ISPRS Journal of Photogrammetry and Remote Sensing, 46 (1991) 37–47
Elsevier Science Publishers B.V., Amsterdam

Application of the WDVI in estimating LAI at the generative stage of barley

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(Received 3 March 1989; revised and accepted 16 February 1990)

ABSTRACT

Clevers, J.G.P.W., 1991. Application of the WDVI in estimating LAI at the generative stage of barley. *ISPRS J. Photogramm. Remote Sensing*, 46: 37–47.

The weighted (near-infrared–red) difference vegetation index (WDVI) can be used for estimating leaf area index (LAI) of green vegetation. This WDVI offers a good correction for soil background in estimating the LAI of green vegetation, e.g. cereals at the vegetative stage.

In this study, it is 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 is 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

Application of remote sensing techniques has the potential to 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 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. The LAI is also a main driving variable in many crop growth models, designed for yield prediction (Penning de Vries and Laar, 1982). Crop growth models describe the relation between physiological processes in

This is a revised version of a paper presented at the ISPRS Congress Kyoto-Japan.

0924-2716/91/$03.50

plants and environmental factors such as solar radiation, temperature and water and nutrient availability. Estimates of crop growth often are inaccurate for sub-optimal growing conditions. Remote sensing may yield information about the actual status of a crop (e.g., in terms of LAI), resulting in an improvement of crop growth modelling.

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 or 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.

Recently, Clevers (1988a, 1989) 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. For estimating LAI a "corrected" (adjusted) 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 a weighted difference between the measured infrared and red reflectance (called WDVI = weighted difference vegetation index), assuming that the ratio between infrared and red reflectances of bare soil is constant, independent of soil moisture content (which assumption is valid for many soil types). Subsequently this WDVI 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.

The starting point of this study was the simplified reflectance model for the estimation of LAI, introduced by Clevers (1988a, 1989) for a vegetative canopy, using calibrated reflectance factors. In this paper, a similar approach is described for the generative stage of cereals. It is tested with real field data.

2 SIMPLIFIED REFLECTANCE MODEL FOR ESTIMATING LAI

2.1 *Vegetative canopy*

The simplified reflectance model derived by Clevers (1988a, 1989) consists of 2 steps. Firstly, the WDVI is calculated as:

$$\text{WDVI} = r_{ir} - Cr_r \quad (1)$$

with r_{ir} = total measured near-infrared reflectance
r_r = total measured red reflectance
and

$$C = r_{s,ir}/r_{s,r} \quad (2)$$

with $r_{s,ir}$ = near-infrared reflectance of the soil
$r_{s,r}$ = red reflectance of the soil.

Secondly, the relation between WDVI and LAI is given by:

$$\text{LAI} = -(1/\alpha)\ln(1 - \text{WDVI}/r_{\infty,ir}) \quad (3)$$

The combination of Eqs. (1) and (3) is called the semi-empirical reflectance model. Parameters α and $r_{\infty,ir}$ have to be estimated empirically from a training set, but they have a physical nature (Clevers, 1988a). Equation (3) is the inverse of a special case of the Mitscherlich function (Mitscherlich, 1923). The effects of different estimates for α and $r_{\infty,ir}$ are illustrated in Figures 1a and 1b, 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. (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 Eq. (1) 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 Eq. (3) must be used. In this regard $r_{\infty,ir}$ in Eq. (3) will be the asymptotically limiting value of the weighted difference between infrared and red reflectance at very high LAI. If the soil type under con-

