THE APPLICATION OF THE WEIGHTED NEAR-INFRARED - RED VEGETATION INDEX FOR ESTIMATING LAI AT THE VEGETATIVE AND GENERATIVE STAGE OF CEREALS

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Commission VII

Abstract:

The (weighted) near-infrared - red difference can be used as a vegetation index for estimating leaf area index (LAI) of green vegetation as described earlier (Clevers, 1986d). This vegetation index offers a good correction for soil background in estimating the LAI of green vegetation, e.g. cereals at the vegatative stage. The derivation of this vegetation index and its mathematical relation to LAI will be evaluated further.

Subsequently, it will be shown that the same vegetation index can be applied at the generative stage of cereals at which a correction for yellow and dead leaves has to be incorporated because of senescence of the crop. The mathematical relation between this index and green LAI will be described resulting in a similar equation with different parameter estimates as at the vegetative stage.

The above was tested with real field data by using reflectance factors ascertained in field trials with multispectral aerial photography.

1. INTRODUCTION

Remote sensing techniques provide information about agricultural crops quantitatively, instantaneously and, above all, non-destructively. During the past decades knowledge about remote sensing techniques and their application to fields such as agriculture has improved considerably. Bunnik (1978) demonstrated the possibilities of applying remote sensing in agriculture, particularly with regard to its relation with crop characteristics such as soil cover and leaf area index (LAI). LAI is defined as the total one-sided green leaf area per unit soil area and it is regarded as a very important plant characteristic because photosynthesis takes place in the green plant parts.

For a green crop canopy, in the visible region only the reflectance of the upper layer of leaves determines the contribution of the canopy to the total measured reflectance (Knipling, 1970). In the near-infrared region there is hardly any infrared absorptance by a green leaf (Gausman, 1974). In this situation leaves or canopy layers underneath the upper layer contribute significantly to the total measured reflectance. This multiple reflectance indicates that the infrared reflectance may be a suitable estimator of LAI.

At the beginning of the growing season, soil reflectance influences the relation between measured infrared reflectance and LAI. At low soil cover, soil reflectance contributes strongly to the composite canopy-soil reflectance in the different spectral bands. Soil moisture content is not constant during the growing season and differences in soil moisture content greatly influence soil reflectance.

At the end of the growing season, annual agricultural plants will show signs of senescence. Leaves turn from green to yellow. This phenomenon starts when the LAI is at its maximum value. In cereals all the leaves have appeared by that moment and the ears are about to appear. Subsequently, both LAI and photosynthetic activity decrease, because only the green parts will be photosynthetically active. During this stage it is important to gain an impression of the speed of senescence and to estimate LAI. Yellow leaves will also influence the relation between measured infrared reflectance and (green) LAI.

If a multitemporal analysis of remote sensing data is required, a correction has to be made for background when ascertaining the relation between infrared reflectance and LAI.

Clevers (1986a, 1986b) has described a simplified, semi-empirical, reflectance model for estimating LAI of a green canopy (vegetative stage). In this model it is assumed that in the multitemporal analysis the soil type is given and soil moisture content is the only varying property of the soil. First of all, soil cover was redefined as: the fractional horizontal area of soil obscured and shaded by vegetation at the particular combination of sun and view angles existing at the instant of the observation ("apparent soil cover"). This definition is valid for a uniform crop as well as for a non-uniform crop (including row crops). In the special situation of the sensor looking vertically downwards (as is often the case in remote sensing), this definition of soil cover is equivalent to the relative vertical projection of green vegetation, the relative area of the shadows (shaded soil) included. Next, the simplified reflectance model derived by Clevers was based on the expression of the measured reflectance as a composite reflectance of canopy and soil: the measured reflectance in the green, red and near-infrared spectral bands is a linear combination of the apparent soil cover (new definition) and its complement, with the reflectances of the canopy and of the soil as coefficients, respectively (cf. section 2.1). For estimating LAI a corrected infrared reflectance was calculated by subtracting the contribution of the soil in line of sight from the measured reflectance of the composite canopy-soil scene. This corrected infrared reflectance was ascertained as the difference between the measured infrared and red reflectance, assuming that the ratio between infrared and red reflectances of bare soil equals one, independent of soil moisture content. In this paper this expression will be generalized for soils with a constant ratio (not necessarily equal one) for a given soil background, which assumption is valid for many soil types. Subsequently this corrected infrared reflectance was used for estimating LAI according to the inverse of a special case of the Mitscherlich function. This function contains two parameters that have to be estimated empirically from a training set. Simulations with the SAIL model (introduced by Verhoef, 1984) confirmed the potential of this simplified (semi-empirical) reflectance model for estimating LAI.

