INFRARED REFLECTANCES OF PLANT LEAVES

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Summary

The total spectral reflectances of leaves have been measured over the wavelength range 2–12 μm or 2–14 μm for 15 plant species, and at the wavelengths 8, 10, and 12 μm for a further 32 species, the radiation being incident at 10° to the normal. At wavelengths greater than 3 μm the reflectances are less than 0·05 for the majority of the leaves, and values greater than 0·1 have been obtained for leaves from only one species. In the 2–3 μm region higher values of reflectance are common.

I. Introduction

In order to understand the radiant exchange of heat between plants and their environments it is necessary to know the spectral properties of the leaves. Two spectral regions need to be considered, the wavelength range 0·3–3 μm which contains most of the solar radiation reaching the earth's surface, and the range 3–70 μm in which bodies at temperatures about 300°K emit most of their thermal radiation. Within the latter region the interval 8–13 μm is specially significant, for two reasons. Firstly, this interval includes the maximum of the spectral energy distribution curve (in terms of wavelength) for black-body radiation at 300°K. Secondly, the atmosphere exhibits only slight absorption in this part of the spectrum and the radiant cooling of the earth's surface at night is largely through this spectral "window".

For wavelengths shorter than 2 μm the spectral properties of leaves are well known, having been measured by several workers including Coblentz (1913), Shull (1929), Billings and Morris (1951), Moss and Loomis (1952), Birkebak and Birkebak (1964), and Gates *et al.* (1965). The spectral absorptances of leaves are commonly about 0·8 or higher in the visible spectrum, decreasing rapidly beyond the wavelength 0·7 μm to a value of about 0·1, but increasing again over the range 1·2–2·0 μm to values approaching unity.

For wavelengths greater than 2 μm, the only detailed investigation of leaves known to us is that by Gates and Tantraporn (1952), who found leaves to be opaque in this spectral region, and measured spectral reflectances at several wavelengths in the range 3–25 μm for 27 plant species. The values obtained were typically about 0·05, the highest being 0·17 for a leaf of *Citrus limonia* at the wavelength 10 μm. However, these measurements took into account only the specular component of the reflected radiation, as clarified in a later article (Gates *et al.* 1965), and were mostly made at the large angle of incidence of 65° to the normal.

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The spectral directional emissivity of a surface can often be evaluated conveniently by applying Kirchoff's Law, which states:

> At a point of a surface of a thermal radiator the spectral directional emissivity is equal to the spectral absorptance for radiation of the same wavelength and incident in the same direction.

It is emphasized, however, that in order to determine the absorptance of an opaque surface from its reflectance, it is necessary to measure the *total* reflectance, including both the specular and the diffuse components. Values of absorptance and emissivity calculated from the reflectance values of Gates and Tantraporn, and quoted by some authors (Knoerr and Gay 1965; Turrell, Austin, and Perry 1962; Turrell and Austin 1965), can be correct only if the diffuse component of the reflected radiation is negligible for leaves.

We have had available an infrared reflectometer suitable for measuring total spectral reflectances for wavelengths up to 12 μm, and less conveniently up to 14 μm, and in this paper report measurements made with it on leaves from 47 plant species.

II. Method of Measurement

The infrared reflectometer, developed by Blevin and Brown (1965), was used in conjunction with a Leiss double monochromator having sodium chloride prisms and, as alternative sources, a Nernst glower and a tungsten filament lamp. A disk of 5 mm diameter was removed by a cork-borer from the leaf under investigation and stuck with a non-toxic, water-soluble glue to a nickel-plated sample holder located at the first focus of the spheroidal mirror in the reflectometer. A central area of the sample, about 1 by 0·5 mm, was irradiated with monochromatic radiation incident at 10° to the normal, the spheroidal mirror collecting both the specular and diffuse components of the reflected radiation and focusing them on a bolometer at the second focus. The reflectometer was calibrated by substituting for the leaf sample a small front-surface mirror of evaporated aluminium, whose infrared spectral reflectance curve was known. The spectral bandwidth of the incident beam, at half peak intensity, ranged from a minimum value of about 0·1 μm at the wavelength 2 μm to a maximum of 0·3 μm at 6 μm.

Each set of measurements occupied up to about 40 min after removal of the disk from the leaf, during which time the sample was exposed to ambient atmospheric conditions. Over the course of the project the laboratory temperature varied within the range 20–24°C, and the relative humidity within the range 50–80%. The power of the incident beam of radiation was of the order of 1 μW and heating of the sample was therefore negligible.

