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A SOLARIMETER FOR MEASURING PHOTOSYNTHETICALLY ACTIVE RADIATION

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SUMMARY

The instrument consists of a solarimeter fitted with a hemisphere of heat-absorbing glass. By this means, a well-tried instrument, already widely used in meteorological stations for the measurement of total incident radiation, is converted into an instrument suitable for measuring photosynthetically active radiation. The good angular response is preserved by using a hemispherical filter. With a commercial electronic microvoltmeter the instrument is sensitive enough for use in phytotrons, and if photosynthetically active radiation is assumed to be bounded by the wavelengths 0.4 and 0.7μ, calculations show that it compares irradiances of common light sources with daylight, in these units, with an error of not more than 20%, reducible to 10% with an improved filter glass. Arguments are presented for specifying and measuring light directly in such units, here called "plantwatts/m^2", rather than using illumination units and a conversion factor for each light source. Daylight measurements with a filtered and an unfiltered solarimeter over several months have shown that the number of plantwatts/m^2 is not a constant proportion of the total irradiance but varies (in one locality) from 48 to 65%. Moreover, the variation is systematic, the highest proportions occurring during the dullest weather, presumably because water vapour is the chief absorber involved. A systematic error would, therefore, be introduced by measuring with an unfiltered solarimeter and assuming that the proportion of photosynthetically active radiation in daylight is constant.

INTRODUCTION

A variety of instruments is available to a plant physiologist who wishes to measure light as a variable in plant-growth studies (ANDERSON, 1964). Among these are instruments which were developed for other purposes (the lighting engineer's luxmeter and footcandle meter, which use selenium cells connected to microammeters, with or without colour-correcting filters; the meteorologist's pyranometer, otherwise known as solarimeter or pyrheliometer) and instruments such as light integrators, which were specially developed for plant growth studies.

They all have different spectral responses, and may be calibrated in a variety of different units (lux, footcandle, gcal./cm^2/min, langley/min, erg/cm^2/sec, etc.). It would not be surprising if the plant physiologist were thoroughly confused by the choice available. He may think it not particularly important which one he chooses, considering the accuracy which he requires of the measurements. The fact is, however, that an absolute accuracy (not just repeatability) of $\pm$ 10% in light measurements is not at all easy to attain, even in the laboratory, and systematic differences between these instruments when they are used to compare different light sources, as they must be when one is trying to reproduce an outdoor light climate in a phytotron, can reach a factor of two.

Some rationalization of units and instruments is therefore needed, and this article is an attempt to help the physiologist to decide between them. We discuss which type of unit is likely to give the best correlation with the actual rate of photosynthesis of green plants, and present a simple and reliable instrument which measures both indoor and outdoor light in these units with sufficient accuracy for the practical purposes of the plant physiologist.

THE PROBLEM OF MEASURING PHOTOSYNTHETICALLY ACTIVE RADIATION

The first step is to choose a unit of measurement, and to agree upon it. Practical instruments can then be built to measure light in these units to a greater or lesser degree of accuracy.

One of the main problems is that of spectral response. It is not beyond the means of modern technology to produce instruments with any desired spectral response. The question is, what response would be nearest to that of a green plant? Our physiologist might answer: "Some plants are more green than others. How could one response be used to represent all green plants?" Now this is just the problem which faced the lighting engineers in 1924. The human eye is also very variable in its spectral response. Yet the engineers were able to agree upon a representative curve, on the basis of a few sets of measurement. This curve and the units based on it, such as the lux and footcandle, have been used for nearly 40 years without any indication that it is not sufficiently representative for all practical purposes. Surely the same situation would prevail in the field of plant growth studies, once agreement had been reached?

RABINOWITCH (1951, p.842) discussed the problem of spectral response, and concluded very reasonably that a thermopile with its infrared response removed with a filter would be the best instrument. The thermopile, being black, absorbs light equally at all wavelengths in the visible, while plants, being green, obviously do not. But the green colour is created by relatively small inflections in the spectral absorption curves. Those measurements which have been made of the action spectrum for photosynthesis suggest that practically all visible light is absorbed and used equally, and it would hardly seem necessary at this stage to introduce any inflections into the thermopile's naturally flat response curve.

In idealised form, this instrument would have a "block" type of response, confined strictly to the visible region of the spectrum. This type of response seems now to be becoming accepted. Thus GAASTRA (1959), in his studies of the photosynthesis of crop plants, measured the light in energy units bounded by the wavelengths 0.4 and 0.7μ, while in the U.S.S.R. a conference held at the Institute of Plant Physiology in 1960 recommended that all measurements be made in energy units bounded at 0.38 and 0.71 μ (NICHIPOROVICH, 1960). Either of these units would be suitable for international adoption. The concept is the same in both cases, though unfortunately they are not quite the same size.