The starting point of this study was the simplified reflectance model for the estimation of LAI, introduced by Clevers (1986c), using calibrated reflectance factors. From this model a simple vegetation index was derived for correcting the infrared reflectance of green vegetation for soil background as well as for yellow leaves. Subsequently, the mathematical relation of this index and LAI, derived by Clevers, was applied for estimating LAI. This approach was verified with real field data.

2. INDEX FOR ESTIMATING LAI

2.1 Vegetation index for a vegetative canopy

The simplified reflectance model derived by Clevers (1986c) was based on the equation:

$$r = r_v.B + r_s.(1-B) \qquad (1)$$

r = total measured reflectance
r_v = reflectance of the vegetation
r_s = reflectance of the soil
B = soil cover.

The apparent soil cover (B) in equation (1) takes the sun-sensor geometry into account, and it can be described as (Clevers, 1986c):

$$B = 1 - e^{-(K+k)\,.\,LAI} \qquad (2)$$

with K = extinction coefficient per leaf layer in the sensor direction (so K varies with view direction);
k = extinction coefficient per leaf layer in the direction of the sun (so k varies with the position of the sun).

Conventionally, for a green canopy, soil cover is defined as the relative vertical projection of the canopy on the soil surface. In this definition the position of the sun is irrelevant and the conventional soil cover (B_c) equals (Bunnik, 1978; Clevers, 1986b):

$$B_c = 1 - e^{-K.LAI} \qquad (3)$$

The relation between B and B_c is illustrated in figure 1 for some values of K and k (cf. Bunnik, 1978). Clevers (1986b) has shown that the relation between the reflectance in a visible spectral band and soil cover, according to the conventional definition, is non-linear. However, using the new definition for soil cover this relation is nearly perfectly linear.

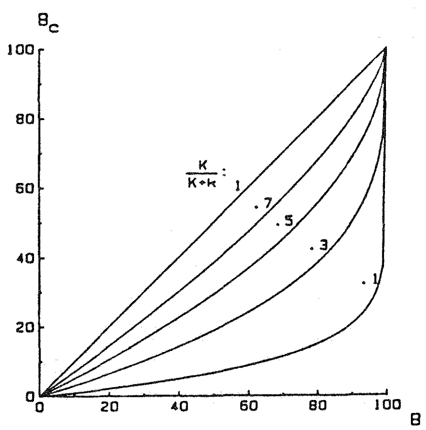

Figure 1: Relation between the apparent soil cover (new definition) and soil cover according to the conventional definition.

A red band will be denoted by the subscript r and an infrared band by the subscript ir. Then equation (1) is written as:

$$r_r = r_{v,r}.B + r_{s,r}.(1-B) \tag{4}$$

$$r_{ir} = r_{v,ir}.B + r_{s,ir}.(1-B) \tag{5}$$

for the red and infrared bands, respectively.

For estimation of LAI the difference r′ between the composite reflectance r and the soil component of the scene could be used. This difference (corrected reflectance) is (according te equation 1) defined as:

$$r' = r - r_s.(1-B) \tag{6}$$

This corrected reflectance is the reflectance one would have obtained with a black background.

In order to obtain the corrected red and infrared reflectances equation (6) has to be applied to the red and infrared band, respectively:

$$r'_r = r_r - r_{s,r}.(1-B) \tag{7}$$

$$r'_{ir} = r_{ir} - r_{s,ir}.(1-B) \tag{8}$$

r'_r = corrected red reflectance
r'_{ir} = corrected infrared reflectance.

