The Reflectivity of Deciduous Trees and Herbaceous Plants in the Infrared to 25 Microns

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OF GENERAL INTEREST to the ecologist, plant physiologist, astrophysicist, and biophysicist is the infrared reflectivity of the vegetation covering large areas of the earth's surface. The albedo of the earth is influenced by the vegetated areas of its surface. The energy exchange between the earth's surface, its atmosphere, the sun, and the cosmic cold of outer space depends upon the radiative properties of the vegetation, as well as upon the other constituents of its surface. Solar radiation as it reaches the outer limits of the earth's atmosphere is that of a black body radiator at approximately 6000° K, with a maximum intensity at about 4750 A.

Depending upon the solar altitude—that is, the number of air masses traversed by the solar radiation in reaching the earth's surface—the solar radiation distribution curve is reduced and distorted until the maximum energy may appear as far out as 7200 A. This is a consequence of the scattering and absorption that take place in the atmosphere. On a clear day considerably more than 50 per cent of the solar radiation incident at the earth's surface is contained in the infrared. For large solar zenith angles this percentage increases, often becoming as much as 65 per cent beyond 7600 A. A black body at the temperature of the earth's surface, 288° K, will radiate with an energy peak near 10 μ.

Accurate knowledge concerning the infrared reflectivity, absorptivity, and emissivity of leaves in the 1.0–15.0-μ region is essential for a detailed understanding of the energy exchange in the biosphere. The infrared heat exchange must be taken into consideration in the energy balance between the leaf and its surroundings. The role of infrared radiation with regard to photosynthesis and the opening and closing of stomata appears to be negligible (*1*). It might be supposed that the intense absorption of infrared solar radiation as well as earth radiation would play an important part in the transpiration of water and the subsequent temperature equilibrium of the leaf. The reflectivities of numerous species of the Spermatophyta have been reported for the visible and the photographic infrared regions. Except for Coblentz (*2*), none of the investigators obtained reflectivities beyond the 1.0-μ region.

The present investigations were undertaken to determine the reflectivity of numerous deciduous trees and shrubs beyond the photographic infrared in the region of 1.0–25.0 μ. The infrared radiant source was the Globar, whose radiation was reflected off the leaf surface at the desired angle by means of spherical front-surfaced mirrors and then focused upon the entrance slit of the infrared spectrometer. For the measurements extending from 3.0 to 25.0 μ a double-beam Baird infrared spectrophotometer with a NaCl or KBr prism was used. One beam was replaced by an external Globar, mirror arrangement, and reflecting surface, with the beam entering the instrument through the usual cell well position. The radiation was interrupted to give an a-c signal at the bolometer detector, and the signal was recorded in the standard manner for this instrument. The reflectivity record for each leaf contained a zero line representing no energy in the "sample beam," a 100 per cent line representing the reflection off a front-surfaced plane mirror, and the line of reflected energy itself. A mica filter was inserted into the beam to obtain the correct zero line for radiations beyond 8.0 μ, thereby eliminating the influence of scattered light of shorter wavelengths. The slit widths normally used for this instrument in gas analysis were used here and were automatically opened toward greater wavelength in order to compensate for the energy decrease of the radiation law. The results may be considered as accurate to ± 0.20 per cent, within a 10 per cent fractional probable error. This is principally due to the inherent noise level of the instruments used.

A Perkin-Elmer infrared spectrometer, Model 12C, with NaCl prism, was employed for the determination of the reflectivities in the region 0.9–3.0 μ. Again the leaf reflectivity was compared to that of a front-surfaced plane mirror. Unfortunately, for convenience only, the Globar radiation was incident upon the sample surface at a 78° angle. A constant slit width of 0.1 mm was used. The energy was interrupted periodically by a shutter at the Globar position to allow for a-c amplification and the subsequent recording on a Brown Electronik recorder.

To prevent overheating of the sample during measurements, the beam of radiation was focused, not at the sample surface, but so that the area filled was approximately 3″ × ½″ at an angle of incidence of 65°. Angle of incidence refers to the angle made by the ray with the normal to the surface. Larger leaves could easily accommodate this image, but smaller leaf surfaces had to be cut and fitted together to form a continuous mosaic. Double-sided Scotch tape was