In order to check that the sample disks did not deteriorate too rapidly, a preliminary test was carried out with a leaf of *Phaseolus vulgaris* (French bean). Reflectance measurements made at the wavelengths 6 and 10 μm within 1 min after removal of a disk from its leaf, and repeated at intervals, showed no change over a period of 2 hr.

To check on the opacity of leaves at wavelengths greater than 2 μm, reflectance measurements at several wavelengths were made on a thin bean leaf of thickness

TABLE 1

TOTAL SPECTRAL REFLECTANCES OF LEAVES FROM 2–14 μm

Angle of incidence 10°. — indicates that the measurement was not made

Plant Species	Leaf Surface	Reflectance at Wavelength (μm)																
		2·0	2·2	2·4	2·6	2·8	3·0	4·0	5·0	6·0	7·0	8·0	9·0	10·0	11·0	12·0	13·0	14·0
Agapanthus umbellatus	Upper	0·07	0·14	0·14	0·05	0·04	0·04	0·05	0·04	0·04	0·04	0·04	0·04	0·05	0·03	0·03	—	—
Agave attenuata	Upper	0·02	0·02	0·02	0·02	0·01	0·02	0·02	0·03	0·03	0·01	0·03	0·03	0·02	0·02	0·01	—	—
Arachis hypogaea (peanut)	Upper	0·06	0·14	0·10	0·04	0·02	0·01	0·03	0·02	0·02	0·02	0·02	0·02	0·04	0·02	0·02	—	—
	Lower	0·04	0·17	0·13	0·07	0·02	0·02	0·05	0·03	0·02	0·01	0·01	0·02	0·05	0·02	0·02	—	—
Atriplex nummularia	Upper	0·09	0·13	0·12	0·10	0·07	0·04	0·08	0·06	0·05	0·05	0·04	0·04	0·06	0·05	0·03	0·02	0·02
(saltbush)	Upper*	0·32	0·33	0·27	0·26	0·14	0·06	0·16	0·16	0·06	0·07	0·07	0·06	0·09	0·09	0·08	0·07	0·06
	Lower	—	—	—	—	—	—	—	—	—	—	0·05	—	0·06	—	0·04	—	—
Avicennia marina	Upper	0·03	0·05	0·05	0·03	0·03	0·04	0·04	0·03	0·03	0·04	0·03	0·05	0·04	0·04	0·04	—	—
var. *resinifera*	Lower	—	—	—	—	—	—	—	—	—	—	0·01	—	0·03	—	0·02	—	—
Citrus limon (lemon)																		
Juvenile leaf	Upper	0·15	0·23	0·16	0·08	0·04	0·03	0·04	0·03	0·03	0·03	0·03	0·05	0·05	0·04	0·05	0·01	0·02
Mature leaf	Upper	0·08	0·15	0·09	0·04	0·03	0·03	0·03	0·03	0·05	0·04	0·03	0·04	0·04	0·05	0·02	0·01	0·01
	Lower	0·21	0·29	0·23	0·13	0·04	0·03	0·08	0·06	0·03	0·03	0·03	0·03	0·04	0·06	0·05	0·02	0·03
Citrus reticulata (mandarin)	Upper	0·07	0·13	0·11	0·04	0·03	0·03	0·04	0·03	0·03	0·03	0·02	0·03	0·03	0·04	0·03	—	—
Epiphyllum sp. (succulent stem)	Upper	0·04	0·04	0·04	0·03	0·03	0·03	0·03	0·02	0·03	0·03	0·03	0·03	0·04	0·02	0·04	—	—
Eucalyptus tetraptera	Upper	0·03	0·05	0·04	0·02	0·02	0·01	0·01	0·01	0·01	0·01	0·01	0·01	0·01	0·02	0·02	0·03	0·03
Gazania hybrid	Upper	0·03	0·07	0·06	0·03	0·03	0·05	0·04	0·04	0·04	0·03	0·03	0·03	0·04	0·04	0·03	—	—
	Lower	0·44	0·47	0·45	0·38	0·18	0·02	0·30	0·27	0·09	0·06	0·05	0·02	0·06	0·08	0·08	—	—
	Lower†	0·08	0·16	0·16	0·10	0·04	0·02	0·09	0·07	0·02	0·04	0·03	0·03	0·03	0·03	0·03	—	—
Macrozamia communis	Upper	0·07	0·13	0·12	0·06	0·03	0·03	0·04	0·03	0·03	0·03	0·03	0·04	0·04	0·03	0·02	—	—
Monstera deliciosa (tropical climber)																		
Mature leaf	Upper	0·05	0·12	0·11	0·04	0·03	0·03	0·04	0·03	0·03	0·03	0·03	0·03	0·04	0·03	0·03	—	—
Juvenile leaf	Upper	—	—	—	—	—	—	—	—	—	—	0·03	—	0·04	—	0·01	—	—
Pennisetum clandestinum	Upper	0·07	0·13	0·12	0·05	0·02	0·01	0·02	0·01	0·01	0·01	0·01	0·01	0·02	0·03	0·01	0·01	0·01
Phaseolus vulgaris	Upper	0·05	0·12	0·10	0·04	0·02	0·02	0·03	0·02	0·02	0·02	0·02	0·02	0·04	0·02	0·01	—	—
cv. Brown Beauty	Lower	0·08	0·15	0·14	0·07	0·03	0·01	0·05	0·03	0·02	0·02	0·02	0·02	0·03	0·02	0·01	—	—
Saccharum officinarum (sugar-cane)	Upper	0·09	0·17	0·14	0·07	0·03	0·02	0·04	0·03	0·02	0·02	0·02	0·02	0·02	0·02	0·02	—	—