As noticed before (see also Clevers, 1986c), the ratio of soil reflectance in an infrared and red band may be constant for a given soil background and independent of the soil moisture content:

$$r_{s,ir}/r_{s,r} = C \tag{9}$$

Combination of equations (7), (8) and (9) gives:

$$r'_{ir} - C.r'_r = r_{ir} - C.r_r \tag{10}$$

The corrected infrared reflectance in equation (8) will be much larger than the corrected red reflectance in equation (7), so a good approximation will be:

$$r'_{ir} = r_{ir} - C.r_r \tag{11}$$

Finally the LAI is estimated by using this corrected infrared reflectance:

$$LAI = -1/\alpha \;.\; \ln(1 - r'_{ir}/r_{\infty,ir}) \tag{12}$$

Parameters α and $r_{\infty,ir}$ have to be estimated empirically from a training set, but they have a physical nature (Clevers, 1986b). Equation (12) is the inverse of a special case of the Mitscherlich function. The effects of different estimates for α and $r_{\infty,ir}$ are illustrated in figures 2a and 2b, respectively.

The main assumption was that C is a constant, meaning that the ratio of the infrared and red reflectance of the soil is independent of the soil moisture content. The validity of this assumption for many soil types is confirmed by results obtained by e.g. Condit (1970) and Stoner et al.

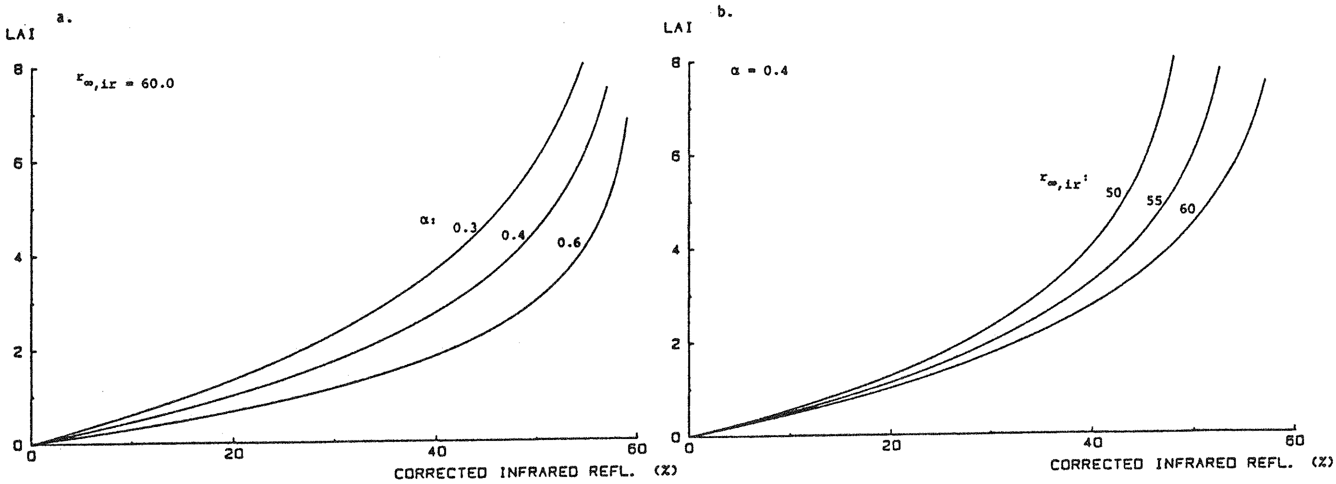

Figure 2: Regression of LAI on corrected infrared reflectance. Effects of different estimates for α (a) and $r_{\infty,ir}$ (b).

(1980). For many soil types, the reflectance in the different spectral bands does not differ very much (e.g. Condit, 1970); often there is only a slight monotonic increase in reflectance with increasing wavelength.

For application of equation (11) in estimating LAI, a weighted difference between the infrared and red reflectance (which is the vegetation index in this paper) must be ascertained and then equation (12) must be used. In this regard $r_{\infty,ir}$ in equation (12) will be the asymptotically limiting value of the weighted difference between infrared and red reflectance at very high LAI. If the soil type under consideration has a similar reflectance in the red and infrared spectral bands (C = 1), equation (11) will result in a simple difference between infrared and red reflectances as a vegetation index:

$$r'_{ir} = r_{ir} - r_r \qquad (13)$$

The above concept is illustrated in figure 3. In this nomograph the infrared reflectance is plotted against the red reflectance as a function of soil moisture content and LAI. We see that the influence of soil

