VARIATION IN INFRARED REFLECTANCE OF *EUCALYPTUS RADIATA* DC.

By R. Story* and G. A. Yapp*

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Abstract

Various workers have reported that green plants which are diseased or in need of water have a lower infrared reflectance and consequently a blue image on false colour film. The infrared reflectance of *E. radiata* leaves rises as they become dry, and produces no blueness of the false colour image. It is suggested that blue images of *E. radiata* recorded in the field are due to lower reflectance of the infrared wavelengths by flowers. Water stress is not likely to be detected on false colour film until the plants are visibly affected.

I. Introduction

In this paper we deal only with false colour film (Kodak Ektachrome infrared) and with the radiation that is in and slightly beyond its photographic range (up to $1 \cdot 2$ μm).

Without detail or technicalities, the operation of false colour film may be described as follows. A yellow (minus blue) filter is used to eliminate wavelengths below $0 \cdot 5$ μm. The film is three-layered, with an infrared-sensitive, cyan-positive image layer over a green-sensitive, yellow-positive image layer over a red-sensitive, magenta-positive image layer. A green object which reflects infrared light will bleach its image in the cyan and yellow layers and be recorded in the magenta layer. A green object which does not reflect infrared will bleach its image in the yellow layer and be recorded in the cyan and magenta layers which combine as blue. Details of these processes are to be found in papers by Marshall (1968), Colwell (1956, 1965, 1968), Fritz (1967), and others.

From time to time, workers on false colour film have reported blue images from plants which are in some way physiologically upset, while other workers have not been able to confirm these findings. The position is summarized in papers by Benson and Sims (1967) and by Cochrane (1968). In our examination of the use of stereoscopic infrared photography for ecological surveys, we found blue-image trees in one of the strips which we had photographed in false colour film over an area of wet sclerophyll forest 20 miles south-west of Braidwood, N.S.W. The flight, during clear and calm weather in midsummer 1967, was at 3000 ft above the ground, to give a photographic scale of 1 : 12,000, and the film was processed 8 weeks later. It

* Division of Land Research, CSIRO, P.O. Box 109, Canberra City, A.C.T. 2601.

showed few striking differences in the normal red of the various species of eucalypts that were represented. What did stand out were the scattered blue trees, some rather faintly blue, but all conspicuous. They could be distinguished also by a much paler tone on the supporting true colour and black and white photography that had been taken at the same time. Field checks established that they were *Eucalyptus radiata*, apparently in no consistent way different from the normal red-image trees of the same species that surrounded them.

Photographic checks on foot with the same type of false colour film in late autumn included underexposed, correctly exposed, and overexposed photos of blue-image and red-image trees with the routine yellow filter (Wratten 12) and also with a green filter (Wratten 59). Most were taken by reflected light, some by mainly transmitted light (the tree between the sun and the camera, with light shining through the peripheral leaves). The subjects photographed included the whole tree, the tree top, and close-up views of leafy detached twigs with mature and immature foliage. Twigs and leaves collected from each tree as the photos were taken were stored in polythene bags for macroscopic, microscopic, and spectral analysis.

II. Preliminary Results

All specimens, whether from the blue-image or red-image trees of the aerial photos, gave a red image on the ground photos. Exposure time and filters had no differential effect between the two groups. Immature leaves gave a paler red image, but no detectable blue image.

Macroscopic examination of the leaves and wood of the blue-image trees showed nothing consistently unusual, and microscopic examination showed no fungal infection and no structural abnormalities.