* Leaf dried in oven. † Hairs removed.

TABLE 2

TOTAL SPECTRAL REFLECTANCES OF LEAVES AT 8, 10, AND 12 μm

Angle of incidence 10°. — indicates that the measurement was not made

Plant Species	Leaf Surface	Reflectance at 8 μm	Reflectance at 10 μm	Reflectance at 12 μm
ANGIOSPERMAE DICOTYLEDONEAE				
Acacia aneura	Upper	0·05	0·05	0·04
Banksia serrata	Upper	0·03	0·05	0·04
Brassica oleracea				
Waxy leaf	Upper	0·01	0·01	0·02
Waxy leaf	Lower	0·01	0·02	0·02
Green leaf	Upper	0·02	0·02	0·02
Camellia japonica cv. Don Pedro	Upper	0·02	0·04	0·05
Cerastium tomentosum	Upper	0·04	0·06	0·04
Chenopodium album	Upper	—	0·03	—
Eucalyptus blaxlandii	Upper	0·03	0·04	0·04
Eucalyptus cinerea (glaucous)	Upper	—	0·03	—
Eucalyptus nitens (green)	Upper	—	0·03	—
Eucalyptus niphophila (glaucous)				
5500 ft, Mt. Kosciusko	Upper	—	0·06	—
2000 ft, Goulburn	Upper	—	0·04	—
Eucalyptus saligna (glaucous)	Upper	—	0·05	—
Homalocladium platycladum	Upper	0·03	0·03	0·04
Kalanchoe sp.	Upper	0·02	0·02	0·02
Lychnis coronaria	Upper	0·02	0·07	0·07
Magnolia grandiflora	Lower	0·03	0·04	0·04
	Upper	0·04	0·06	0·05
Mentha rotundifolia	Upper	0·02	0·03	0·02
Nicotiana tabacum cv. Hicks	Upper	0·02	0·03	0·01
Nymphaea sp.	Upper	0·02	0·03	0·01
Populus alba	Upper	—	0·05	—
	Lower	—	0·05	—
Protea grandiflora	Upper	0·03	0·01	0·01
Ruscus aculeatus	Upper	0·03	0·04	0·03
MONOCOTYLEDONEAE				
Avena sativa cv. Algerian	Upper	0·02	0·03	0·01
Eichhornia crassipes	Upper	0·02	0·02	0·01
Spinifex hirsutus	Upper	0·02	0·02	0·02
	Lower	0·02	0·06	0·05
Trachycarpus fortunei	Upper	0·05	0·05	0·05
Xanthorrhoea resinosa	Upper	0·02	0·03	0·03
GYMNOSPERMAE				
Encephalartos altensteinii	Upper	0·04	0·05	0·04
FILICINAE				
Angiopteris sp.	Upper	0·01	0·02	0·02
Marsilea drummondii	Upper	0·02	0·02	0·02
Phyllophyte				
Parmelia sp.	Upper	0·03	0·04	0·03
Fruits				
Citrus sinensis	Outer skin	0·03	0·03	0·04
Pyrus malus	Outer skin	0·04	0·04	0·04

about $0 \cdot 2$ mm, first with the sample mounted over the opening of a small blackened cavity, and second with it glued to the usual nickel-plated sample holder. The results were not affected by the change of background.

III. Materials and Results

The leaves were obtained during the summer months of early 1966 from the University of New South Wales garden, the Sydney Botanic Gardens, and the Royal National Park of New South Wales, usually being removed from their plants only a few hours before measurement. Except where stated otherwise the sample disks were cut from mature leaves (fourth to sixth leaf from the terminal bud), at sites with least veins present.

