ESTIMATING APAR BY MEANS OF VEGETATION INDICES: A SENSITIVITY ANALYSIS

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ABSTRACT

The last decennia, the leaf area index (LAI) has been a very important crop characteristic used in studies concerning growth, modelling and yield forecasting of agricultural crops. At the moment, interest is shifting towards the fraction of absorbed photosynthetically active radiation (APAR), which is a key parameter in the photosynthetic process of the plant. In this study, a sensitivity analysis was performed for both crop parameters and external factors, using the SAIL canopy reflectance model and the PROSPECT leaf reflectance model, for studying the possibilities of using vegetation indices (VI) for estimating APAR.

Results from this theoretical study show that a linear relationship may be assumed between WDVI (Weighted Difference VI) or NDVI (Normalized Difference VI) and APAR as an approximation. External factors (soil background, ratio diffuse/total irradiation, solar zenith angle) do not have a large influence on the relationship between APAR and the WDVI (which is related to greenness and perpendicular VI). Moreover, leaf parameters (such as leaf chlorophyll content, leaf mesophyll structure and hot spot size-parameter) also have quite a small influence for green leaves, as concluded from simulations with the combined PROSPECT-SAIL model. The main crop parameter influencing the relationship between WDVI and APAR is the leaf angle distribution (LAD). So, for differing LADs differing regression functions must be used. Although the relationship between APAR and NDVI is slightly less influenced by LAD and solar angle, important disturbing factors are the soil background and the leaf chlorophyll content.

KEY WORDS: APAR estimation, WDVI, NDVI, reflectance models, sensitivity analysis

1. INTRODUCTION

Remote sensing techniques have the potential to provide information about agricultural crops quantitatively, instantaneously and, above all, non-destructively. In the past decades, knowledge about optical remote sensing techniques and their application to fields such as agriculture has improved considerably (cf. Asrar, 1989; Steven & Clark, 1990). The possibilities of applying remote sensing in agriculture have been demonstrated, e.g. with regard to the estimation of crop characteristics such as soil cover and leaf area index (LAI).

Much recent research has been aimed at determining combinations of reflectances (vegetation indices, VI) in order to correct for the effect of disturbing factors (particularly soil background) on the relationship between crop reflectance and crop characteristics, such as the LAI. Huete (1989) has reviewed the main VIs. He made a distinction between ratio-based VIs, utilizing red and NIR canopy reflectances or radiances, and linear combinations (of the response in several spectral bands). Of the ratio-based VI the Normalized Difference VI (NDVI = (NIR-red)/(NIR+red)) is the most common one. Clevers (1986) showed that the NDVI did not satisfy for estimating LAI under western European agricultural conditions (with high LAI values). Therefore, Clevers (1988, 1989) has described a simplified, semi-empirical, reflectance model for estimating LAI of a green canopy (CLAIR model). In this approach, he applied the so-called "Weighted Difference VI" (WDVI, see section 2.1). Clevers showed that this index is comparable with the greenness index of Kauth & Thomas (1976) for the two-dimensional case and with the perpendicular VI of Richardson & Wiegand (1977). The latter VIs are so-called orthogonal-based indices (Huete, 1989).

In the current study attention was focused at the estimation of the absorbed photosynthetically active radiation (APAR). The APAR is particularly interesting from an agronomical point of view. This applies particularly to the possible combination of remote sensing with crop growth models. Incoming photosynthetically active radiation (PAR) is partly reflected by the top layer of the canopy. The complementary fraction is potentially available for absorption by the canopy. The product of the amount of incoming photosynthetically active radiation (PAR) and the absorptance yields the amount of absorbed photosynthetically active radiation (APAR). The rate of CO_2 assimilation (photosynthesis) is calculated from the APAR and the photosynthesis-light response of individual leaves. The assimilated CO_2 is then reduced to carbohydrates which can be used for crop growth.

Estimating APAR requires both incident PAR and the fraction of PAR absorbed by the vegetation. The latter can be estimated from a remote sensing platform. The present study was focused at the estimation of the fraction APAR (canopy absorptance) by some vegetation index. Emphasis was on the WDVI and the NDVI. A theoretical sensitivity analysis has been performed by studying the relationship between WDVI (and NDVI) and the fraction APAR, which might be influenced by parameters incorporated in canopy and leaf reflectance models. Such parameters may be other varying canopy characteristics or external factors. The final objective of this research was to be able to give findings about which variables have a clear impact on the estimation of APAR from a remote sensing platform and what the accuracy should be with which such variables have to be ascertained.

2. MATERIALS AND METHOD

2.1 Simplified Reflectance Model for Estimating LAI

Clevers (1988, 1989) has described a simplified, semi-empirical, reflectance model for estimating LAI of a green canopy. In this model it is assumed that the soil type is given and soil moisture content is the only varying property of the soil during the growing season.