The photographic infrared range of false colour film is from about $0 \cdot 7$ to about $0 \cdot 9\ \mu m$. We measured the leaf reflectance through and a little beyond this range ($0 \cdot 65$–$1 \cdot 2\ \mu m$) at $0 \cdot 1$-μm intervals by means of a Zeiss SPM2 mirror monochromator fitted with a quartz prism. The light source is a tungsten car-headlight bulb powered by a well-stabilized 12 V, 60 W d.c. supply. The monochromator is arranged to irradiate, with approximately normal incidence, a $1 \cdot 5$ by 20 mm area at the centre of a 20-mm diameter leaf sample disk, mounted with double-sided sticky tape on a brass sample holder. The surface of the sample holder was coated with a black, infrared-absorbing paint. The holder is at the geometrical centre of a hemispherical polished aluminium reflector, which focuses the radiation reflected by the sample on to a Kodak-type N2 lead selenide photoresistor mounted adjacent to the sample. The sample holder is arranged so that it may be reversed and so present a calibration surface to the monochromator. The wavelength drive of the monochromator is arranged to run synchronously with a chart recorder. The d.c. signal from the photoresistor passes through a preamplifier to the Y-axis of the recorder.

The procedure used was to run a reference curve over the $0 \cdot 65$–$1 \cdot 2\ \mu m$ wavelength region using the reference surface on the sample holder, return the monochromator and the recorder to their starting points, and rerun a curve with the leaf sample in place. Each reading was expressed as a percentage of that obtained from the reference surface at the same wavelength. Changes in reference level over one period of sample measurement did not exceed 2%.

We found no consistent differences in the reflectance of the leaves from the red-image and blue-image trees, in fact there were at times bigger differences between different leaves from the same branch. This suggested either that the blue image was connected with the altitude at which the photos were taken, or that the spectral properties of the trees had changed in the time between the taking of the two sets of photos.

III. Further Work

We thereupon checked both these possibilities. The altitudinal effect was investigated by photographing the strip again in early winter at the same height as the original, and also at 8000 and 500 ft above the ground (scales 1 : 32,000 and 1 : 2000 respectively). All these photographs confirmed the ground photography in showing that the former blue-image trees now had the characteristic red image of the normal *E. radiata*, i.e. the blue image had been connected with spectral properties and not altitude.

We next investigated as follows the trend of reflectance and photographic image of the leaves as they wilted.

Twelve samples from *E. radiata* were analysed for spectral reflectance from 0·65 to 0·9 μm, weighed, and photographed on false colour film. We then dried them in position on the holders for 2 hr under light pressure between botanical drying paper and repeated the observations, continuing in this way for 20 consecutive hours, when water loss had for practical purposes ceased. The sticky tape used for mounting the samples maintained its weight when the samples were dried, enabling us to make an accurate assessment of water loss, and errors were further cut down by analysing the samples always in the same order, and by choosing (arbitrarily) to attach the samples with the adaxial side exposed.

An identical check with *E. radiata* leaves from a different locality and with different sample holders confirmed all the findings of this test, discrepancies being in detail only.

IV. Results

(1) The visual appearance changed from a fairly bright green to a paler green as the samples dried.

(2) The photographic image became slightly paler red.

(3) Until about 40% of fresh weight is lost the change in reflectance is slight and erratic, usually with gains between 0·65 and 0·7 μm and braided curves between 0·7 and 0·9 μm. As the moisture content drops further there is a distinct but wavering rise in reflectance, with some minor irregularities between adjacent curves, that is between one 2-hourly reading and the next. Figure 1 shows the curves at the beginning, the middle, and the end of the series, and the position of the curve at 36% weight loss.

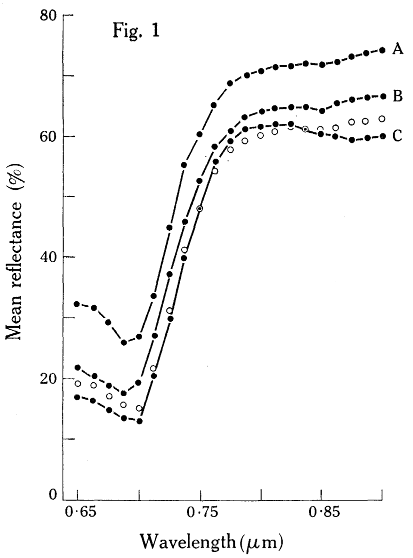
(4) Water loss (Fig. 2) is at first quick, then slow, and fits closely to a smooth curve.