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TABLE 1

THE REFLECTIVITY OF LEAVES IN PERCENTAGE TO INFRARED RADIATION AT 65° ANGLE OF INCIDENCE

Plant species	Wavelength in microns							Comments
	3.0	5.0	7.5	10.0	15.0	20.0	25.0	
Acer saccharinum	3.0	4.0	4.5	5.5	5.0			Maple leaf
Asclepias syriaca	0.5	0.5	0.5	1.0	1.0			Milkweed
Canna generalis	0.7	1.2	2.0	2.2	3.0			
Catalpa speciosa	0.0	0.2	0.2	1.0	1.7			Upper surface
	0.0	0.2	0.2	0.6	1.0			Lower surface
Elaeagnus angustifolia	1.0	1.3	1.3	1.5	2.0			Russian olive, upper surface
	2.0	1.3	1.3	1.5	2.0			Lower surface
Euonymus europaea	0.0	1.0	1.7	2.5	3.0	6.0	5.0	
Helianthus annuus	0.0	0.0	0.0	0.3	0.5			
Nymphaea sp.	1.0	3.0	4.0	7.0	8.0			Water lily
	0.8	1.0	2.0	4.0	6.0			
Opuntia sp.	0.5	1.0	1.4	1.4	1.4			Prickly pear cactus
Parthenocissus quinquefolia	2.8	3.0	3.7	4.5	4.0			Upper surface
	2.8	3.0	3.7	4.5	4.0			Lower surface
Populus alba					4.0	6.5	6.0	
P. deltoides	5.0	6.0	7.0	7.5	7.0			Cottonwood
P. tremuloides var. *aurea*	0.2	0.2	1.4	2.3	3.5			Aspen, green, 11,000′
	0.2	0.2	1.4	2.3	3.5			Aspen, yellow, 11,000′
Quercus robur	2.0	3.0	3.5	4.3	4.0			Oak, shade leaf
	2.0	2.5	3.0	4.2	3.7			Shade leaf
	2.0	2.0	2.0	2.0	2.2			Sun leaf
	2.0	2.0	2.0	2.0	2.4			" "
Rhus glabra	1.0	1.8	1.8	2.5	2.2			Sumac, shade leaf
	1.0	1.5	1.2	2.0	2.2			Sun leaf
Ricinus communis	0.8	2.0	2.6	3.5	4.0			Castor bean
Salix babylonica	4.0	4.7	5.3	7.0	6.0			Willow
Sestuca elatior	1.0	1.0	1.5	2.0	2.0			Grass
Syringa vulgaris	0.8	1.5	2.0	3.0	4.0	6.0	6.0	Lilac
Typha latifolia	1.0	1.0	1.5	2.0	2.0			Cattail
Ulmus americanus	2.2	2.4	2.4	2.4	2.5			American elm
	2.2	3.0	3.0	4.0	4.0			Old, dark elm leaf
	0.5	1.0	1.2	2.3	2.5			Young, light elm leaf
Verbascum thapsus	0.0	0.0	0.0	0.0	0.0			Mullen, hairy surface
Viburnum lantana	2.0	1.5	1.5	2.0	2.0	4.0	5.0	
	1.0	1.0	1.0	1.0	1.5			
Yucca glauca	0.2	0.2	0.5	1.0	1.5			
Citrus limonia	6.0	8.2	14.0	17.0	10.0	11.0	9.0	Lemon leaf
Ficus elastica	4.0	5.0	5.0	6.0	5.5			Rubber leaf, upper surface
	5.5	7.6	8.2	8.7	9.3			
	4.0	6.0	8.0	8.7	9.3			
	6.0	7.0	8.0	9.2	9.4			
	1.0	1.3	2.0	2.5	3.0			Lower surface
	0.5	0.8	2.0	3.5	4.9			" "
Musa paradisiaca var. *sapientum*	2.5	2.5	4.2	5.5	9.0	15.0	15.0	Banana leaf
	1.2	2.5	4.4	6.0	6.0	8.0	7.0	

mounted on a flat metal surface with the leaf sections pressed onto its upper face to form a flat mat surface. The leaves used were freshly cut from woody plants and herbs, mostly from the campus of the University of Denver (altitude 5372 feet above sea level), or greenhouses in the city. Aspen leaves were obtained at 11,000 feet in the mountains to the west, and *Sasa japonica* leaves were collected at Manhattan, Kansas. This research was conducted during August and September 1951.

Table 1 contains the reflectivities of the leaves of many species at 65° angle of incidence, in percentage relative to mirror reflection as 100 per cent. As an indication of the functional dependence of the reflectivity on the angle of incidence, a few determinations were made at a 20° angle. These are given in Table 2. Of course all angles are realized in practice. Separate listings for the same species always refer to individual leaves, except where both the upper and lower surfaces were tested. The infrared reflectivities beyond 1.0 μ are generally uninterrupted by any abrupt changes, appearing to have a very slight maximum in the 10-μ region. The rise reported by many authors at 0.72 μ has dropped to a low value again by 3.0 μ. In contrast to the work of Obaton (*3*) on the reflectivities of plants in the near photographic infrared, we have noticed no systematic distinction differentiating the reflectivities of plants native to the Denver region in one ecological situation from those in an-