The unit adopted will need to be given a name. The simple and short names of the lux, footcandle and langley have surely helped them to be used widely, both inside and outside the field for which they were intended. Gaastra and the Soviet committee have used the c.g.s. units "erg/cm^2/sec 0.4–0.7 μ" and "gcal./cm^2/min 0.38–0.71 μ", without abbreviating them. International bodies generally favour m.k.s. units; thus the unit stipulated by the International Commission on Illumination (C.I.E.) for radiant energy (irradiance) measurements is the w/m^2. "Watt per square metre" is a shorter name than "erg per second per square centimetre" and it is also of more convenient size, full sunlight being several hundred units. The erg/cm^2 sec being exactly a thousand times smaller, confusing prefixes such as 10^5 have to be used in practical measurements. In this paper the unit "watt 0.4–0.7 μ" is abbreviated to "plantwatt", irradiance figures being given in plantwatts/m^2. Illumination figures are given in lm/m^2 (lux).

GAASTRA (1959) and RVACHEV et al. (1963) have calculated how to convert illumination measurements in lux or footcandles to irradiance measurements in plantwatts/m^2, for a number of common western and Soviet light sources. Some further calculations are given later in this paper (Table III). These calculations are useful while illumination measurements continue to be used, but as the manufacturers are continually changing their lamps the calculations will have to be repeated at intervals.

It would be better to specify and measure directly in plantwatts. The widespread use of these units might even stimulate the manufacturers to develop lamps with greater efficiencies for plant growth, just as the present measurements in lumens lead them to compete for greater luminous efficiencies.

The next question which needs to be debated is whether or not the plantwatt does give a significantly better correlation with plant growth than the lumen. GAASTRA (1959) has measured the rates of carbon dioxide uptake of sugar beet leaves under tungsten, fluorescent and mercury lamps. The maximum rates were proportional to the irradiances in plantwatts/m^2 to within 30%, whereas illumination measurements in lux would have been in error by up to 2.5 times. The error could be further reduced by correcting for the probable spectral absorption of the leaf. Further measurements of this type are required for more leaves and more lamps. Tests with practical light sources are more useful than action spectra for photosynthesis, in view of the known non-additivity of spectral lights of different colour.

What instruments are available for measuring directly in plantwatts? Those based on selenium cells as detectors have quite a suitable spectral response, if they are not colour-corrected for illumination measurements with a green filter. Cells which have enhanced red sensitivity, such as the Megatron "Pan", are even closer to the desired "block" response, though they may be less stable. But selenium cells in general are not particularly stable devices. They need to be checked at least once a year to achieve a repeatability of $\pm$ 20%. They are also temperature sensitive, and they may suffer from "fatigue" in high light. A relatively large current can be extracted from them, but only at the expense of linearity. In general, selenium cell instruments are only suitable for rough field measurements, where their simplicity is an advantage,

Photoemissive cells are more stable and linear, and less temperature sensitive, but their low current output and high internal impedance call for an electronic amplifier with very good insulation throughout. They are, therefore, more useful in the laboratory than in the field. A variety of cells with different spectral responses is available, but none which has the "block" response without the use of correcting filters. There is often a considerable variation in spectral response from cell to cell, within one type.

Cadmium sulphide cells are now being made in larger numbers, but are mainly used for switching, or other work where high stability is not required.

Thermopiles are probably the most useful basic receivers for instruments measuring in plantwatts, because they have a flat spectral response which can rather easily be modified to a block response with cut-off filters. They are stabler and not temperature-sensitive if properly compensated. They have a low sensitivity, which calls for a fairly sensitive amplifier or recorder. GAASTRA (1959), GULYAEV (1963) and ÅNGSTRÖM and DRUMMOND (1961) have used thermopiles for plantwatt measurements, in conjunction with a deep red IR–UV-transmitting filter having a sharp cut-off at 0.7 μ. By subtracting the reading with the red filter from the reading without it, one obtains a measure of the irradiance below 0.7 μ. Where ultraviolet radiation (below 0.4 μ) is appreciable, it may be excluded by a second filter (Gulyaev) or calculated (Gaastra).

This subtraction method, though quite suitable for the isolated laboratory measurement, has the obvious disadvantage for continuous recording that two instruments would be required. Our instrument, which will now be described, uses a single filter of heat-absorbing glass, The IR cut-off is not so sharp, and there is some unwanted loss in the visible, but our calculations show that the errors are within acceptable limits for most light sources.