V. Discussion

(a) *Infrared Reflectance of Leaves*

The strong infrared reflectance of healthy green vegetation has been tentatively ascribed to "the spongy structure of the mesophyll tissue of the healthy green leaf" (Clark 1946, cited by Colwell 1956) and it has been suggested that the reflectance will drop if the intercellular spaces are obliterated through loss of turgor in the spongy mesophyll or through the entrance of fungal hyphae (Colwell 1956; Colwell *et al.* 1966).

It is most unlikely that this theory can apply to *E. radiata*, for although its leaves have the normal high infrared reflectance of most leaves, all those we examined had six or seven rows of palisade parenchyma and virtually no spongy mesophyll or air spaces. This is the rule with many other eucalypts as well (McLuckie and McKee 1954). Whether the theory would hold good even for mesophytic leaves is



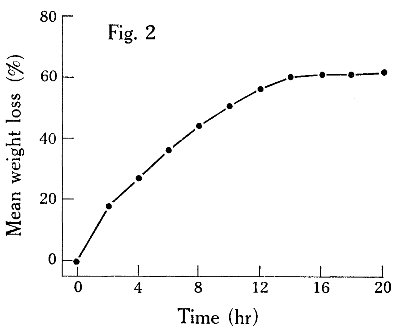


Fig. 1.—Infrared reflectance of *E. radiata* leaves with wilting (Zeiss monochromator). *A*, 60% weight loss, 20 hr wilting. *B*, 50% weight loss, 10 hr wilting. *C*, fresh leaves. ○ 36% weight loss, 6 hr wilting.

Fig. 2.—Weight loss of leaves of Figure 1.

open to doubt, for a check with elm leaves showed a similar rise in infrared reflectance as the samples dried (Fig. 3), and we confirmed that these leaves had the "spongy tissue containing large lacunae" described by Metcalfe and Chalk (1957). Soaking the dried leaves in water reversed the process. We did this by immersing them overnight, drying their surfaces with filter paper, and then repeating the tests (Fig. 3). Not only did infrared reflectance drop after soaking, it dropped well beyond that of the fresh green leaves, perhaps through filling of the air spaces and consequent supersaturation, as the gain in weight indicates. Similar results have been reported by Weber and Olson (1967), and by Wong and Blevin (1967) for the influence of water in another part of the infrared, with leaves from a bean and *Atriplex nummularia*. Several references to the same effect are cited by Murtha (1968). It therefore seems likely that leaves have high infrared reflectance not because of the water they contain but in spite of it.

(*b*) *Correlation of Water Loss and False Colour Image*

Even at the beginning of the drying tests, the false colour images of our material showed no sign of blue, i.e. the infrared reflectance was evidently strong enough to bleach the cyan layer in the film completely, and the rise in this reflectance as the leaves dried would have had no further effect on the image. On the other hand, an increase in the water content, because of the diminishing infrared reflectance that goes with it, might well cause a blue bias. However, we have not been able to see it.

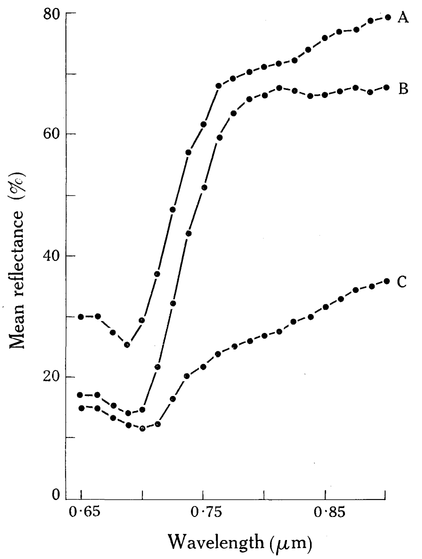


Fig. 3.—Infrared reflectance of elm leaves with wilting and soaking (Zeiss monochromator). *A*, 44% weight loss, 6·5 hr wilting. *B*, fresh leaves. *C*, 14% weight gain, overnight soaking.