For estimating LAI a so-called Weighted Difference VI (WDVI) is ascertained as a weighted difference between the measured NIR and red reflectances, assuming that the ratio between NIR and red reflectances of bare soil is constant, independent of soil moisture content (which assumption is valid for many soil types).

The simplified reflectance model derived by Clevers consists out of two steps. First, the WDVI is calculated as:

$$WDVI = r_{ir} - C \cdot r_r \tag{1}$$

with r_{ir} = total measured NIR reflectance
r_r = total measured red reflectance

$$\text{and } C = r_{s,ir}/r_{s,r} \tag{2}$$

$r_{s,ir}$ = NIR reflectance of the soil
$r_{s,r}$ = red reflectance of the soil.

Secondly, the relationship between WDVI and LAI is modelled as:

$$LAI = -1/\alpha \cdot \ln(1 - WDVI/WDVI_\infty) \tag{3}$$

with α as a function of extinction and scattering coefficients and $WDVI_\infty$ as the asymptotically limiting value for the WDVI. They have to be estimated empirically from a training set (Clevers, 1988).

Within the above approach emphasis was on estimating LAI. As described in the introduction we are now focusing at estimating the fraction APAR. The relationship between LAI and fraction APAR has been described by e.g. Guyot & Baret (1991) (cf. also Asrar et al., 1984; Sellers, 1985):

$$LAI = -1/K_{par} \cdot \ln(1 - APAR/APAR_\infty) \tag{4}$$

with K_{par} as the extinction coefficient for photosynthetically active radiation (PAR: 400-700 nm), which depends on canopy geometry and irradiance conditions, and $APAR_\infty$ as the asymptotically limiting value for APAR ($\approx$ 0.94 according to Guyot & Baret).

We may note a clear analogy between Eqs. (3) and (4). However, α is particularly related to the NIR region where scattering is the dominating process (measured in terms of WDVI) and K_{par} is related to the visible region where absorption dominates (measured in terms of APAR). Although α and K_{par} are related to different spectral regions, they will be influenced by parameters such as leaf angle distribution (LAD) or solar angle in a similar way. If we could assume α and K_{par} to be equal as an approximation, we would obtain a linear relationship between WDVI and APAR:

$$APAR = WDVI * APAR_\infty/WDVI_\infty \tag{5}$$

Finally, the fraction APAR can be related to the total photosynthetic activity of a canopy by integrating the APAR over time. This is what is done in crop growth models. Input in these models often are estimates for parameters such as the canopy scattering coefficient for visible light, the extinction coefficient for PAR, the LAD and the total daily irradiation. The daily APAR may also be calculated by directly multiplying the fraction APAR and the daily PAR irradiation. Since it was found in literature that the NDVI may also be suitable for estimating APAR (e.g. Asrar et al., 1984, found a linear relationship between the NDVI and APAR), a comparison between WDVI and NDVI performance was made with respect to APAR estimation.

2.2 SAIL Model

The one-layer SAIL model (Verhoef, 1984) simulates canopy reflectance as a function of canopy variables (leaf reflectance and transmittance, LAI and LAD), soil reflectance, ratio diffuse/direct irradiation and solar/view geometry (solar zenith angle, zenith view angle and sun-view azimuth angle). Recently, the SAIL model has been extended with the hot spot effect (Looyen et al., 1991). LAD functions used with the SAIL model are given by Verhoef & Bunnik (1981) and Bunnik (1978).

The SAIL canopy reflectance model may also be used for simulating the fraction APAR instead of the canopy reflectance. The total canopy absorptance may be calculated as one (or 100%) minus the hemispherical canopy reflectance (what is lost above the canopy) and the soil absorptance (what is lost underneath the canopy). The calculations for the one-layer SAIL version will be explained using the terminology and formulae of Verhoef (1985).

APAR can be defined from the sum of the net fluxes incident on the canopy at the top and the bottom of the layer. With the following flux types:

$E_s(t)$, $E_s(b)$ = direct solar fluxes at top and bottom,
$E_-(t)$, $E_-(b)$ = diffuse downward fluxes at top and bottom,
$E_+(t)$, $E_+(b)$ = diffuse upward fluxes at top and bottom,

the flux absorbed by the canopy layer is given by:

$$A = [E_s(t)+E_-(t)-E_+(t)] + [E_+(b)-E_s(b)-E_-(b)] \ . \tag{6}$$

For a Lambertian soil with reflectance r_s

$$E_+(b) = r_s.[E_s(b)+E_-(b)] \ . \tag{7}$$

The interactions with the canopy layer can be described by

$$E_s(b) = \tau_{ss}E_s(t) \ , \tag{8}$$
$$E_-(b) = \tau_{sd}E_s(t) + \tau_{dd}E_-(t) + \rho_{dd}E_+(b) \ , \tag{9}$$
$$E_+(t) = \rho_{sd}E_s(t) + \rho_{dd}E_-(t) + \tau_{dd}E_+(b) \ . \tag{10}$$

Here the ρ and τ parameters are reflectances and transmittances for the canopy layer. The first subscripts refer to the type of incident flux, i.e. s for solar flux and d for diffuse (upward or downward) flux, and the second subscript refers to the type of reflected or transmitted flux. Among others, these ρ and τ parameters are given as output quantities of the SAIL model.