TABLE 2

THE REFLECTIVITY OF LEAVES IN PERCENTAGE TO INFRARED RADIATION AT 20° ANGLE OF INCIDENCE

Plant species	Wavelength in microns							Comments
	3.0	5.0	7.5	10.0	15.0	20.0	25.0	
Catalpa speciosa	0.0	0.0	0.0	0.7	2.0			
Euonomous europaea					2.0	4.0	4.5	
Populus alba	0.3	1.0	1.8	2.0	2.0	3.0	3.5	
P. deltoides	1.5	1.5	2.0	3.0	3.0	3.8	3.5	
Syringa vulgaris	0.5	1.0	1.0	2.0	3.0	4.0	3.5	Lilac
Ulmus americana	0.5	1.0	1.5	2.0	4.0	4.3	3.2	American elm
Citrus limonia	3.0	3.0	3.5	4.5	6.0			
Ficus elastica	1.0	1.0	2.5	3.0	4.0			
Musa paradisiaca var. *sapientum*	0.3	1.0	1.5	2.5	3.0			

other, although this feature was not extensively explored. The tropical vegetation from the greenhouses possessed greater reflectivities than the native flora. Obaton obtained twice as much reflectivity from mountain flora as from flora of the plains. Billings and Morris (*4*) report on the monochromatic reflectance from 400 mμ to 1100 mμ, as measured by means of a Beckman DU spectrophotometer from the upper leaf surfaces of 20 species of plants selected from five environments in the Western Great Basin. To quote:

> The environments ranged from the desert to an open subalpine slope through three distinct wooded stations. Averages showed that the desert species reflected the greatest amount of visible radiation, followed by subalpine, west-facing pine forest, north-facing pine forest, and shaded campus species in that order. In the infrared, the differences between groups were not so marked, but the greatest reflectance here also was shown by the desert species, with an average value of about 60 per cent.

The reflectivities of leaves given by Pokrowski (*5*), Shull (*6*), and Clark (*7*) show for the visible and photographic infrared that the lower surface of the leaf reflects considerably more than the upper surface, presumably because of the lack of the palisade cells on the lower side. Table 3 gives the ratio of the reflectivity of the upper surface to that of the lower surface for several leaves at 78° angle of incidence. This shows the consistently higher reflectivity of the upper surface with respect to the lower. The single exception to the upper: lower ratio being greater than unity was for *Rhoeo discolor,* in which the upper epidermis is clearly giving rise to the normal green appearance, whereas the lower epidermis contains a deep-red anthocyanin pigment. Microscopic examination revealed the upper surface to be only slightly smoother than the lower. The curves given by Clark show a switching over of the reflectivity curves of the upper and lower surfaces for Swiss chard, *Cinchona succirubra,* and *Hevea brasiliensis* in the region of 7200 A. For many plant leaves this switching over does not occur until farther out, as evidenced by the single value less than unity for *Acer saccharinum* at 1.2 μ.

Inversion of the reflectivities can be understood when one considers the possible mechanism involved.

TABLE 3

RATIO OF THE REFLECTIVITY OF THE UPPER TO THE LOWER LEAF SURFACE

Plant species	Wavelength in microns				
	1.2	1.6	2.0	4.2	5.6
Acer saccharinum	0.7	2.5	3.5	4.4	2.8
Catalpa speciosa			3.5	5.1	4.7
Ficus elastica	2.6	3.2	2.9	1.9	1.5
Populus deltoides		1.7	2.2	2.5	2.3
Quercus robur	3.7	2.0	2.7	2.1	1.8
Salix babylonica		1.4	1.3	1.3	1.1
Sasa japonica		3.5	3.2	2.4	2.2
Tilia americana		3.3	3.3	5.4	10.0 or greater

Willstätter and Stoll (*8*) described the process by which visible and near infrared radiations are reflected internally in a leaf. The radiations are transmitted by the epidermal and palisade layers, and are internally reflected and scattered in the cells of the spongy parenchyma, thereby returning some of the rays toward the outside. Chlorophyll is very transparent in the red and photographic infrared, permitting the penetration of the rays to the spongy parenchyma, where the relationship of cellular structure and air-filled interstices permits the proper reflection of the rays at angles of incidence greater than the critical angle on the internal cell walls. Rabideau, French, and Holt (*9*) reported on the absorption and reflection spectra of leaves, chloroplast suspensions, and chloroplast fragments, as measured in an Ulbricht Sphere in the spectral range 400–800 mμ. They show clearly the correlation between absorption minima for the leaf and the reflection maxima, further substantiating the belief that the radiations in this portion of the spectrum penetrate into the parenchyma cells before returning to the outside.

