solar radiation that it is subjected to in the same habitat." He apparently prefers measurements of the radiant energy with panchromatic plates or with the MacBeth Illuminometers, in which the eye is the photo-sensitive device. He further properly emphasizes that "[33] although there appear to be

33. Toumey, Loc. Cit. 1926, p. 326.

correlations between the distributions of radiant energy expressed in these units (absolute gram calorus per sq. cm. per min.) and the effect produced on plants, the total amount of radiant energy received on a given site tell little or nothing of the actual amount of that energy to which the plant on the site reacts." But he further states that "[34] Only the light rays are important in photosynthesis and chiefly those

34. Toumey, Loc. cit. 1926, p. 327

in the red end of the spectrum."

This last statement may be misleading. The relative importance of the red end of the spectume is not due to the exclusive use of energy of this wave length in photosynthesis. Warburg and Negelein (see previous citation p.   and see also Table I) showed that the relative used of the red, yellow, and blue portions of the spectrum were as 59 :53.5 : 33.8. These are, taking 59 equal to 100%, decreases in use of energy of 9.3% in the yellow and 42.77% in the blue respectively of value in the red. Furthermore, there is the factor of chromatic adaptation to be considered, and its quantitative values are not known though it may compensate for lower use in the region of shorter wave lengths. The relatively greater importance of the red lies in the fact that the peak of the energy distribution curves for total sun and sky is at .5 (an the green) for 6000° K, - zeinth distance 78.7°, and at .58 (in the yellow) for 5000° K, - zeinth distance of the sun. (see Fig. 8).

[35]. These values are in general for clearer days. No date could be

35. From Kimball, Monthly Weather Rev. 52:473-479, 1924.

found for the "color temperature"[36] of the overcast sky.

36. Priest. Journ. Opt. Soc. Amer. 4:480-484

Journn. Opt. Soc. Amer. & Rev. Se. Inst. 7:180, 1923.

It will be noticed that the peak of the visibility curve of the eye falls between these maxima, - at .550 .

On either side of the maximum the visibility curve of the eye falls away sharply till at .6 it is 50%, .65 it is 10%, and .66 it is 6%. It is apparent that the illuminometer measurements transgress quite as much on the under estimation of total radiation - due to failure to give full value to the red portion of the spectrum - as the thermopile may be at fault by including the irradiant band .70 to 2.00 at its full value, though it is of doubtful significance as a source of photo chemical energy in photosynthesis. That this region may be important in its effect on the temperature coefficient of photosynthesis is a subject for experiment.

But in so far as the relative energy measurements are concerned, the thermopile measurements are apparently as valid as illuminometer determinations. Kimball[37] has shown that radiation

37. loc. cit., Monthly Weather Rev. 52:473-477, 1924

"Comparisons between photometric measurements of daylight and pyrheliometric measurements of total radiation .... indicate that if the radiation intensity on a horizontal surface, expressed in gram-calories per minute per cm.,^{2} is multiplied by 6,700, the result will give the illumination intensity on a horizontal surface in foot-candles within ± 5 per cent, giving values which near noon are too low and which are too high when the sun is near the horizon."

This finding justifies the use of the thermopile for ecological work. Furthermore, the continuous and approximately simultaneous records from widely separated sites which are possible with the automatic commutating galvanometer give it an immense advantage over the personal attention required for the visual apparatus. Another gain is attributed to the integration of sky and direct solor irradiation without the effect of the cosine of the angle of incidence entering as a coefficient.

For delimiting the radiant energy to the effective region of .7 to .4 it is planned to use screens with the apparatus.

In using the thermopile as a static instrument the circuit is comparatively simple. The desired number of thermopile bulbs are connected in series with negatives to positives. The negative and the positive of the series arrangement are then connected to the respective posts of a galvanometer. A variable resistance is placed in one of the other of the leads and serves to alter the sensitivity of the thermopile circuit, permitting adjustment so that all bulbs register alike with the same irradiant energy.

Wave Length Sensitivity Curve of the Ecological Thermopile.

The thermopile galvanometer records automatically, demanding attention only for removing record, winding, oiling, and similar attention to the mechanical operation. Fig. 9. shows the apparatus set up in the field.

The chart as obtained from the machine shows the variation of irradiant energy intensity in east of four stations at intervals of four minutes.

A record from one of the four stations is obtained every minute, the commutation cycle being completed in four minutes.