Eqs. (7), (8) and (9) can be used to solve for the total downward flux at the bottom of the canopy. This yields:

$$E_s(b) + E_-(b) = [(\tau_{ss}+\tau_{sd})E_s(t) + \tau_{dd}E_-(t)]/(1-\rho_{dd}r_s) \ .$$

Then, application of (7) in Eq. (10) gives

$$E_+(t) = \rho_{sd}E_s(t) + \rho_{dd}E_-(t) + \tau_{dd}r_s[(\tau_{ss}+\tau_{sd})E_s(t)+\tau_{dd}E_-(t)]/(1-\rho_{dd}r_s) \ .$$

Now, A may be rewritten as

$$A = E_s(t) + E_-(t) - \rho_{sd}E_s(t) - \rho_{dd}E_-(t) + (-\tau_{dd}r_s+r_s-1)[(\tau_{ss}+\tau_{sd})E_s(t)+\tau_{dd}E_-(t)]/(1-\rho_{dd}r_s) \ . \tag{11}$$

This result can be split up in contributions due to direct solar flux and due to diffuse downward flux as follows. With

$$A_s = 1-\rho_{sd}-(1-r_s+\tau_{dd}r_s)(\tau_{ss}+\tau_{sd})/(1-\rho_{dd}r_s) \ , \text{ and} \tag{12}$$

$$A_d = 1-\rho_{dd}-(1-r_s+\tau_{dd}r_s)\tau_{dd}/(1-\rho_{dd}r_s) \ , \tag{13}$$

Eq. (11) can be written as

$$A = A_s.E_s(t) + A_d.E_-(t) \ . \tag{14}$$

Finally, the fraction APAR may be calculated as (using leaf properties for the PAR spectral region):

$$APAR = [A_s.E_s(t) + A_d.E_-(t)] \ / \ [E_s(t) + E_-(t)] \ . \qquad (15)$$

This equation has been implemented into the SAIL code.

2.3 PROSPECT Model

The PROSPECT model, as developed by Jacquemoud & Baret (1990), is a radiative transfer model for individual leaves. It is based on the generalized "plate model" of Allen et al. (1969, 1970), which considers a compact theoretical plant leaf as a transparent plate with rough plane parallel surfaces. An actual leaf is assumed to be composed of a pile of N homogeneous compact layers separated by $N-1$ air spaces. The thickness of the air spaces that separate the layers was taken as infinitesimal. The compact leaf ($N = 1$) has no intercellular air spaces or the intercellular air spaces of the mesophyll have been infiltrated with water. The discrete approach can be extended to a continuous one where N need not be an integer. N ranging between 1.0 and 1.5 corresponds to monocotyledonous plant species with a compact mesophyll structure. Dicotyledonous species, characterized by a sponge parenchyma with many air cavities, have N values between 1.5 and 2.5. N values greater than 2.5 represent senescent leaves with a disorganized internal structure. PROSPECT allows to compute the 400-2500 nm reflectance and transmittance spectra of very different leaves using only three input variables: leaf mesophyll structure parameter N, chlorophyll content and water content. All three are independent of the selected wavelength.

Since the output of the PROSPECT model equals part of the input for the SAIL model, a combined PROSPECT-SAIL model was made. This combined model may simulate the spectral bidirectional reflectance and the fraction APAR of a canopy as a function of the leaf properties used as input for the PROSPECT model and as a function of canopy parameters and external factors used as input for the SAIL model.

2.4 Procedure Sensitivity Analysis

To investigate the sensitivity of the relationship between VI and APAR to parameters incorporated in reflectance models, two methods could be applied:
Method 1:
Here we assume the model parameters known and we simulate forward towards simulated VI and simulated APAR with the combined PROSPECT-SAIL model. Then this VI can be indirectly compared with this simulated APAR by using some (semi-)empirical relationship between VI and estimated APAR. The difference between simulated and estimated APAR yields a measure for the error in APAR estimation.
Method 2:
An alternative, but more elaborate way is that we assume that only measurements (canopy reflectances or VIs) are available. By using inversion techniques, a set of model parameter combinations could be generated matching the measurements (usually the inversion process does not lead to one unique parameter combination!) using the combined PROSPECT-SAIL model. Due to model linearization and optimization (local or global extrema) in the n-dimensional parameter space, the inversion process will yield an error. Subsequently, the APAR can be predicted with the combined PROSPECT-SAIL model. This will not result into one unique APAR as in method 1. Estimating APAR from the measurements using the empirical relationship as in method 1 and then compare it with the APAR obtained from the inversion, leads to a sensitivity measure for APAR.