THE INSTRUMENT

The basic receiver is a solarimeter (pyranometer, pyrheliometer) of the type commonly used by meteorologists. These instruments are stable, reliable and sufficiently accurate (better than $\pm 5\%$). A worldwide network of recording stations already exists for the purpose of measuring total solar radiation. To make the instrument suitable for recording plantwatts, all that is necessary is the fitting of a filter to eliminate the infrared component. This we have done with a hemispherical cap of heat-absorbing glass.

The cap must be hemispherical to retain the good angular response of the solarimeter. In its native state the solarimeter is quite a good representation of a flat surface, one of the two types of surface generally accepted as standard in plant growth studies (the other being the spherical surface). The fitting of a flat filter would mean the cutting-off of the radiation coming from low angles, which is often a considerable proportion of solar radiation. Thermopiles not specifically designed for outdoor measurements often have a flat window and are, therefore, only suitable for measuring directional light at near-normal incidence. A flat filter would be of no further disadvantage with these instruments.

It is not necessary for the cap to be of good optical quality, but only of sufficiently uniform thickness that light coming from any angle gives sensibly the same reading. Our hemisphere was produced by sagging a flat sheet of glass over a hemispherical mould, then grinding and polishing away the gross imperfections of the inside surface. (A segment which was of greater radius and not quite a hemisphere would have been easier to grind.) The final thickness was 3.6 mm.

The glass used in this instrument was Chance ON 20, which we had in stock. Chance filter glasses are no longer available in sufficiently large sheets to cover our solarimeter.

Of the Schott glasses, KG 3 has the most suitable spectral characteristics (higher IR absorption and lower visible absorption than ON 20, for the same thickness), but the manufacturers state that it is not a very stable glass chemically, and may be attacked in some atmospheres. We have yet to try this glass in practice. If it is unsuccessful, a third alternative would be Corning 1–69. A sharper spectral cut-off might be obtained with interference filters, but it would be difficult to produce these in hemispherical form.

The solarimeter used in our instrument is made by the Eppley Laboratory, Inc. (Newport, U.S.A.). This company also makes a Precision Spectral Radiometer (pyranometer) which can be supplied with an extra outer hemisphere of heat-absorbing (or of red) glass, but this instrument is considerably more expensive than the one we used. The extra precision is hardly needed in plant growth studies.

Photographs of the complete instrument, and of the bare Eppley solarimeter, are shown in Fig.1. The hemisphere is waxed to the top of a simple white-painted brass cylinder, which is open at the bottom. Any condensation which forms on the inside surface of the glass disappears when the radiation reaches an appreciable level. The glass being heat-absorbing, it soon becomes warmer than its surroundings, and the moisture evaporates. After several months, however, repeated condensation leaves a slight deposit on the glass, and we have sometimes had to use polishing powder to remove it. In future models it would be better to seal the hemisphere.

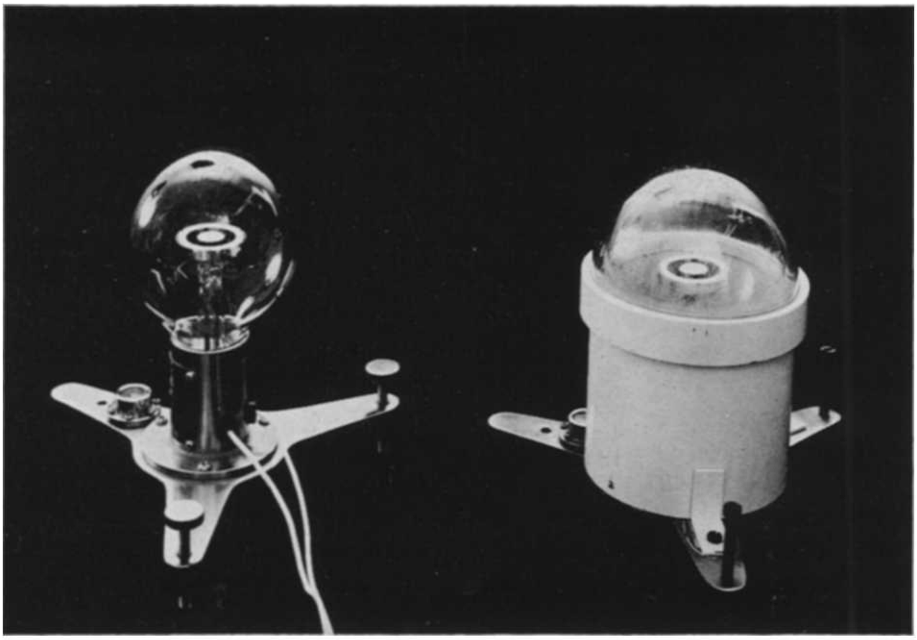

Fig.1. Basic solarimeter (left) and complete instrument (right).