Viewed as a graph, with the intensity laid off along the axis of the ordinates and time along the axis of the abscissae, the area "underneath" the curve (between zero intensity and the plotted reading) is <u>work</u>:

$$\text{Time} \times \frac{\text{gram-calories irradiant energy}}{\text{unit area} \times \text{time}} = \text{work.}$$

It is these work-terms which are compared for the different sites; they are the values obtained by comparison of the areas enclosed by the curves.

The areas underneath the curves were obtained in two ways. The massive-base type produced a very jagged curve due to the lag of the cold junction. Because of the acute angles and long reaches from point to point involved it was considered better to get the area by an indirect method rather than by planimetering. The curves were therefore traced onto a uniform bond paper, cut out, and weighed. The weight of the paper per unit area was checked and found to be ± 1.5%. All the weighings were done in a dry warm laboratory within a short period, and it is believed the error due to method of obtaining area is negligible. The relative ratios of the weights of the cut-outs are the relative ratios of the work values which are desired.

Ridgeway[39] recommended the use of the photochemical decomposition of oxalic acid in the presence of uranium as a means of

39\.
Ridgeway Plant World 21:234-240 1918

Monthly Weather Rev. 46:117-119 1918

Bacon Phillip. Journ. Sci. (a) 5:281-303 1910

measuring light, and advised the use of uranium nitrate as the uranyl salt.

Braid[40] and Buchi showed that after the concentration

40\.
Braid. Journ. Ecol. 11:49-63 p. 60 1923

of the oxalic had diminished 25% - that is, to 75% of the original concentration, the reaction rate was altered. Spoehr[41] found a

41\.
Private communication

temperature coefficient. The writer checked these results by the qualitative tests about to be described.

Anderson and Robinson[42] using uranium sulfate

42\.
Journ. Amer. Chem. Soc. 47:(3) 718-725 1925

found that the reaction rate was not altered until half the oxalic acid had been decomposed. They also found that the reaction had no temperature coefficient and was of the zero order. They give[43] a table

43. Loc. cit. p.722

of amounts of decomposition for varying parts of the spectrum and the corresponding energy contents.

By bracketing these values and substracting as shown in Fig. 10 we may arrive at a crude sensitivity curve. This data is by no means final or conclusive, but it is known that the subject of this sensitivity curve is being investigated, and it is hoped that data will be available shortly.

The method is as follows: Two solutions are made up (1) the photosensitive solution containing 6.3 g.p.l. of pure oxalic crystals and 4.27 g.p.l. of uranium sulfate ($UO_2\ SO_4 \cdot 3H_2O$).

(2) the standard permanganate titration solution, 3.16 g.p.l. of potassium permanganate, to be standardized, volume for volume, against the standard photosensitive solution.

For exposure of the photosensitive solution the writer uses a spherical pyrex flask containing approximately 25 ml, inches in diameter. The flask has a short neck so that a No. 0 (A.H.Thomas) stopper makes a snug fit when the inner end of the stopper is flush with the point where the neck flares into the bulb. The flask is filled with solution just above this point and the stopper inserted. Tube T (Fig. 11) is then pushed in until it just clears the bottom of the flask and the whole inverted as shown in the figure. The tubulature allows for volume changes in the liquid and the escape of the gas (CO_2 and CO)formed during the decomposition.

For measurement of the radiation the bulbs were usually exposed in pairs. A standard period of exposure was used which varied according to the intensity of the radiation. Thirty minutes under a clear blue sky in June will decompose half the oxalic acid in the solution of the described concentration. After exposure the bulbs were brought in, shaken, and allowed to stand a couple of minutes until the gas might be released, and the liquid cooled (or warmed) to standard temperature. A 25 ml. sample was then drawn off, enough concentrated H_2SO_4 added to warm to about 75 to 95° C., and the solution titrated with the standard permanganate. The end-point is determined by the barest trace of pink lasting about two minutes. Let S_p be the amount of permanganate in ml. necessary to neutralize a 25 cc sample of the unexposed uranium sulfate-oxalic acid solution S_o (containing 6.3 g. of oxalic acid per liter). After exposure let it take A ml. to reach an endpoint. The amount of decomposition, which is the measure of the effective absorbed radiation, is in terms of standard permangante -

$$S_p \text{ ml.} - \underline{A} \text{ ml.} = N \text{ ml. decomposition}$$

in terms of standard oxalate

$$S_p \text{ ml.} - \underline{A} \text{ ml.} = N \text{ ml.} \frac{S_p}{S_o}$$

in terms of oxalic acid

$$S_p \text{ ml.} - \underline{A} \text{ ml.} = N \text{ ml.} \frac{S_p}{S_o} \times 6.3 \text{ mg. oxalic acid.}$$