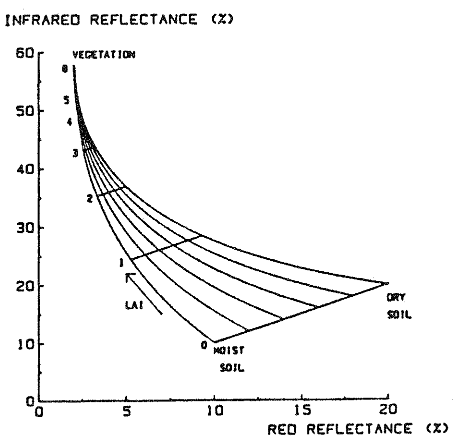

Figure 3: Relation between red and infrared reflectance with constant leaf colour and leaf angle distribution as a function of soil reflectance (or soil moisture content) and LAI.

moisture content on the individual reflectances can be very large at low LAI. From this figure it is also evident that the infrared reflectance is most sensitive to changes in LAI.

2.2 Vegetation index for a generative canopy

The literature reveals little about the changes in reflectance that occur during senescence. Because leaves change colour, the reflectance in the visible bands will increase. This means a return to a situation comparable with an increasing contribution from bare soil. Ahlrichs & Bauer (1983) found that the spectral reflectances for a wheat canopy at the seedling and mature stages were similar. After estimating the reflectance of a yellow vegetation, it may be possible to estimate the relative amount of yellow leaves visible from above by using e.g. equation (4), in which soil reflectance is replaced by the estimated reflectance of yellow vegetation.

During senescence the infrared reflectance will decrease (in a manner comparable with the influence of bare soil). This decrease in the infrared reflectance of a discolouring leaf will be gradual: there will be no abrupt distinction between green or yellow leaves, as must be made when measuring LAI from harvested plants. Because the decrease in photosynthetic activity is also gradual, it is possible for the infrared reflectance to give a better estimate of the actual (photosynthetically active) LAI than field measurements on harvested plants. This is very difficult or nearly impossible to prove because one has to compare the reflectance measurements with the (subjective) field measurements.

If it is assumed that the ratio of reflectance factors of yellow vegetation in the red and infrared spectral bands can be estimated, it should be possible to use equation (11) to correct the infrared reflectance for the background of yellow leaves (the ratio now relates to yellow vegetation instead of to bare soil). When the infrared reflectance of yellow vegetation is at a similar level to that of the red reflectance of yellow vegetation it may be possible to ascertain the corrected infrared reflectance by using an equation analogous to (13). Finally, equation (12) may be used to estimate LAI. However, we now need to ascertain whether the two unknown parameters of this latter equation are the same as when the vegetation is green.

At the end of the season senescence may have advanced so far that the leaves shrivel and finally fall off. Then soil background will again be visible, providing a background with soil and yellow and dead leaves. If the same vegetation index can be applied to the two individual situations (bare soil + green vegetation and yellow leaves + green vegetation), this index may also be suitable in the combined situation because the whole theory is based on addition of the components.

3. FIELD EXPERIMENT

3.1 Field data

The research was carried out at the ir. A.P. Minderhoudhoeve, experimental farm of the Wageningen Agricultural University (the Netherlands). Results of Clevers (1986d) confirm the validity of the assumption that the ratio between the infrared and red reflectance is constant for the soil type investigated. This ratio also tends to the value one, meaning that for this specific soil type equation (13) in stead of equation (11) can be applied.

For investigating the relation between reflectances and LAI results of a field trial in 1982 were used. The trial considered (No. 116) was a split-plot design with three replicates with barley, cultivar "Trumpf". Whole-plot treatments were 2 sowing dates: 26 March (Z1) and 22 April (Z2). Split-plot treatments were 6 randomized nitrogen levels (applied before sowing): 0, 20, 40, 60, 80 and 100 kg/ha nitrogen (N1 to N6). Each subplot was 6 m by 18 m and the row width was 13 cm.

3.2 Method of gathering data

LAI was ascertained by harvesting all the plants within a row section of 1.0 metre length (0.13 m^2). After ascertaining fresh weight of the whole sample, a subsample was separated into green and yellow leaf blades, stems and ears. Each component was weighed and the area of the green leaf blades was measured with an optically scanning area meter. These measurements were converted to give LAI values. LAI was measured on three harvest dates during the vegetative stage of the barley crop.