In order to isolate the boundaries at which the reflection takes place, it was desired to separate the epidermis from the parenchyma, and then to determine the transmissivity and reflectivity of the epidermis and of the underlying parenchyma. The only epidermis readily available of a size for our instrumentation that could be easily stripped off was that from a *Bryophyllum* plant. The transmissivity of the

TABLE 4

Percentage Reflection and Transmission of *Bryophyllum* Leaf and Epidermis

	Wavelength in microns			
	1.43	2.0	4.2	5.6
Reflection from leaf at 78°	5	7	12	12
" " parenchyma at 78°	2	2	4	4
" " epidermis at 78°	5	7	9	8
Transmission of epidermis	26	41	48	47

epidermis 15 μ thick was of the order of 40 per cent or more at normal incidence (Table 4). Also shown in Table 4 is that the parenchyma alone, with the epidermis stripped off, reflected two fifths as much as the epidermis at 1.43 μ, two sevenths as much at 2.0 μ, and one half as much at 5.6 μ. Allowing for the transmission of the epidermis after two traversals, this results in about 80 per cent or more of the total reflectivity of the leaf taking place at the outer epidermal surface to radiations in the infrared beyond 1.0 μ. The infrared radiations entering the parenchyma layers are totally absorbed therein, since zero transmission was indicated for all leaves measured beyond 1.0 μ. That this is the expected result is indicated by the numerous absorption bands for chlorophyll and xanthophyll in the infrared beyond 3.0 μ, as reported by Coblentz and Stair (*10*). Furthermore, water absorbs intensely at 1.1, 1.4, 1.9, 2.7, and 6.3 μ.

A layer of waxy cuticle on the leaf surface will greatly enhance the reflectivity at the outermost surface. Inspection under a microscope with strong side illumination reveals the details of the leaf surface. Invariably, leaves of high reflectivity, such as *Ficus elastica, Citrus limonia,* and *Populus deltoides,* showed the cutin producing a smooth surface over the bead-like protrusion of the epidermal cells. Often the cuticle layer itself will have a jagged or granulated appearance. If the cuticle is thin or entirely lacking, the surface may have the contour formed by the epidermal cell walls. The degree of roughness or smoothness will be the determining factor governing the reflectivity of the infrared wavelengths beyond 1.0 μ. The upper surface of *Quercus robur* is smoothly contoured, broken up only by the venation, whereas the lower surface is finely granulated, reduced in reflectivity by a factor of 2.0 or more.

Additional information strengthening the thesis that the infrared reflection occurs principally at the outer epidermal surface resulted from the observation that young, light-green elm leaves reflected less than old, dark-green elm leaves, in contradiction to the opposite for visible radiation. Furthermore, the comparison of green and yellow leaves of *P. tremuloides* from 11,000 feet altitude showed no differences in reflectivity, indicating that the radiations do not penetrate enough to be appreciably affected by the pigmentation of the parenchyma. Shull (*6*) has clearly shown that these factors definitely influence the reflectivity in the visible region. The measurements on *Q. robur* and *Rhus glabra* listed in Table 1 show the shade leaf to reflect more than the sun leaf. The shade leaves were thinner, lighter in color, smaller, and of smoother surface than the sun leaves.

A fine pubescence on a leaf surface may either enhance or diminish its reflectivity. In general, if a leaf surface without hairs has a high reflectivity, then the presence of hairs will most probably diminish the reflectivity. At times this can appear misleading, because the human eye compares the relative brightness of the hairs as against the brightness of the surface. The illusion is that, although each hair reflects a relatively large amount of energy per unit area per unit solid angle toward the observer, thus appearing very bright, the reflecting surface is small, so that the total energy reaching the eye is small. In general, the hairs will scatter the radiation and trap it within the hairy blanket. This mechanism is apparently more effective in the infrared than in the visible. The extreme case of *Verbascum thapsus* possessed zero reflectivity, and that for *Asclepias syriaca* was very low. Billings and Morris (*4*) showed a high reflectivity in the visible for *Eurotia lantana,* and a diminished reflectivity in the infrared relative to that for other leaves from the same environment. The upper and lower surfaces of *Elaeagnus angustifolia* (Russian olive) possessed the same reflectivities in our measurements. In visible light the upper surface appears green and the lower silvery. The silvery appearance of the lower surface is due to thousands of small hairs in the form of closely overlapping pin wheels.

The reflectivity of leaves in the infrared beyond 2.0 μ is generally small, being less than 10 per cent for an angle of incidence of 65°, and less than 5 per cent for an angle of 20°. The reflection takes place principally at the outer epidermal surface, with about one fifth or less of it contributed by the epidermal-palisade boundary. The upper surface reflects more than the lower, old leaves more than young, and the shade leaf more than the sun leaf. For each of these the inverse is true in the visible. The structure of the leaf surface and the covering by the cuticle appear to be the factors determining the reflectivity. The transmissivity of leaves is zero in the infrared beyond 1.0 μ, although the transmissivity of the clear epidermis is 40 per cent or more.

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