For solar radiation recording, the instrument is connected to a potentiometric recorder (5 mV) in the normal way. For indoor light measurements, where recordings are not normally required, it is used with an electronic microvoltmeter (Philips GM 6020). The output is 4 μV/plantwatt/m^2. An increase of about 5 times could be obtained by using a 50-junction solarimeter, instead of the 10-junction instrument which we used.

It is a particularly useful feature, that the same instrument, calibrated in the same units, can be used both for recording solar radiation and for measuring the light in a phytotron or controlled environment cabinet. There are some errors, caused by differences between the spectral distributions of the daylight and artificial lights, acting on an instrument with an imperfect "block" response. These will now be discussed.

ACCURACY

In the present instrument, used in daylight, the unwanted infrared radiation transmitted by the ON 20 is almost exactly balanced by the visible light absorbed. The sensitivity of the unfiltered solarimeter, in mV/W/m^2 (millivolts per watt per square metre) can therefore be taken as the sensitivity of the filtered instrument in mV/plantwatt/m^2. This would not apply for other glasses such as KG 3, nor of course for other types of instrument which are not based on filtered thermopiles. They would have to be calibrated specifically in plantwatts/m², and it would be logical to do this in daylight and apply correction factors (if necessary) for other light sources.

Our calculations of the errors involved have therefore been made as follows:

First of all (Table I), we calculated the ratio of the reading of the instrument to that of an ideal "block" receiver having the same peak spectral sensivity (peak sensitivity without filter, for the two filtered solarimeter instruments). This is the ratio of: (*a*) the integrated total, for all wavelengths, of the instrument spectral sensitivity multiplied by the spectral light distribution of the source, to (*b*) the integrated total from 0.4 to 0.7 μ of the spectral distribution of the source. Next (Table II), we set this figure to be 100 in daylight, for each instrument. This second table, therefore, shows how accurately an instrument calibrated in plantwatts in daylight measures the number of plantwatts from other light sources. Thirdly (Table III), by assuming

TABLE I

RATIO OF RESPONSE OF RECEIVER TO THAT OF IDEAL "BLOCK" RECEIVER (0.4–0.7 μ), FOR DIFFERENT LIGHT SOURCES AND RECEIVERS

Receiver	*Light source*					
	sun and sky	*white fluorescent*	*mercury fluorescent*	*mercury tungsten*	*xenon*	*tungsten*
Solarimeter + ON 20, 3 mm	0.98	0.85	0.85	1.22	1.14	1.18
Solarimeter + KG 3, 2 mm	0.87	0.79	0.79	0.99	0.97	0.90
Selenium cell (type B)[1]	0.70	0.79	0.59	0.68	0.69	0.57
Selenium cell (type Pan)[1]	0.94	0.94	0.90	0.97	0.97	0.93
Colour-corrected illumination meter[2]	0.37	0.50	0.39	0.45	0.35	0.36

[1] For field instruments: stability not comparable with that of solarimeter.
[2] With spectral sensitivity of human eye.

TABLE II

RATIO FROM TABLE I NORMALIZED TO 100 FOR DAYLIGHT

Receiver	*Light source*					
	sun and sky	*white fluorescent*	*mercury fluorescent*	*mercury tungsten*	*xenon*	*tungsten*
Solarimeter + ON 20, 3 mm	100	87	87	124	116	120
Solarimeter + KG 3, 2 mm	100	91	91	114	112	104
Selenium cel (type B)[1]	100	113	84	97	99	82
Selenium cell (type Pan)[1]	100	100	96	103	103	99
Colour-corrected illumination meter[2]	100	135	105	122	95	97

[1] For field instruments: stability not comparable with that of solarimeter.
[2] With spectral sensitivity of human eye.

TABLE III

NUMBER OF PLANTWATTS PER THOUSAND LUMENS, FOR DIFFERENT LIGHT SOURCES[1]

Sun and sky	*White fluorescent*	*Mercury-fluorescent*	*Mercury-tungsten*	*Xenon*	*Tungsten*
3.96	2.95	3.78	3.26	4.14	4.08

[1] 1 plantwatt = 10^7 ergs/sec, 0.4–0.7 μ.