Method 2 is a more independent and systematic way of studying the sensitivity of APAR estimation. No uniqueness in parameter combinations also indicates the possible existence of different relationships between VI and APAR. However, since the objective of the present study was to elaborate which parameters do influence this relationship and to what extent, and since the inversion process is a computational tedious procedure, method 1 was applied in this study.

Starting point for the model simulations was some sort of "standard crop" measured under "standard irradiation and viewing conditions" (table 1). Subsequently, the effect of changing one input parameter at a time is studied.

Table 1: Definition of a standard crop under standard conditions.

chlorophyll content	34.24 $\mu g.cm^{-2}$ leaf area†
N parameter	1.8320†
water content	0.0137 cm†
LAD	spherical
size-parameter	0
soil reflectance	20% (red and NIR)
ratio diffuse/direct irr.	0
solar zenith angle	45°
viewing angle	0°

†Example of a dicotyledonous plant as given by Jacquemoud & Baret (1990).

The influence of plant water content (equivalent water thickness) needed not to be studied, because it has no influence on NIR and red reflectance (and thus on WDVI and NDVI) as defined by the PROSPECT model.

From an agronomical point of view a determination of the percentage APAR with an accuracy within 10% in absolute units is assumed acceptable (or 0.1 as a fraction). The sensitivity study should result into statements concerning the accuracy with which the input parameters studied must be known in order to reach the accuracy of 10% APAR. It is realized that inaccuracies in a number of input parameters may add up to a large inaccuracy of APAR estimation, but the ultimate goal is to define which parameters are important as disturbing factors and in what range of values (both of the input parameter as well as of the estimated APAR). Then further research activities should focus on these factors. LAI itself is not regarded as a disturbing factor on the relationship between VI and APAR. The latter two are both a function of LAI (see section 2, Eqs. (3) and (4)) and both will be simulated as a function of LAI.

Figs. 1 and 2 suggest a linear relationship between VI and APAR for a given LAD (cf. also the considerations at the end of section 2.1 and Asrar, 1989). The results of the sensitivity analysis in section 3 confirm this linearity. In the rest of this paper a linear relationship between VI and APAR will be assumed as an approximation.

The sensitivity analysis is performed in the following way:

1) Assume a known linear relationship between VI and APAR that runs through the origin (for a given LAD):

$$APAR = a * VI \qquad (16)$$

with a known. This linear relationship should be determined for the standard crop.

2) Vary one input parameter by some value (e.g. a maximal deviation from the value used for the standard crop).
3) For the resulting crop under the resulting circumstances the VI is simulated for a given LAI and the APAR is estimated by applying Eq. (16).

This estimated APAR is assumed to be in the range 0% - 100%.

4) For the resulting crop under the resulting circumstances the APAR is also simulated for the same LAI as used under step 3. This yields the real APAR.

5) By taking the absolute difference of the result of 3) and 4), an estimation of the absolute accuracy of APAR estimation (dAPAR) is obtained if one of the input parameters deviates from the standard crop.

Subsequently, this is repeated for LAI values in the range between 0 and 8, in order to see whether the influence of a deviation in some input parameter varies with the LAI value (or better with the APAR).

For ascertaining the WDVI and the NDVI by means of the combined PROSPECT-SAIL model, the red reflectance was simulated at 670 nm and the NIR reflectance at 870 nm. APAR was simulated by simulating the average leaf reflectances and transmittances for the 400-700 nm region using PROSPECT and subsequently using these as input into SAIL. This yielded an enormous reduction in computing time.

3. RESULTS AND DISCUSSION

The combined PROSPECT-SAIL model was used for this sensitivity analysis. Since no significant interactions between the various variables were found in affecting the relationship between VI and APAR, each variable will be discussed separately. A more extensive presentation is given by Clevers et al. (1992).

3.1 Influence of Soil Background

The influence of soil reflectance on the relationship between WDVI and APAR is illustrated in Fig. 1 for the standard crop. This figure shows that there existed a small effect of soil background on the APAR for such a large range in soil reflectances. The WDVI concept was developed in order to correct largely for the influence of soil background.

Fig. 2 illustrates the influence of soil background on the relationship between NDVI and APAR. Results are much worse than for the WDVI; so mainly results for the WDVI will be elucidated in detail in this paper.