And since one milligram of oxalic acid takes 21.7 gr. cal[44]

[44] Anderson and Robinson. Journ. Amer. Chem. Soc. 47:723. 1925

for decomposition, the energy in calories represented by the decomposition of the oxalic acid for a given exposure is -

$$\text{gr. cal.} = N \frac{S_p}{S_o} \times 6.3 \text{ mg. oxalic} \times 21.7 \text{ gram. cal.}$$

If the time of exposure is represented by P (period) in minutes, the average rate of energy used per minute is

$$\frac{\text{gr. cal.}}{P} = \frac{\frac{S_p}{S_o} \times 6.3 \text{ mg. oxalic acid}}{P} \times 21.7 \text{ gram cal.}$$

The writer substantiated the assertion of Anderson and Robinson that the rate of decomposition does not vary until approximately 50% of the solution is decomposed. By exposing pairs of bulbs containing partially decomposed solutions beside bulbs containing fresh unexposed solutions, the decompositions were identical within the limits of error of titration, which was less than 2%.

The temperature coefficient was determined by parallel exposures under a Hg arc of four sets of bulbs in the air and in a water bath run at 20°, 40° and 60° respectively. Ratios between decomposition at the different temperatures, $N_{20°}$, $N_{40°}$, $N_{60°}$, and in the air N_a, were equal within the limits of error.

$$\frac{N_{20° C}}{Na} = \frac{N_{20° C}}{Na} = \frac{N_{60° C}}{Na} = 1. \pm 1.0\%$$

The bulbs were set up and exposed in the field, working from a field station near the recording galvanometer. In all cases the period of exposure was noted as a necessary part of the observation, and for accurate results the period of exposure should not be longer than to permit half decomposition of the oxalic acid. The intensity recorded is the average for the given period.

Photo-electric Cell.

In the field of electrical selective photometers the photoelectric cell is very promising. It has been used in ecological work by Shelford[45] who used a potassium hydride cell for determination

45. Shelford and Gail. Pub. Puget Sound Biol. Sta. 3:141-176. 1922
Shelford. Proc. Soc. Exp. Biol. And Med. 23 (7):520-523, 1926

of radiant energy penetration into sea water.

Ives[46] uses a Case cell for the measurement of luminous

46. Ives. Astrophys Journ. 40:182-186, 1914
Trans. Illum. Eng. Soc. and subsequent papers.

sunlight out of doors, which forms the comparison standard for indoor illumination studies.

The photoelectric cell can be used in a simple circuit. A potential (V) is connected with the cell (c) and a galvanometer (G) in series, as shown in Fig. 11. A damping resistance (R) is occasionally necessary. The electrons ejected from the photosensitive surface serve in the flow of current which is increased proportionally as the number of ejected electrons is increased. The deflection of the galvanometer is directly proportional to the light intensity. It is possible to use the potentiometer method if desirable. Ives[47] finds the use of

47. Astrophys. Journ. 39:428, 1914

electrometer, or ballistic deflections undesirable because the rates of the effect are not constant over various different intervals of time.

The small potential may be amplified with a three electrode (thermionic, vacuum) tube, and a less sensitive galvanometer used. But such a circuit requires constant checking of the "A" potential and "B" current, and therefore more attention is necessary.

The choice of the photosensitive material depends upon what region of the spectrum is to be investigated. A number of elements and compounds have been investigated, and among them available either commercially or at a price are:

(1) Potassium hydride, sensitive in the blue[48].

48. General Electric Company Circular.

(2) Thalofide[49] sensitive in the blue but can be modified

49. Case Research Laboratory Circular.

by screens and filters to match almost exactly with the eye sensitivity curve.

(3) Cadmium, in the ultra-violet[50].

50. Dorno Met. Zeit 38:1-8 1921

A number of factors which concern the manufacturer, as listed mainly from Ferree and Rand, are:

(1) The nature and amount of the gas in the cell determines its resistance to some extent. Hydrogen, helium, and especially argon are used.