TABLE IV

SELECTED VALUES OF THE PROPORTION OF PHOTOSYNTHETICALLY ACTIVE RADIATION (0.4–0.7 μ) IN THE DAYLIGHT FALLING ON A HORIZONTAL SURFACE[1, 2]

Sky conditions	*Time (L.T.)*	*Sun's altitude*	*Air mass*	*Total irradiance (W/m²)*	*Proportion of visible (%)*
Clear	06h35	15°	3.8	340	51
Clear	11h35	70°	1.0	1100	47
Clear	15h20	50°	1.3	830	49
Clear	17h25	26°	2.3	420	48
Light high cloud	14h00	65°	1.1	990	52
Light high cloud	16h40	35°	1.7	330	52
Dense high cloud	13h20	70°	1.0	480	50
Passing low cloud	10h00	55°	1.2	330	53
Sunny period	10h00	55°	1.2	1100	47
Heavily overcast	08h00	33°	1.8	70	54
Heavily overcast	09h00	44°	1.4	80	58
Rain	09h35	49°	1.3	140	59
Rain	10h00	55°	1.2	80	65
Clear sky before sunrise	06h00	—	—	60	69
Clear sky (sun masked)	13h00	73°	1.0	—	69

[1] Recorded at Lower Hutt, New Zealand (latitude 41°18′S, longitude 174°42′E).
[2] $1 W/m^2 = 10^3$ ergs/cm² sec $= 1.43 \cdot 10^{-3}$ gcal./cm²/min.

that the peak sensitivity of the idealised "human eye" curve was 680 lm/W of radiation, we were able to calculate from Table I the number of plantwatts/lm, for each light source.

The calculations have been made for the two filtered solarimeter instruments, for unfiltered selenium photocells of both the normal and the red-sensitive type (data for Megatron Type B and Type Pan cells), and for cells which have been perfectly colour-corrected for illumination (photometric) measurements (C.I.E. "luminosity curve", representing the human eye).

The light sources considered are daylight (sun and sky), fluorescent, colour-corrected mercury (with both fluorescent powder and tungsten filament), xenon arc and tungsten lamp. The light from the mercury–tungsten, xenon and tungsten lamps has been assumed filtered through 1 cm of water (a greater thickness would make no appreciable difference to the figures). The spectral distribution of daylight has been computed from MOON's (1940) figures for the sun alone (altitude 30°, atmospheric pressure 760 mm Hg, precipitable water 20 mm, dust 300 particles/cm^3, ozone 2.8 mm) and HULL's (1954) figures for a clear blue sky, mixed in the proportion 5 : 1 at 0.55 μ. According to Hull's figures, in the visible region sky radiation averages about 1/5 of sun radiation on clear days. No figures for infrared sky radiation being available, Hull's figures for the visible were extrapolated to zero at 0.9 μ. Some extrapolation in the ultraviolet was also involved. The resulting distribution agreed well with Hull's figures for the spectral distribution of sun plus sky in the visible region. Both HULL (1954) and TAYLOR and KERR (1941) showed that the distribution in the visible varies relatively little with cloud cover. The proportion of visible (0.4–0.7 μ) in our daylight is 48 %, and it produces 3.96 plantwatts per thousand lumens. The corresponding figures for Moon's sunlight are 44 % and 3.82, respectively.

Figures for the spectral distributions of the fluorescent lamp (white, Philips colour 33) and the mercury-fluorescent lamp (Philips HPL) were taken from VAN DER VEEN and MEIJER's book (1959). Those for mercury-tungsten are for a G.E.C. (Great Britain) 200 W lamp, and for xenon the Osram (Berlin) XB0 900 W short-arc lamp. Figures for a tungsten lamp at colour temperature 2854°K and for the transmission factor of water were obtained at the National Physical Laboratory, Teddington, and this laboratory.

The distributions assumed for all these lamps, and the sensitivities of the various receivers, are shown in Fig.2. The calculations were made for a wavelength interval of 0.02 μ. (It is important to specify the waveband when discussing the mixed "line" and "continuous" spectra of fluorescent lamps.)

These calculations show that the instrument fitted with ON 20 glass may be relied on to compare the irradiances in plantwatts from these light sources to about $\pm$ 20 % (systematic error only). With KG 3 the accuracy would improve to about $\pm$ 10 %. Errors of a similar magnitude would be experienced with a Type B selenium photocell, but would be down to about $\pm$ 4 % with the "Pan" type cell. A colour-corrected illumination meter would have errors of over 30 %. The figures for the ratio of illumination to irradiance (lux/plantwatt/m^2) agree quite well with those of GAASTRA (1959). The differences could be explained by slightly different figures being taken for the spectral distributions of the sources, and by the fact that Gaastra used a figure of 650 lm/W for the peak luminous efficiency of the human eye, while we took the more generally accepted figure of 680 (WALSH, 1953, p.139; CONDAS, 1964).