Assuming a linear relationship between WDVI and APAR running through the origin, the standard crop (with a soil reflectance of 20% and a spherical LAD) yielded a regression coefficient of 2.39 (R^2 = 0.97) for the data in Fig. 1 (using LAI values up to 4.0; the latter yielding nearly maximal APAR values). One also obtained

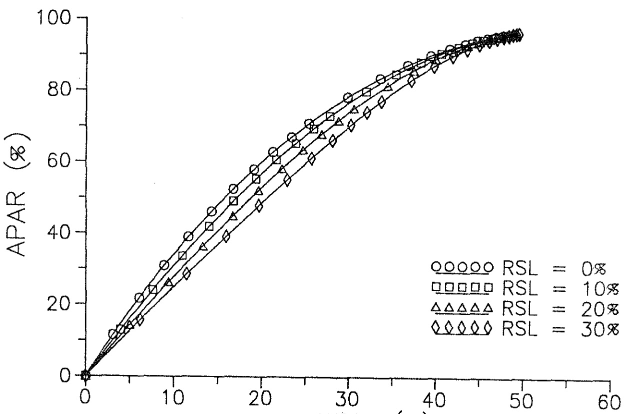

Figure 1: Influence of soil reflectance (RSL) on the relationship between WDVI and APAR for the standard crop.

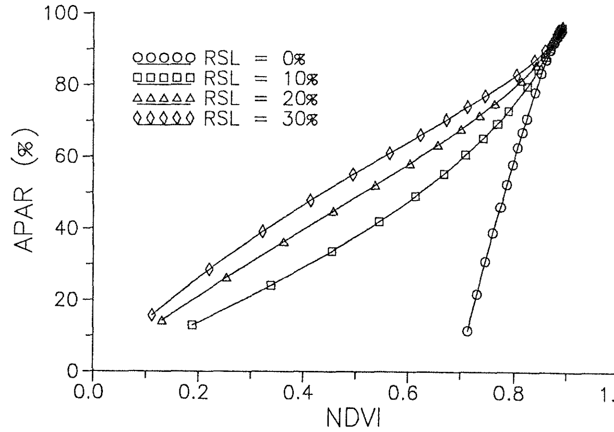

Figure 2: Influence of soil reflectance (RSL) on the relationship between NDVI and APAR for the standard crop.

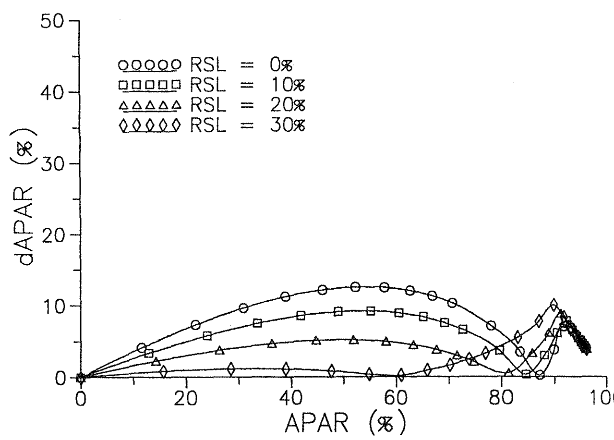

Figure 3: Absolute errors in APAR estimation by means of the WDVI, caused by deviations from Eq. (17) due to soil reflectance (RSL) variations for the standard crop.

this regression coefficient by incorporating all four soil curves of Fig. 1 into the linear regression analysis (R^2=0.94). So:

$$APAR(\%) = 2.39 * WDVI \text{ (spherical LAD).} \quad (17)$$

By also assuming a linear relationship between NDVI and APAR running through the origin, the standard crop (with a soil reflectance of 20% and a spherical LAD) yielded a regression coefficient of 100.0 (R^2 = 0.99) for the data in Fig. 2 (using LAI values up to 4.0). Incorporating more soil curves of Fig. 2 into the regression analysis dramatically increased the deviations.

The sensitivity of the regression of APAR on WDVI for errors in soil reflectance can be quantified by applying the procedure described in section 2.4. The resulting maximal absolute errors in APAR estimation for the standard crop are illustrated in Fig. 3. This figure shows that errors for a soil reflectance of 20% were not zero. This was caused by the fact that the relationship between WDVI and APAR as illustrated in Fig. 1 was not perfectly linear. The errors in Fig. 3 for the 20% curve were caused by this non-linearity. Fig. 3 shows that the curve for 30% soil reflectance followed the regression line of the 20% curve even better (yielding smaller errors). With decreasing soil reflectance errors increased (larger deviations from 20% soil reflectance) up to about 80% APAR. Maximal errors for the 10% curve were just within the maximal allowable deviation of 10% in terms of APAR. The 0%

soil reflectance curve (a theoretical case) yielded errors larger than 10% for APAR values between 35% and 70%. As expected, maximal errors were much larger when using the NDVI, particularly for low soil reflectances (results not shown).