(2) Up to a certain point the current increases with the impressed potential. After this point is passed, the increment of current with additional voltage is but slight.

(3) Elster and Geitel[51] found that the angle of inci-

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51. Wied, Ann. Der Phys. 52:433 1894

55:684 1895

61:445 1897

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dence varied the curve of selective response.

(4) Certain types of cells pass a current in the dark. These are mostly difficulties due to leakage along the interior glass surface of the cell and must be corrected gy design.

(5) Certain cells show fatigue or decreased photo-emission after exposure. The nature of the photo-sensitive surface controls this defect - apparently the alkali and alkali-earth surfaces are free from it.

Ferree and Rand's discussion of the advantages of the photo-electric cell as a device for measuring radiation is now out of date. It may be said: (1) apparently the predetermination of the constant of efficiency of cells varies from unit to unit. (2) The reproducibility of measurable photo-effect and selectiveness of well-made cells are satisfactory. (3) A linear relation exists between the light intensity of a given range of wave lengths and its effect. (4) The cell is extremely sensitive and minute increments of radiation can be measured. With the help of the Vacuum amplifier circuit it is possible to use an insensitive galvanometer. (5) It must be standardized spectroscopically in terms of absolute units against filtered energy standards.

The present disadvantages are:

(1) A certain amount of mechanical fragility which is now being corrected by the manufacturers.

(2) The fact that a temperature above 30° C (84° F) is unsafe for certain cells such as the potassium hydride.

The photo-electric cell was the "PJ-5 Vacuum" cell obtained from the General Electric Company, Schenectady, New York. The circuit is simple; the negative of 220 volts "B" Battery was connected to the X-ray tube electrode on the outside of bulb, and the positive connected to the positive of the galvanometer. The electrode at the base of the photo-electric cell was connected to a variable resistance and the resistance connected to the negative of the galvanometer. By adjusting the series resistance the relative drop in potential across the galvanometer could be varied and the sensitivity, the deflection for a given irradiation intensity, altered.

Difficulties with fragility have proved to be an obstacle to general use, and the low injury temperature 30° C. (84° F) prevent the use of the apparatus in the sun.

<u>Sensitivity Curve</u>.

The sensitivity curve of the apparatus has not been worked out. The makers state that it has a narrow band of sensitivity in the blue; wave lengths are not stated.

The Thermopile Data.

The data for the thermopile is given in the form of graphs rather than in the less convenient form of tables.

Fig. 12 shows the record for the three shelterwood stations in the Tom Swamp Block as obtained in 1925 with the Massive Base Thermopile.

The results are given in two ways. The work - terms in the open - the area under the curves obtained as already discussed - are given in relative values. The data under the canopies are stated as percentages of the intensity penetrating the canopy, based on the total radiation in the open as 100%. The scale of relative values of the radiation and the scale of the percentage penetration thru canopies, are, it will be noted, inverted with respect to each other. The data for the open is that for Station A (Fig. 3), the 40% and 85% canopies are the values obtained at Stations B and C respectively (Fig. 3).

The moving average for a ten-day interval is also plotted in Fig. 12. This average is the arithmetical mean of a ten-day period plotted on the fifth day of that interval.

Fig. 13 contains the data for the same sites in May and June and in September of 1926. In these 1926 determinations the Spherical Hot-Junction Thermopile was used. In July and August the equipment was used in measuring the radiation in the open and under the dense two-storied white pine - hemlock reserve.

In setting up the apparatus in the open it was set over a dry, hot soil cover of needle litter characteristic of a clear-cut coniferous site. It was noted that a "noon-time" dip occurred. Experiments showed that the cause was the heating effect of re-radiation from the litter onto the lower "cold"-junctions. By painting the bulbs with a Bakelite varnish mixed with lampblack, the cold junctions were stabilated and an improvement in the record resulted. The data for the Adams Fay and later observations which are presented in Fig. 13 are all made with the blackened bulbs. The data for the Shelterwood in May and June were made with the unpainted bulbs. This may be the cause of the discrepancy to be noted in the two years' records in 1925 and in 1926, in the Shelterwood sites.

Fig. 13 also contains for late August and early September data in the Spruce Sample Plots, Cherry Mt., New Hampshire. The moving ten-day averages are also given for this figure.

Fig. 14 gives the superimposed moving ten-day averages for the two years' records.

Discussion of Thermopile Data.