The solarimeter is not intended to be used under or within a crop. It is too large, and rather too delicate for a field instrument. Selenium cells are more suitable for field measurements. By combining a portable two-cell instrument, to measure the ratio of the light within the crop to the light above it, with a solarimeter installation recording incident light, it would be possible to measure the light received at any point over a large area of ground.

The spectral errors involved in such a transmission measurement cannot profitably be discussed until more figures are available for the spectral distribution

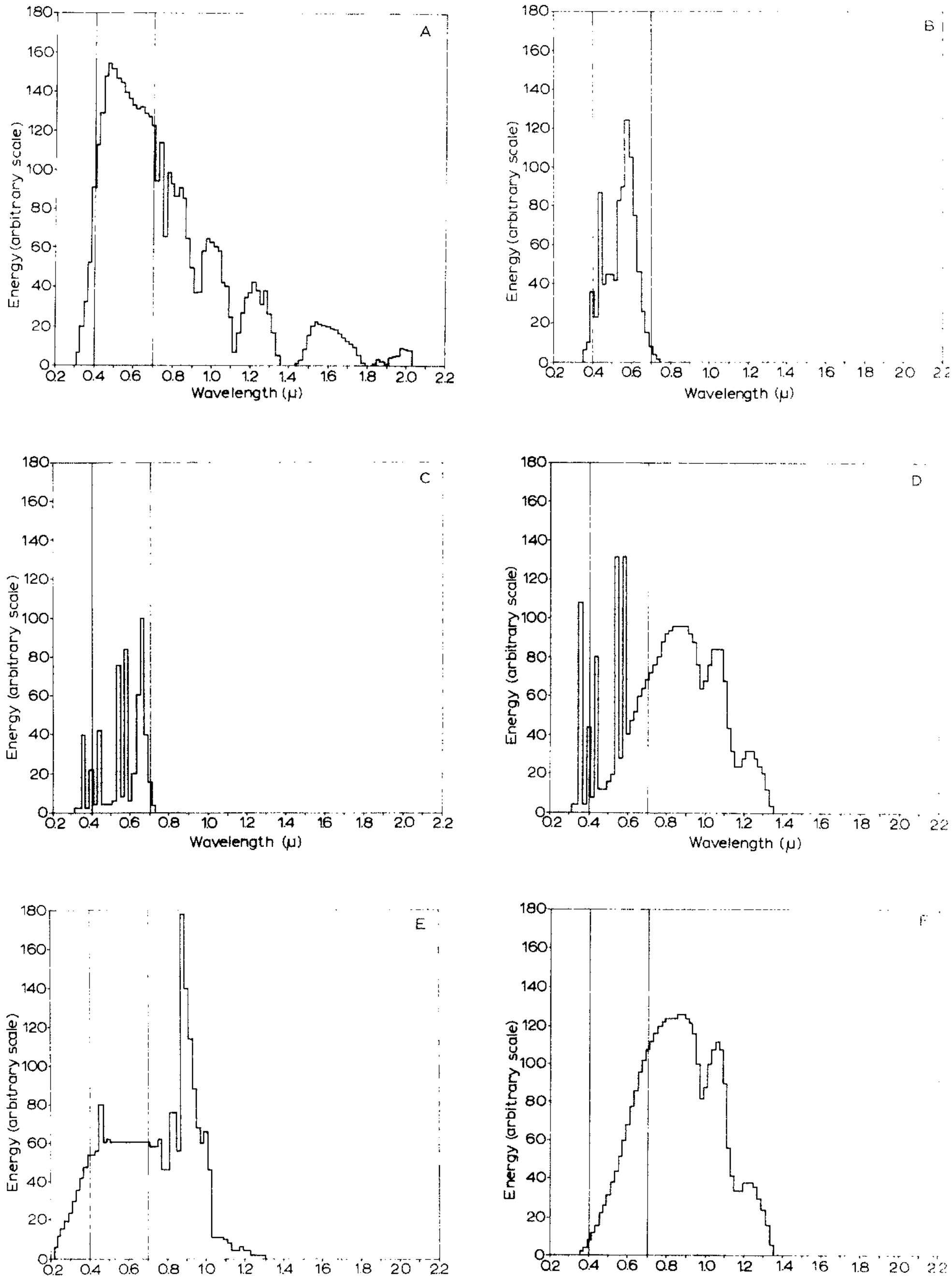

Fig.2A–F. Legend see p.363.

of the light within a crop. The spectra published by YOCUM et al. (1964) for two spots in a certain crop of corn indicate that a "shady" spot might be characterized by a rather high amount of the near infrared radiation (0.7–0.9 μ) which is transmitted by leaves. An instrument having appreciable infrared sensitivity would not give a correct measurement of the photosynthetically active part of this spectrum. However, a "sunny" spot showed no such peak in the infrared, and one wonders how much of the daily growth of a plant is due to "shade" light of high infrared content.