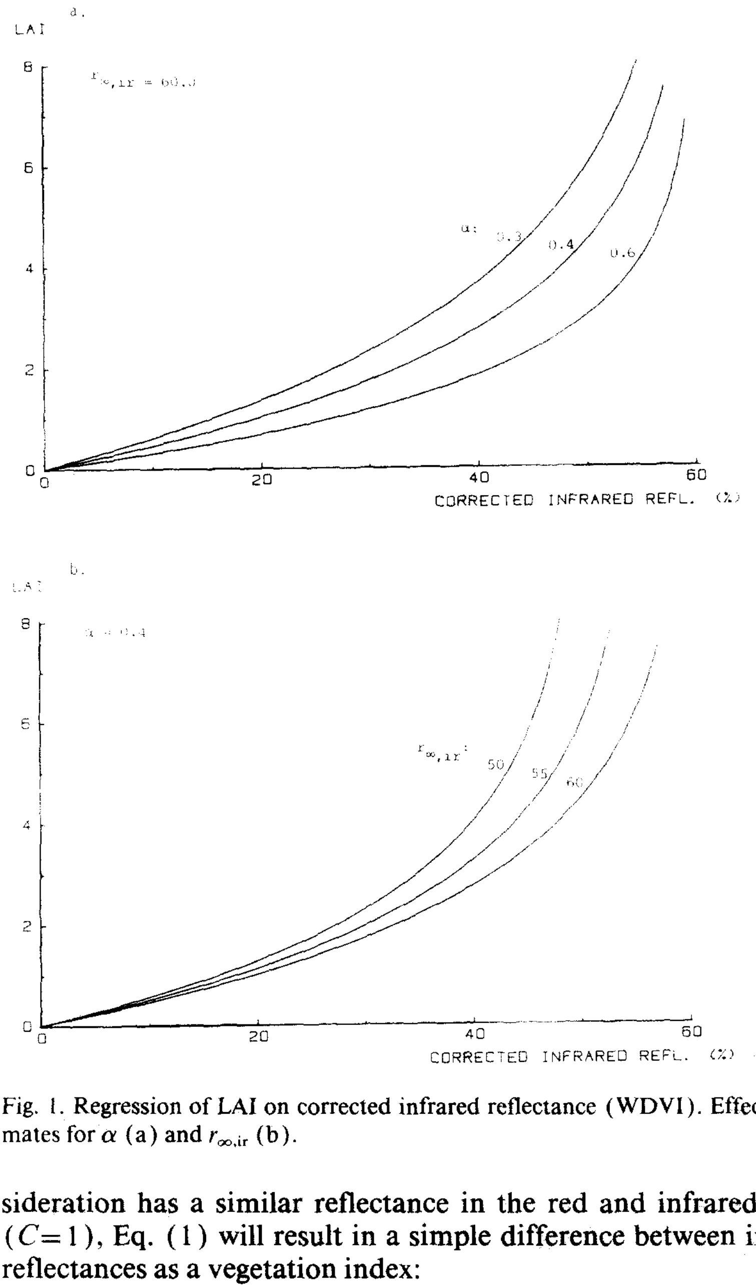

Fig. 1. Regression of LAI on corrected infrared reflectance (WDVI). Effects of different estimates for α (a) and $r_{\infty,\mathrm{ir}}$ (b).

sideration has a similar reflectance in the red and infrared spectral bands ($C=1$), Eq. (1) will result in a simple difference between infrared and red reflectances as a vegetation index:

$$\mathrm{WDVI} = r_{\mathrm{ir}} - r_{\mathrm{r}} \tag{4}$$

The above concept is illustrated in Figure 2. In this nomograph the infrared reflectance is plotted against the red reflectance as a function of soil moisture

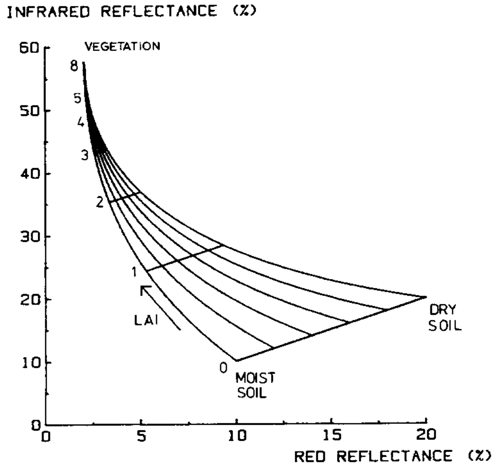

Fig. 2. Relation between red and infrared reflectance with constant leaf colour and leaf angle distribution as a function of soil reflectance (or soil moisture content) and LAI.

content and LAI. We see that the influence of soil 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 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 and Bauer (1983) found that the spectral reflectances for a wheat canopy at the seedling and mature stages were similar.

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 Eq. (1) to correct the infrared reflectance for the background of yellow leaves (the ratio in Eq. (2) 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 equation (4). Finally, Eq. (3) 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 (1989) 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 Eq. (4) instead of Eq. (1) 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 3 harvest dates during the vegetative stage and on 3 harvest dates during the generative 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 and on 4 dates during the generative stage. This technique has been described extensively by Clevers (1986, 1988b).

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 3. 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 ear is about

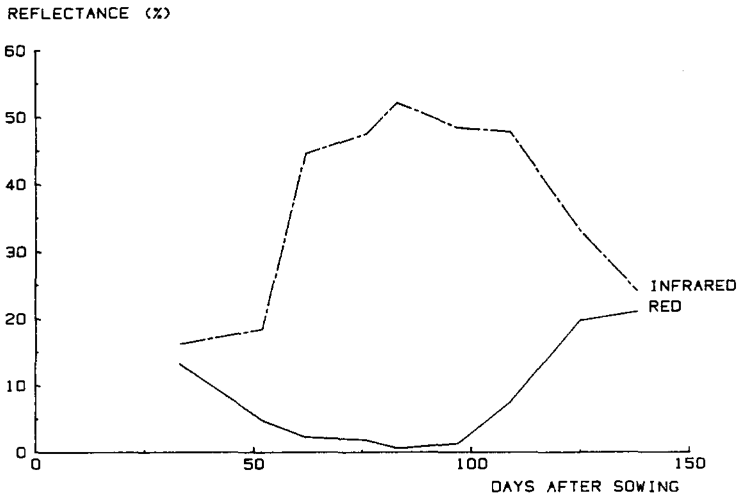

Fig. 3. Seasonal change in the red and infrared reflectances for the barley crop at the early sowing date (averaged over all nitrogen levels).