Reflectances presented in section 4 of this paper were obtained by means of multispectral aerial photography (MSP). Calibrated reflectance factors were obtained by atmospheric correction and radiometric calibration of the digitized photographs on 5 dates during the vegetative stage. This technique has been described extensively by Clevers (1986a, 1986b).

4. RESULTS AND DISCUSSION

The general pattern of red and infrared reflectances for the barley crop are plotted as a function of days after sowing in figure 4. The reflectance in the red decreased with increasing growth during the beginning of the growing season. At complete soil cover the reflectance in the red remained fairly constant. At the end of the season this reflectance increased due to senescence of the crop. In general, the pattern in the infrared band was opposite to that in the red band.

4.1 Vegetative stage

Let us first consider the vegetative canopy only. The vegetative stage of cereals ends after the appearance of the last leaf; at this point the

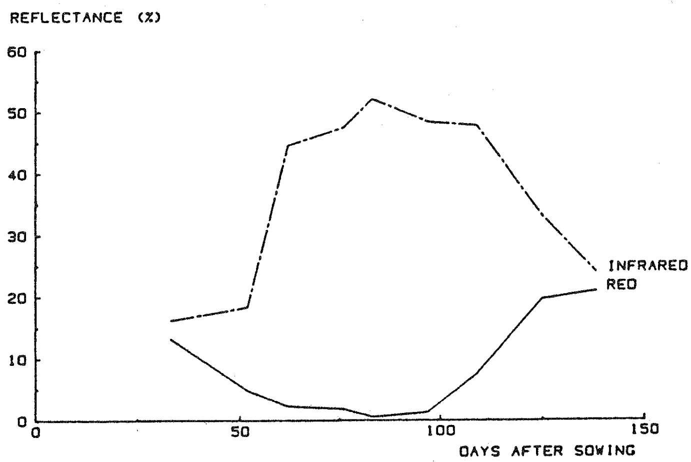

Figure 4: Seasonal change in the red and infrared reflectances for the barley crop at the early sowing date (averaged over all nitrogen levels).

ear is about to appear and senescence will soon begin. This moment also coincides with maximum LAI.

Since the ratio of infrared reflectance to red reflectance of the soil at the experimental farm did not differ greatly from the value 1.0, equation (13) may give a good approximation of the corrected infrared reflectance. The reflectance of bare soil and of vegetation in the different spectral bands are not needed explicitly. The regression of LAI on this corrected infrared reflectance is illustrated in figure 5. The estimates of the two parameters in equation (12) were: $\hat{\alpha} = 0.252$ and $\hat{r}_{\infty,ir} = 68.57$. The coefficient of variation (CV) was 0.214. This variability was at the same level as the variability within the LAI measurements ascertained in the field. So, the validity and applicability of the concept described in section 2.1 was confirmed by these results. An important conclusion derived from the regression of LAI on corrected infrared reflectance for the vegetative stage of barley was that measurements of all dates may be combined, resulting in one curve. Similar results were found for other cereals and in other seasons (Clevers, 1986b).

4.2 Generative stage

Senescence at the end of the season caused an increase of the red reflectance and a decrease of the infrared reflectance (figure 4) for the field trial investigated. Red reflectance increased at the end of the season to a level that was higher than that of bare soil at the beginning of the season (about 20% at the end of the season). Infrared reflectance decreased at the end of the season to a value similar to the red reflectance, and was also higher than the infrared reflectance of bare soil. Results obtained by Ahlrichs & Bauer (1983) illustrate that the red and infrared reflectances of a wheat crop at maturity are very similar to those of bare soil.

In estimating LAI the measured infrared reflectance should be corrected for the background of yellow and dead leaves. For the situation with only bare soil and green vegetation, the difference between infrared and red reflectance (equation 13) appeared to be a good approximation for this corrected infrared reflectance. This presumably occurred because the reflectance of bare soil in the red band did not differ greatly from that in the infrared. Because both reflectances also appeared to be nearly equal at the end of the season, the same equation may be used for correcting the infrared reflectance in this period. Then this equation would also be valid