The angular response of the solarimeter, with and without the cap of ON 20, is shown in Fig.3. The loss of response at high angles of incidence is due to the heat-absorbing hemisphere being somewhat thicker around the edge than in the centre, and the inflections are due to similar variations in thickness. These measurements

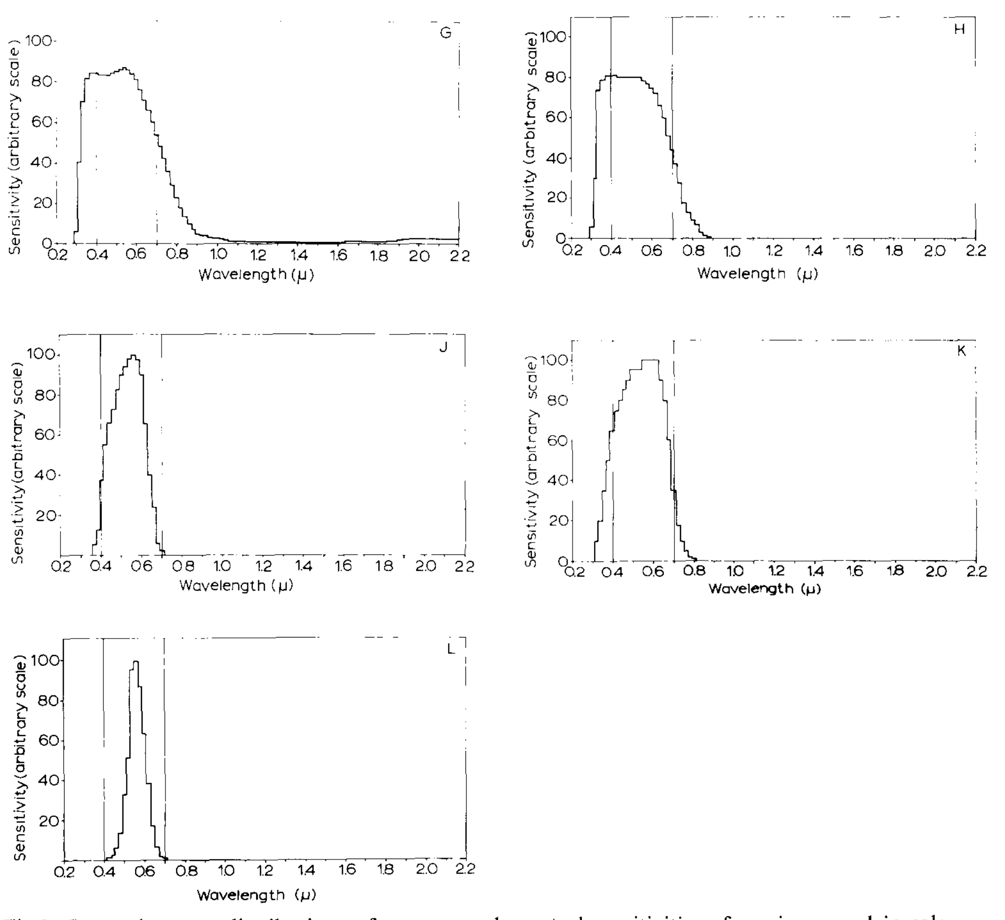

Fig.2. Spectral energy distributions of sources and spectral sensitivities of receivers used in calculations of errors (Table I, II and III).

A. Sun and sky. B. White fluorescent. C. Mercury fluorescent. D. Mercury-tungsten + water, E. Xenon + water. F. Tungsten + water. G. Solarimeter + ON 20, 3 mm. H. Solarimeter + KG 3, 2 mm. J. Selenium cell (type B). K. Selenium cell (type Pan). L. Colour-corrected illumination meter.