For 15 plant species (Table 1) spectral reflectances were measured over the wavelength range 2–12 μm or 2–14 μm, at $0 \cdot 2$ μm intervals from 2 to 3 μm where rapid variations with wavelength were common, and at 1 μm intervals from 3–14 μm. Measurements on a further 32 species (Table 2) were restricted to the wavelengths 8, 10, and 12 μm within the long-wave atmospheric "window". The tabulated values of reflectance are considered to be correct to within about $\pm 10\%$ of the reflectance value or $\pm 0 \cdot 01$, whichever is the larger.

IV. Discussion

The results for all 15 species examined in detail are similar in so far as the spectral reflectance values at wavelengths greater than 3 μm are low. Most of the species show a considerably higher reflectance peak between the wavelengths 2 and 3 μm, but this is not the case with *Agave attenuata*, *Avicennia marina*, *Epiphyllum* sp., and *Eucalyptus tetraptera*.

As usually only one leaf from each plant species was measured, it was of interest to investigate differences between leaves of different ages from the same species. Spectral reflectance curves measured for juvenile, mature, and old yellowed bean leaves (Fig. 1) were found to be very similar, though the peak reflectance value at the wavelength $2 \cdot 2$ μm decreased with aging of the leaf.

Liquid water strongly absorbs radiation of wavelength greater than $1 \cdot 5$ μm, its absorption spectrum having maxima at 2, 3, 6, and 15 μm. It might be expected *a priori* that the presence of water would have considerable influence on the spectral reflectance curves of leaves, and the observed absorption bands for bean leaves (Fig. 1) and several other species (Table 1) are consistent with this suggestion. In order to test further the influence of water, a reflectance curve was measured (Fig. 1) for a mature bean leaf which had been dried in a fan-oven at 60°C for 2 days. The drying markedly increased the reflectance throughout the spectral range, but the absorption bands remained. The effect of drying a leaf of *Atriplex nummularia* was also investigated (Table 1) and found to be qualitatively very similar.

The numerous results for the 8–12 μm region (Tables 1 and 2) show only small variations between species, all reflectances at the wavelength 10 μm, for example, lying within the range $0 \cdot 01$–$0 \cdot 07$. Most of the leaves with the higher reflectance values had surface structures which could account for this behaviour. For example, a thick mat of hairs was present on the upper surfaces of leaves of *Cerastium tomentosum* and *Lychnis coronaria*, and on the lower surfaces of leaves of *Gazania* hybrid and *Spinifex hirsutus*; and dry vesicular tissues (scale) were observed on the cuticular and epidermal layers of *A. nummularia*. Investigations with two species, *Agapanthus umbellatus* and *Gazania* hybrid, showed that stripping off the cuticle and epidermal cells reduced the leaf reflectances markedly, and confirmed that these outer cells have a major influence on the reflectances of leaves.