Although the individual day-to-day observations exhibit great individual differences the moving ten-day averages exhibit several marked tendencies.

While the curves from Kimball's data (Fig. 3) indicates the probability of maximum radiation in July and August, the data here presented also show that total daily radiation maxima are most likely to occur in July and August.

The irradiation under the 85% white pine canopy according to the data for 1925 runs very close to 30%, being a bit above 30% at times of lower radiation in open, and a bit below 30% at times of higher intensity in the open. If the day-today radiation values are followed more closely it will be noted that this inverse relationship between percentage penetration thru canopy and the relative intensity in the open is even more strongly marked.

That the percentage penetration and relative intensities in the open are inversely related does not mean that less light penetrates the canopy on bright days. On the contrary, more light penetrates the canopies on bright days. The net result is toward a stabilization of the irradiant energy underneath the canopy: the higher percentage penetration on the cloudy days makes for a more equable daily radiation environment. This effect is doubtless due to the fact that the less bright days have a high percentage of diffuse sky radiation which constitutes the greater part of source of radiation under canopies.

The radiation underneath 40% canopy shows the same percentage effect as does the heavier canopy. In general, the brighter days show a smaller percentage penetration. It is notable that in June occurs the maximum percentage penetration at a value of approximately 80%. During the summer the percentage penetration gradually falls off to 50% in July and 40% in August. This falling off is attributed to two causes. The first is the relative increase in radiation during the summer months with the resulting operation of the percentage effect. The second is the gradual increase in the zenith distance of the sun. The sky brightness about the sun varies inversely as the distance from the sun. Lines of equal brightness of sky may be drawn around the sun as center. Thus the whole radiant source alters its position with relation to the canopy as the declination of the sun decreases with the increasing elapsed time after the summer solstice. The sparse canopy - viewed from overhead - is effectively more dense due to a "shingling" effect of the individual crowns as the zenith distance of the sun increases. The additive effects of the percentage relationship and the shingling phenomenon are considered to account for the decreased percentage under the 40% white pine canopy in July and August.

The agreement between the 1925 and 1926 data is not close enough to be entirely satisfactory. The instruments have not been calibrated in terms of absolute units, and secondary standards are not available for calibration at intervals. The difficulties in a scale of purely relative calibration as enforced by work under these conditions will never be corrected until the sensitives have been calibrated in absolute units and a secondary standard is available.

The method adopted for comparing the two moving curves was simply to superimpose the two moving averages for May and June. It is possible that the unpainted bulbs because of the heating of the cold junctions were reading 20% too low as compared with the readings later in the summer with the painted bulbs. If this was so, this would decrease the summer maxima in the Adams Fay in 1926, 20% and bring them to values more comparable with those of the summer maxima in the Tom Swamp in 1925.

The discrepancy between the 1925 and 1926 would also be thus corrected because the 20% correction applicable to the readings in the open would not be applied to the 85% canopy or to the 40% canopy data. The temperature of the ground surface under the canopies is relatively low and stable. If these values are relatively increased 40%, they then approach the values obtained with the massive base thermopile.

in the region wave length 0.30 to 0.33 .

A photo-electric cell sensitive in the blue was also used for comparative determinations in the blue (0.49 to 0.42).

These observations were made in two sites on the Harvard Forest. (1) The shelterwood cutting in Tom Swamp Block (Meadow Water"); comp. 5 (Sub-compartments 0 0 0) and (2) in the Adams Fay Block (Subcompartments E-W 100 ft. clearcut and the reserve to the south of the ends of the N-S clearcut strips). Some data from sites in the Cherry Mountain spruce plots are also included.

Description of Shelterwood Sites

The northeast corner of Compartment 5 of Tom Swamp (Meadow Water) Block was, in 1911, covered with dense, exceptionally regular, even-aged pure white pine about 50 years old. The area is comparatively level, with a slight slope toward the west. The soil is a fresh sandy loam, and is classified as site quality II. In the winter of 1911-12 an area of three acres, bounded on the north and east by the two roads shown in the map (Fig. 4) was thinned, 17 M board feet being removed. The stumps from that cutting are located in the map of 1924 by full black circles. After the thinning an abundant reproduction of pine came in over the whole area, but died in three or four years.