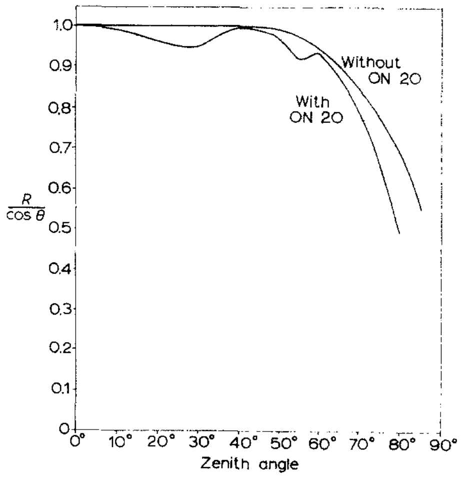

Fig.3. Angular response of solarimeter, with and without heat-absorbing filter (R), as a proportion of the response of an ideal flat receiver (cos θ). Measured with tungsten radiation, filtered through copper sulphate solution. The solarimeter used here was an obsolete type, in which carbon black in lacquer was used for the black surface. The instruments now being produced, with Parson's Optical Black, have a better angular response.

were made with tungsten radiation, not daylight. The radiation was filtered through copper sulphate solution to remove excess infrared, but the ratio of infrared to visible was still greater than that occurring in daylight, and this would exaggerate the effects of variations in the thickness of the glass.

TRIAL RECORDINGS OF SOLAR RADIATION

The instrument has been tested for several months on the roof of the laboratory. During this test, simultaneous recordings were taken with a second Eppley solarimeter without any heat-absorbing filter. This has enabled us to find out how the proportion of visible or photosynthetically active radiation (0.4–0.7 μ) varied with the weather conditions. There do not seem to have been any previous measurements of this ratio, though one might expect it to vary considerably with the water-vapour content of the atmosphere. Measurements of the ratio of illumination to total irradiance, which would show similar variations, the spectrum of daylight within the visible region being relatively constant, have been made by KIMBALL (1924), BLACKWELL (1953), JONES and CONDIT (1948) and DRUMMOND (1958). Drummond's summary of measurements made at Pretoria, Washington, Kew, and Vienna showed that the monthly means of the ratio varied over the year by up to 23%, depending on the locality. ÅNGSTRÖM and DRUMMOND (1961), in their paper on the use of a red filter with solarimeters, state that the infrared component generally amounts to between 40 and 60% of the total.

In our measurements, the two solarimeters were placed side by side on the roof with an unobstructed view in all directions except east, where there was a hill subtending an angle of about 15°. They were run without filters for a few days to establish the ratio of their readings (it was constant to within $\pm$ 2%). The hemisphere of ON 20 glass was then mounted over one instrument and the recordings continued, under a variety of weather conditions. It was assumed that the filtered instrument measured the irradiance in the visible region (0.4–0.7 μ), though in fact it only does this by balancing a slight infrared sensitivity by a slight loss in the visible. It would therefore underestimate the variations. We cannot calculate this error without figures for the full spectrum of daylight under the various conditions.

The results of the comparison (Table IV) showed that at this particular place (which has a temperate, rather moist, island climate), the proportion of visible radiation was between 47 and 52% on a clear day, increasing to 50–58% with increasing cloud and reaching 59–65% in heavy rain. For a clear sky alone it was 69%.

There is little point in speculating from these measurements what the variations might be at other places. The recordings have demonstrated that there is a significant variation, and what is more important, that the proportion of visible light varies systematically, being greater when the light is low and less when the light is high. This means that a plant physiologist who used recordings from an unfiltered solarimeter and assumed that the photosynthetically-active radiation was a constant proportion would be likely to find that he was systematically underestimating it in low light and overestimating it in high light.

CONCLUSIONS

The time is well overdue when the use of illumination units for the measurement of photosynthetically active radiation should be abandoned. Before this can safely be done:

(*1*) There must be agreement on a new unit, of a suitable size and with a short name.

(*2*) It must be shown, in practice as well as in theory, that measurements in the new unit give a better correlation with plant growth rate than illumination measurements.

(*3*) A reasonably cheap, reliable instrument must be available for measurements in the new unit, and it must be able to compare different light sources with sufficient accuracy.

Our views are that:

(*1*) The new unit should be an energy (radiant power) unit with boundaries either at 0.4 and 0.7 μ or at 0.38 and 0.71 μ. It should be an m.k.s. unit, and a suitable name might be "plantwatt/m^2".

(*2*) Although the advantages of such a unit have been sufficiently well demonstrated by calculation, more demonstrations of its practical superiority are required.

We put forward this modified solarimeter as an example of the type of instrument which we think the practical plant physiologist needs for his light measurements.

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