The tests were with material collected on the first day after 3 days of rain totalling nearly 5 in., but photographs of the specimens and of the tree showed no perceptible deviation from the normal red, though the leaves must have been close to full turgor. Their moisture content averaged 61·5%. Sampled during a spell of normal fine summer weather 8 days before this rain, *E. radiata* leaves averaged 49·5% moisture.

That the leaves become visibly paler green as they dry should cause a yellow bias in the false colour image. This also we have been unable to see, even with the severe water loss that occurred during these tests. The effect in fact is that the red image fades in step with the fading green. False colour trials with live cotton plants, wilted and fresh, have also proved negative (H. A. Nix, personal communication).

(*c*) *Reason for Blue Image*

As to what caused the blue image of the trees under discussion, the evidence so far presented indicated that it was unlikely to be anything in the foliage, and photographic tests ruled out the possibility of any blue influence from the twigs. There remained the possibility that the flowers might provide a simple and matter-of-fact explanation. They are creamy white, and in this respect at least satisfy the requirements, since before a subject can produce a false colour image in blue (or cyan, which is pale blue) it must reflect white, yellow, or green light to bleach or partly bleach the yellow-forming layer of the film. Secondly, flowers in *E. radiata* are sometimes confined to one or two branches, and some of the blue images were in one particular segment of the crown. Thirdly, blue-image trees noted on other flights and from ground shots proved to be flowering specimens of other trees with similarly coloured flowers (*Acacia melanoxylon*, *E. melliodora*, *E. blakelyi*, *E. bridgesiana*, *E. sieberi*). Direct evidence was elusive, for flower production by *E. radiata* is infrequent and irregular. Ground and air searches in the Canberra and Braidwood areas during the three seasons following the tests revealed only two flowering specimens, neither of which could be photographed from the air. We eventually found flowering trees near Moss Vale and Bungendore, and photographed them on December 31, 1970. They produced blue images similar to those of December 1967, as shown in Figures 4 and 5. The difference in tonal quality is in our experience usual when a

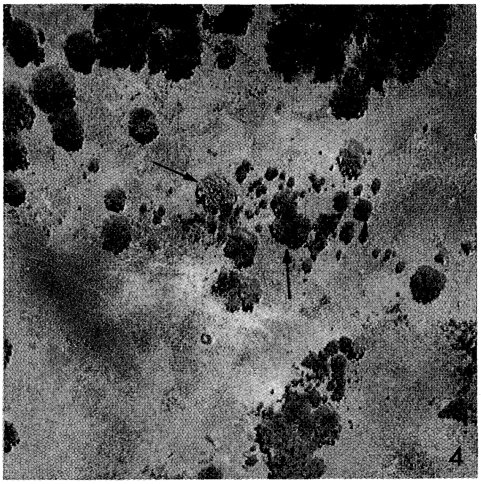


Fig. 4.—False colour. Blue-image *E. radiata* near centre, one partially blue to the right and slightly below. Probably in flower. December 1967.

Fig. 5.—False colour. Blue-image *E. radiata* top centre, confirmed in flower. December 1970.

series of infrared photos is taken of the same subject, even at short intervals in the same area, for although the latitude of false colour film is given as $\pm$ half a stop, we have found that half a stop either way can throw the colours well off balance. Additional influences are weather, time of day, age of leaves and flowers, angle of reflectance, set of the leaves, perhaps film batch, and others that we cannot yet explain.

Spectral reflectance of the flowers and leaves was determined in the laboratory to see whether the results agreed or conflicted with the false colour image. The flowers owe their showiness to the stamens, as petals and sepals in the generally accepted sense do not occur among the eucalypts. Since the leaves are relatively dense and the stamens threadlike, direct comparison of the spectral signatures presents some difficulty. The instrument used was a Shimadzu recording spectrophotometer MPS50, with a 45–90° reflection accessory in which the sample may be secured behind a glass-fronted slit. For the stamens we improvised a sample holder in the form of a short collar of Perspex. The stamens were removed by hand, packed into the collar from the back, and held firmly in position against the glass by a spring-loaded plunger. After analysis the process was repeated with the addition of more material to the stage of maximum reflectance, i.e. to the stage where negligible radiation was lost in transmission through the material. For the leaves we used the same process but without the collar, building up the sample a leaf at a time to a similar end.