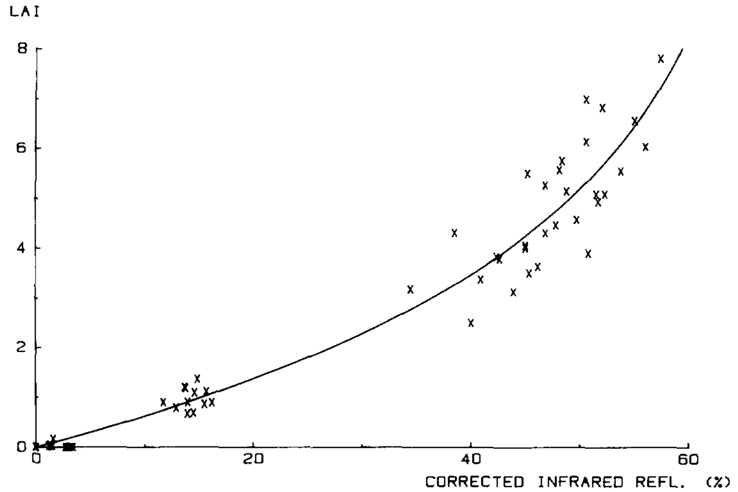

Fig. 4. Regression of LAI on corrected infrared reflectance (WDVI) at the vegetative stage of the barley crop.

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, Eq. (4) 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 4. The estimates of the two parameters in Eq. (3) were: $\alpha=0.252$ and $r_{\infty,\mathrm{ir}}=68.57$. The coefficient of variation (CV) was 0.214. This variability was at the same level as the error 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 (WDVI) 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, 1986).

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 (Fig. 3) 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 and 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 (Eq. 4) 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 in the situation of some bare soil being visible within the canopy at the end of the season. Equation (3) 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 Eq. 4) is illustrated in Figure 5 for the field trial investigated. The two parameters in Eq. (3) were estimated as: $\alpha = 0.530$ and $r_{\infty,\mathrm{ir}} = 57.89$. 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

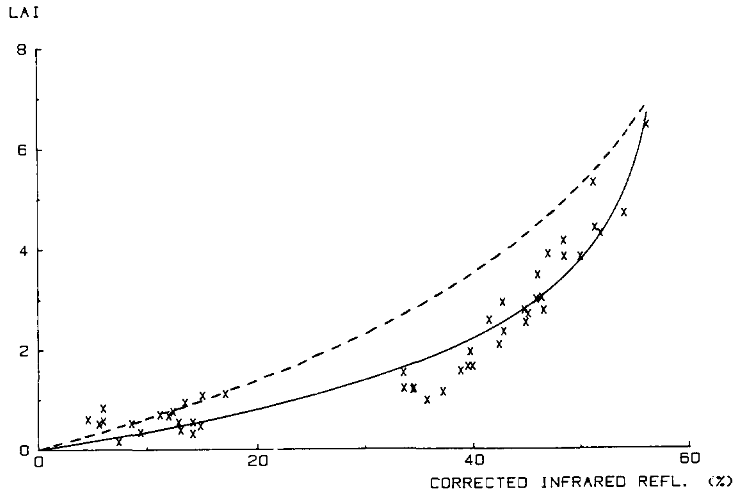

Fig. 5. Regression of LAI on corrected infrared reflectance (WDVI) at the generative stage of the barley crop (the broken line represents the fitted curve of Fig. 4).

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 4 and 5 (cf. solid and broken line in Fig. 5) was also found by e.g. Asrar et al. (1984), Gallo et al. (1985).

4.3 Operation procedure

The following practical procedure has been elaborated by Clevers (1986): The regression function of LAI on corrected infrared reflectance (WDVI) 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 $r_{\infty,\mathrm{ir}}$ in Eq. 3). In future, such a database may be consulted in stead of analysing a training set.

5 CONCLUSIONS

(1) If the ratio between the reflectance factors of yellow vegetation in the red and infrared spectral bands is constant, the WDVI may be used to correct the infrared reflectance for the background of yellow and dead leaves at the generative stage of barley.

(2) At the generative 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 WDVI, as described in conclusion 1.

(3) A similar approach may be valid for cereals in general.

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