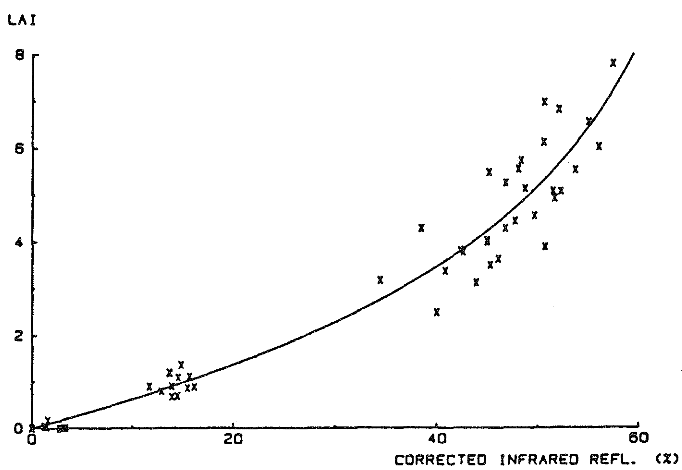

Figure 5: Regression of LAI on corrected infrared reflectance at the vegetative stage of the barley crop.

in the situation of some bare soil being visible within the canopy at the end of the season. Equation (12) was again used for estimating the LAI from the corrected infrared reflectance. Because the crop structure at the generative stage will be different from that at the vegetative stage (at the generative stage ears will be present at the top of the canopy, while bare soil background will be replaced by yellow and dead leaves), the estimates of the two parameters will be different.

For the generative stage the regression of LAI on corrected infrared reflectance (by using equation 13) is illustrated in figure 6 for the field trial investigated. The two parameters in equation 12 were estimated as: $\hat{\alpha} = 0.530$ and $\hat{r}_{\infty,ir} = 57.89$. The coefficient of variation was 0.217, which is similar to the CV for the vegetative stage. As expected, the estimates of the parameters differed from those at the vegetative stage. This means that the vegetative and generative stage cannot be combined, but have to be treated separately. A similar difference as between figures 5 and 6 (cf. solid and broken line in figure 6) was also found by e.g. Asrar et al. (1984), Gallo et al. (1985).

4.3 Operational procedure

The following practical procedure has been elaborated by Clevers (1986b):
The regression function of LAI on corrected infrared reflectance is established by analysing a training set, in which both LAI and reflectances are ascertained. The inverse of a special case of the Mitscherlich function is used for describing the regression function of LAI on the infrared reflectance corrected for background. Subsequently, this regression function is applied for estimating LAI in an entire field trial, field or region with the same crop and soil type. In this way a database can be built of spectral soil information (ratios of soil reflectances) and of spectral crop information (α and $r_{\infty,ir}$ in equation 12). In future, such a database may be consulted in stead of analysing a training set.

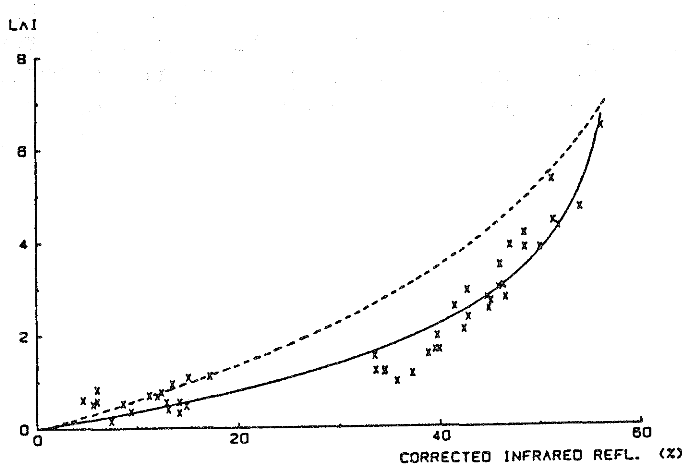

Figure 6: Regression of LAI on corrected infrared reflectance at the generative stage of the barley crop (the broken line represents the fitted curve of figure 5).

5. CONCLUSIONS

1. If the ratio between the reflectance factors of bare soil in the red and infrared spectral bands is constant, the corrected infrared reflectance may be ascertained as a weighted difference between the measured infrared and red reflectance.
2. At the vegetative stage of barley, the inverse of a special case of the Mitscherlich function, namely the one running through the origin, was suitable for describing the regression of LAI on the corrected infrared reflectance, as described in conclusion 1.
3. A similar approach as in conclusion 2 was applied at the generative stage of barley, by correcting the infrared reflectance for the background of yellow and dead leaves in ascertaining the difference between infrared and red reflectances.

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