3.2 Influence of Solar Angle

The solar zenith angle affects the simulated APAR and WDVI in a similar way. The influence of solar zenith angle on the relationship between WDVI and APAR is illustrated in Fig. 4. This figure confirms the small influence of solar zenith angle in qualitative terms. Largest errors will occur for large zenith angles.

The maximal absolute errors in APAR estimation for the standard crop caused by an inaccuracy in solar zenith angle are illustrated in Fig. 5. With increasing solar zenith angle errors increased (except for large APAR). Maximal errors for all curves were within the maximal allowable deviation of 10% in terms of APAR, except for the 80 degrees zenith angle curve. When using the NDVI for estimating APAR, a maximal error of 8% APAR was found. So, it performed slightly better than the WDVI.

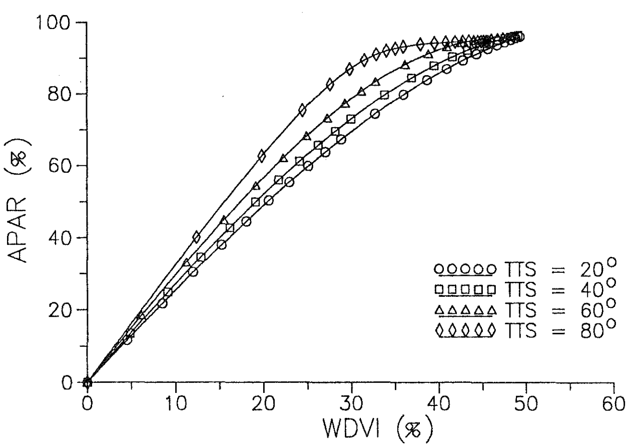

Figure 4: Influence of solar zenith angle (TTS) on the relationship between WDVI and APAR for the standard crop.

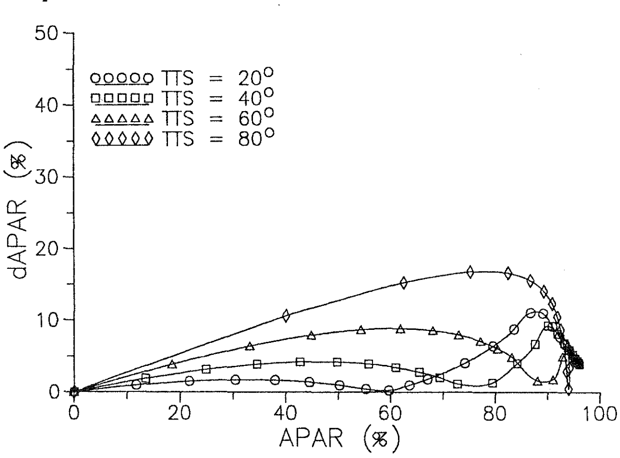

Figure 5: Absolute errors in APAR estimation by means of the WDVI, caused by deviations from Eq. (17) due to solar zenith angle (TTS) variations for the standard crop.

3.3 Influence of Diffuse/Total Irradiation

The influence of the ratio diffuse/total irradiation on the relationship between VI (WDVI or NDVI) and APAR was only minor. Figures are not presented within this paper.

3.4 Influence of Leaf Inclination Angle

In order to simplify the analysis, in this section LADs consisting of one leaf angle were used. The LAD is the main disturbing parameter on the relationship between WDVI and LAI (Clevers & Verhoef, 1990). In particular, significant differences in asymptotic value of the WDVI occurred as a function of LAD. The WDVI was not developed for correcting for differences in leaf inclination angle. Clevers (1989) described a practical procedure for applying the WDVI, whereby a training set is used for establishing the regression function of LAI on WDVI. The influence of LAD on the relationship between WDVI and APAR is illustrated in Fig. 6. As expected, the influence was huge, which is primarily caused by the influence of LAD on WDVI.

The maximal absolute errors in APAR estimation by the WDVI for the standard crop caused by an inaccuracy in LAD are illustrated in Fig. 7. This figure shows that errors in APAR estimation due to errors in LAD may be very large. Errors larger that 10% APAR occurred for a planophile LAD (at 25 degrees between 50% and 90% APAR and at 45 degrees between 80% and 90% APAR). An erectophile LAD (65 degrees) just reached the 10% APAR error around 50-70% APAR.

The influence of LAD on the relationship between NDVI and APAR is illustrated in Fig. 8. The curves in Fig. 8 all run through the origin and at large NDVI values they all run towards nearly 100% APAR. However, a huge influence of LAD occurred at intermediate values. In terms of APAR estimation by means of the NDVI, the results for the standard crop yielded a maximal error that just reached the 10% level (Fig. 9).