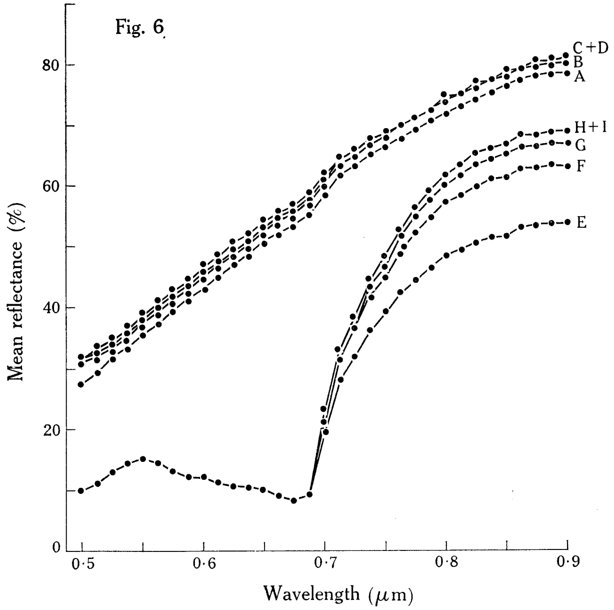


Fig. 6.—Percentage reflectance of *E. radiata* through the range used for false colour photography (Schimadzu spectrophotometer). Curves *A*, *B*, *C*+*D*, flower layers; curves *E*, *F*, *G*, *H*+*I*, leaves.

Curves for flowers and leaves through the range for false colour film are given in Figure 6, and the derived numerical values in the following tabulation:

	Visible (0·5–0·7 μm)	Infrared (0·7–0·9 μm)
Reflectance (as % of total incidence)		
Flowers	23·11	37·20
Leaves	5·96	28·89
Relative reflectance (%)		
Flowers	38·31	61·69
Leaves	17·09	82·91

They indicate that if massed flowers and massed leaves were photographed separately and with optimum exposure in each case, the leaves could be expected to bleach more of the cyan layer and the flowers less, i.e. the flowers would give a bluer image.

In the field, where flowers and leaves are mixed, the exposure value is a compromise. If the flowers predominate their greater aggregate reflectance will prescribe a short optimum exposure, and they should give a blue false colour image, with the leaves underexposed and dark red. If the leaves predominate a longer optimum exposure will be prescribed, resulting in paler red leaves and white flowers.

The curves derived from the Zeiss monochromator, which has been fitted with a hemispherical light-collecting system, differ from those of the Shimadzu's 45–90° system. Direct comparison of the results from the two instruments is not possible.

VI. Conclusions

The experiments indicate that false colour film will not record previsual moisture stress in *E. radiata*.

It will indicate flowering in this and some other species by a blue image which varies in tone according to the amount of flowering material and according to incidental influences, but in our opinion it has no advantage in this respect over black and white or normal colour film.

The fact that many eucalypts flower at set times which do not overlap provides a way of identifying them from aerial photos that is easier and less ambiguous than most. Figure 6 shows that the greatest spectral difference between flowers and leaves is at $0 \cdot 655$ μm, from which one may infer that the contrast could best be brought out by employing a red-sensitive film (which most modern films are) and utilizing only the radiation between about $0 \cdot 65$ and $0 \cdot 7$ μm. This could be done cheaply and simply with panchromatic film and a Wratten 70 filter or its equivalent. If filters are to be used for this purpose, false colour and normal colour film are inadvisable, as it would be a waste of money to pay for the unusable dye layers. Moreover, false colour film would need an additional filter to cut off the radiation between $0 \cdot 7$ and $0 \cdot 9$ μm. It is doubtful if such filters are available for they would have very little application.

VII. Acknowledgments

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