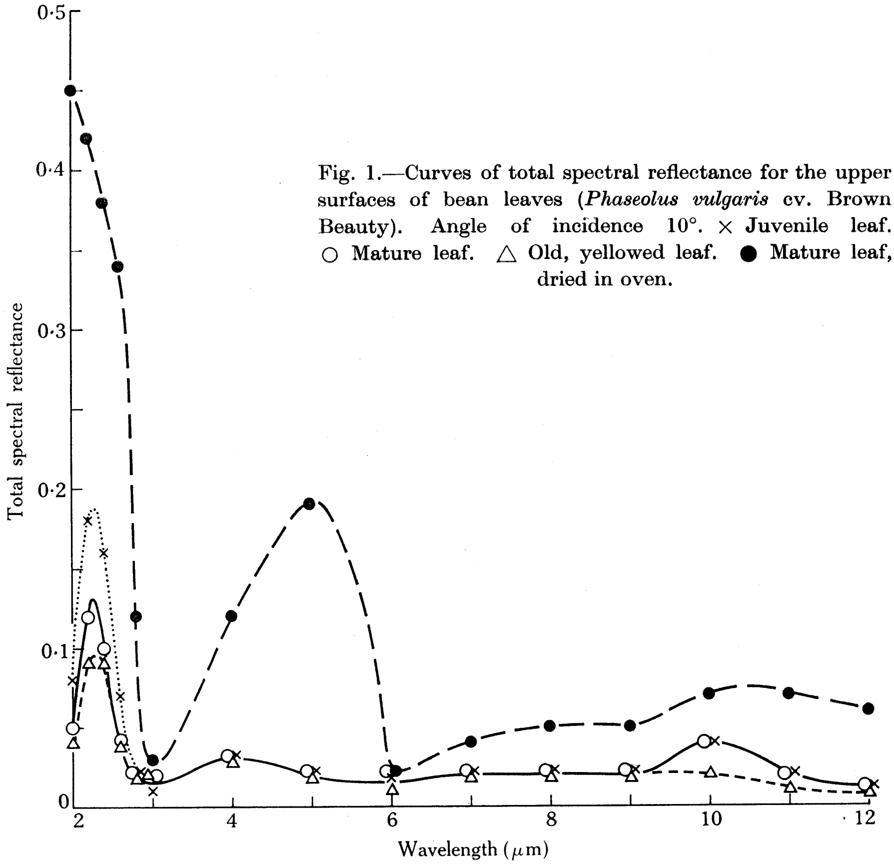

Fig. 1.—Curves of total spectral reflectance for the upper surfaces of bean leaves (*Phaseolus vulgaris* cv. Brown Beauty). Angle of incidence 10°. × Juvenile leaf. ○ Mature leaf. △ Old, yellowed leaf. ● Mature leaf, dried in oven.

For several plant species reflectances were measured for both the upper and lower surface of the leaf (Tables 1 and 2), the differences observed being neither marked nor systematic. Gates and Tantraporn (1952), on the other hand, found that the upper surfaces tend to have considerably higher values of infrared reflectance than the lower surfaces. However, their conclusion was based on measurements of specular reflectance for a 78° angle of incidence, which were more likely to be indicative of the diffusing properties of the surfaces than of their absorption properties.

With four plant species the reflectometer was used to measure the directional distribution of infrared radiation reflected by the leaves. The leaf sample was irradiated at 10° incidence as previously, and measurements were made of the radiation

TABLE 3

ANGULAR DISTRIBUTION OF INFRARED RADIATION REFLECTED FROM LEAF SURFACES

Angle of incidence 10°

Plant Species	Surface	Radiant Flux in each Angular Zone (expressed as a fraction of the total for four zones)							
		Wavelength = 2 μm				Wavelength = 10 μm			
		10–30°	30–45°	45–60°	> 60°	10–30°	30–45°	45–60°	> 60°
—	Specular reflector	1·00	0·00	0·00	0·00	1·00	0·00	0·00	0·00
—	Perfect diffuser	0·22	0·25	0·25	0·27	0·22	0·25	0·25	0·27
Citrus limon									
Juvenile leaf	Upper	0·3	0·3	0·2	0·2	0·9	0·1	0·1	0·0
Mature leaf	Upper	0·4	0·3	0·2	0·2	0·9	0·0	0·1	0·0
Gazania hybrid	Lower	0·2	0·2	0·2	0·3	0·2	0·3	0·3	0·2
Monstera deliciosa									
Juvenile leaf	Upper	0·3	0·3	0·2	0·2	0·8	0·1	0·1	0·0
Mature leaf	Upper	0·3	0·3	0·2	0·2	0·5	0·2	0·1	0·2
Phaseolus vulgaris cv. Brown Beauty	Upper	0·3	0·4	0·1	0·2	0·3	0·6	0·1	0·0

reflected in each of the angular zones 10–30°, 30–45°, 45–60°, and >60°, the angles being measured from the incident beam. Measurements at angles less than 10° were not practicable. For perfectly specular surfaces all the reflected radiation would fall within the 10°–30° zone, but for perfect diffusers it can be calculated that the distribution of radiation among the four zones would be approximately uniform, as shown in Table 3. The measurements on leaves were made with radiation of wavelengths 2 and 10 μm (Table 3). All the leaf surfaces examined behaved as rather diffuse reflectors at the shorter wavelength but, with the exception of the hairy lower surface of *Gazania* hybrid, they were less effective diffusers at 10 μm. The behaviour of *Phaseolus vulgaris* in concentrating a large fraction of the reflected radiation in the 30°–45° zone is thought to be due to the microtopography of the leaf surface.

V. Conclusions

Within the wavelength range 3–14 μm, most of the reflectance values measured for natural leaves were less than 0·05 and, with the exception of some of those for the hairy lower surfaces of leaves of *Gazania* hybrid, all were less than 0·10. In the 2–3 μm range, higher values of reflectance were commonly obtained.

As the results reported are values of *total* spectral reflectance for 10° incidence, the difference between each value and unity equals the spectral emissivity of the leaf in a direction at 10° to the normal. The wavelength range investigated includes the principal infrared "window" in the atmosphere, but is insufficient for values of total emissivity to be obtained by integration.

Leaves should not be regarded as perfectly specular or diffuse reflectors in the infrared region. The measurements of the directional distribution of the reflected radiation suggest that there may frequently be a tendency for the specular component to become more pronounced with increasing wavelength.

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