Another large reproduction followed the seed year of 1914. During the winter of 1917-18 a small area 150 by 50 feet (shown on the map as areas A, B, and C) was clear cut. A seedling count of the area in the spring of 1918 by a student examiner at the Harvard Forest[26] gave 28,000 per acre in the cleared area and 60,000 per acre under the stand. The difference was attributed to destruction during the logging operation. During the summer of 1918, the first after cutting, the seedlings in the open were attacked by the beetle Hylobius Pales, and in September a count showed a survival of 60.5% (17,000 per acre) uninjured. Of the other 40%, which were potential or actual loss, 33.5% (9,500) were dead from Hylobius attack, 4.5% were still living but showed signs of the attack by Hylobius and were withering, and only 1.5% (400) were dead from other causes.

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26 Compartment records of the Harvard Forest.

The examiner (Sep. 1918) comments: "When this examination was made, the seedlings had completed their fourth growing season. They were small for that age and not especially vigorous, averaging only 3.1 inches in height. This is undoubtedly due to their having grown for the first three years in the shadow of a still dense, though previosly thinned, stand of pure pine. Nor did they give any indication of having responded to the increased light during the fourth growing season. In fact, the measurement of nearly 200 seedlings growing along the middle line of the cleared strip, and of about the same number of the same age growing under the cover of the adjacent pine stand, gave for the latter an average height .2 inch higher than on the cleared strip. This shows, at least, that no immediate recovery from suppression may be expected of pine seedlings.

"The deciduous seedling and seedling-sprout growth is relatively sparse on this area, due to the density of the original pure pine stand. The chief exception is that of red maple seedlings, which the table shows to average 10,000 per acre, but they are tiny plants only a few inches high. If most of them survive they may in two or three years form a low but dense cover which will have to be removed in the first weeding. The seedling white ash, red oak, chestnut, etc., average about one foot in height, and the seedlings-sprouts about three to four feet.

"From the seed crop of '17 only eleven seedlings were found on the strip, or an average of 220 per acre. All observed were healthy.

The Adams Fay Sites.

A mixed stand of dominant white pine, with an underwood of hemlock, both approximately sixty years old, occupied the southern part of the Adams Fay Block until the winter of 1924-25. In that years a number of plots were laid out and variously treated. In the southern part of the tract [26] a gridiron cutting was laid out. Of these areas

[26] See Map, Fig. Bull # Harvard Forest, by R. Marshall.

the sites selected for study were :-

(1) Open, clear cut E.W. strip 100 feet wide.

(2) Dense 100% canopy, to the south a "reserve".

The latter formed a double decked stand with a complete canopy, the tolerant hemlock under the pine giving an exceedingly dense shelter.

The area is a comparatively level top of a long esker-like formation, sloping off into a swamp on both sides and with several large pot-holes forming hollows at intervals.

The soil is a fresh medium to coarse sand, site qualityII. Under the canopy it is covered by two to four inches of mixed pine and hemlock duff, but in the open this is fast disappearing. A ground cover of herbaceous material only is developing in the open, but under the canopy there is nothing except Indian pipe.

The two sites in the Adams Fay are also being used for fire weather studies. The records of air temperature, air humidity, evaporation from Livingston atmometers, duff temperature, and duff humidity cited in connection with the Adams Fay study were obtained from fire weather study records.

The Cherry Mountain Spruce Plots

Four permanent sample plots[27] have been established by the Forest Service in New Hampshire on the Cherry Mountain sale area. These plots are in the spruce and hardwoods type. They are being developed in order to study the effect of method of cutting on (a) the subsequent composition of the stand, and (b) on the increment of the residual stand.

Four half-acre plots have been established; each with a 100 foot isolation strip;

(1) The clear-cutting which has been cut according to the usual practice on that forest.

(2) The selection area in which selected conifers and hardwoods were cut.

Through the accident of windfall this area has become divided roughly into two areas. In the southern half the fall of eleven trees has opened up the stand more than had been planned at the time of marking. In the northern part there has been less windfall.

The windfall in the southern portion was because of the shallow rooting of the conifers due to dampness of a stony hollow in that area. In it a bush briar vegetation has come up. In the northern area some increased growth of the advance reproduction is evident but it was not marked within two years after cutting, and a negligible amount of raspberry bushes has appeared.

(3) A "cut-spruce" plot, on which the hardwoods were left. The canopy of this stand was but slightly altered.

(4) A control plot, on which no cutting was made.

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27 Westveld, U. S. D. A. Bul. from Forest Service, in press