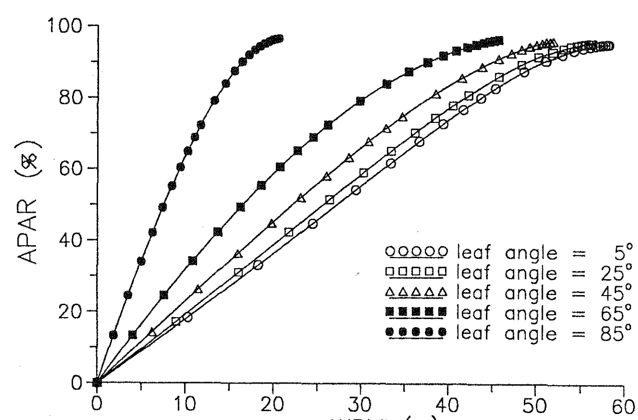

Figure 6: Influence of LAD on the relationship between WDVI and APAR for the standard crop.

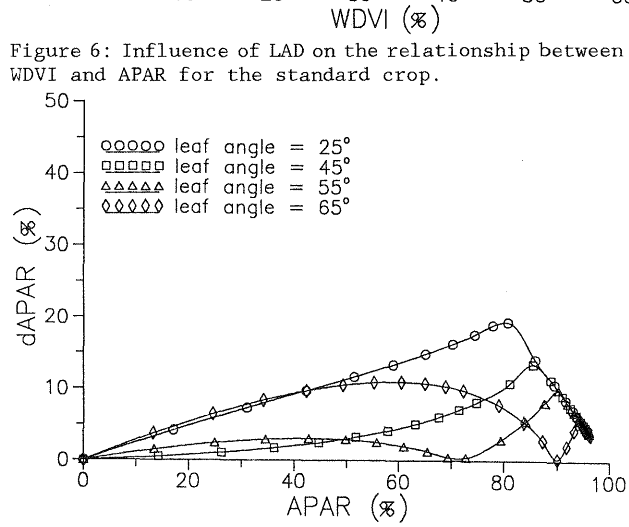

Figure 7: Absolute errors in APAR estimation by means of the WDVI, caused by deviations from Eq. (17) due to variations in the LAD for the standard crop.

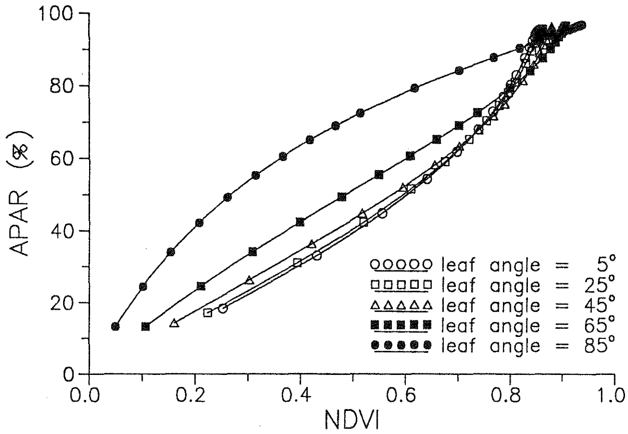

Figure 8: Influence of LAD on the relationship between NDVI and APAR for the standard crop.

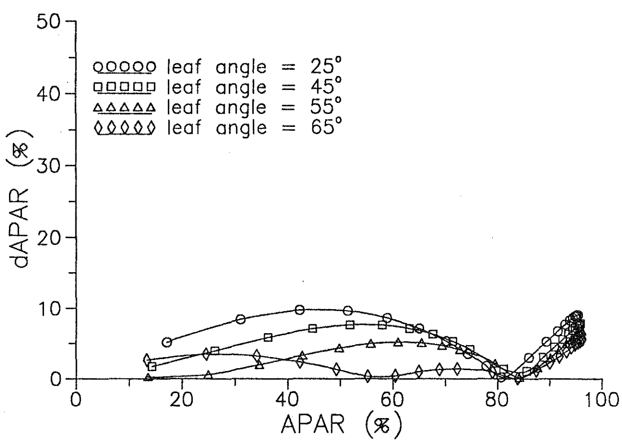

Figure 9: Absolute errors in APAR estimation by means of the NDVI, due to variations in the LAD for the standard crop.

3.5 <u>Influence of Hot Spot Size-parameter</u>

The hot spot size-parameter was introduced into the SAIL model for improving simulations of bidirectional reflectance distributions. It has no meaning for the fraction APAR. However, in Looyen et al. (1991) it was shown from simulations that outside the actual hot spot, the hot spot size-parameter still may have a considerable influence on crop reflectance. A larger size-parameter leads to higher reflectances and a broadening of the zone in which the hot spot effect is significant.

Clevers & Verhoef (1990) have shown that the hot spot size-parameter does have a small effect on the WDVI. Since errors in APAR estimation due to an inaccuracy of the hot spot size-parameter were all small, results are not illustrated in this paper.

3.6 <u>Influence of Chlorophyll Content</u>

The effect of chlorophyll content on APAR was found to be very similar to its effect on WDVI (Clevers, 1992). The influence of chlorophyll content on the relationship between WDVI and APAR is illustrated in Fig. 10. From a chlorophyll content of 2 $\mu g.cm^{-2}$ onwards there was hardly any influence.

The maximal absolute errors in APAR estimation for the standard crop caused by an inaccuracy in the chlorophyll content are illustrated in Fig. 11. As expected, largest errors were obtained for low chlorophyll contents (smaller than 10 $\mu g.cm^{-2}$, which are yellow leaves). For green leaves (chlorophyll content of 20-80 $\mu g.cm^{-2}$) errors were all small. Errors larger than 10% APAR occurred for the 10 $\mu g.cm^{-2}$ curve between 85-90% APAR. Lower chlorophyll concentrations do not reach such high values for APAR resulting also into smaller errors.

It was found that the chlorophyll content had a very significant influence on the relationship between NDVI and APAR (Fig. 12), especially for chlorophyll contents below about 20 $\mu g.cm^{-2}$. This resulted into considerable errors when using the NDVI for APAR estimation.

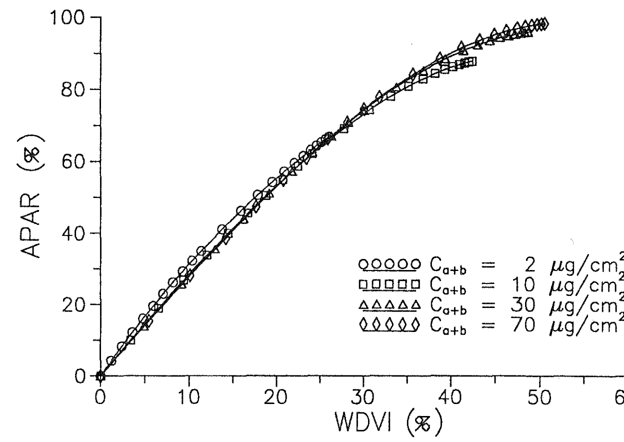

Figure 10: Influence of chlorophyll content (C_{a+b}) on the relationship between WDVI and APAR for the standard crop.

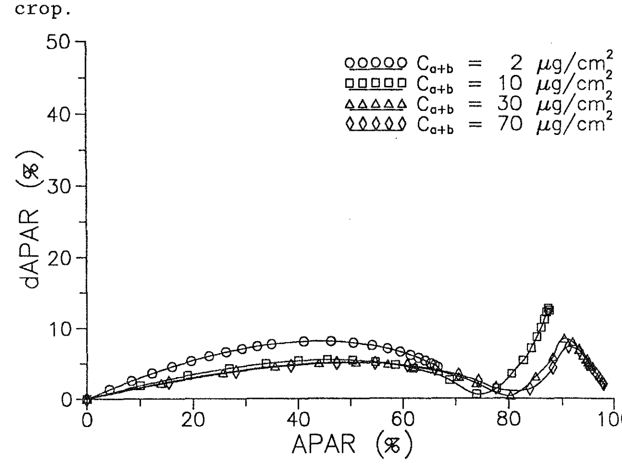

Figure 11: Absolute errors in APAR estimation by means of the WDVI, caused by deviations from Eq. (17) due to leaf chlorophyll content (C_{a+b}) variation for the standard crop.

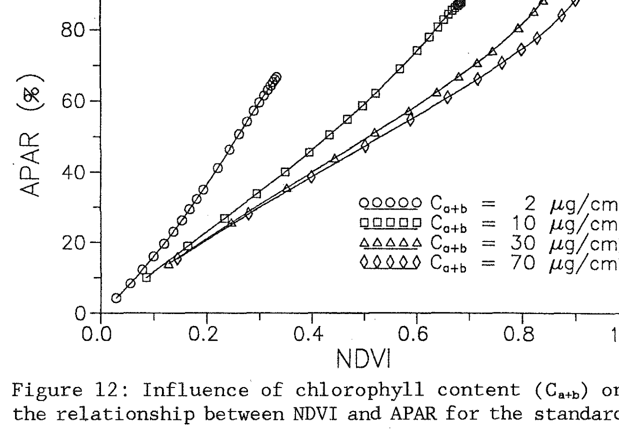

Figure 12: Influence of chlorophyll content (C_{a+b}) on the relationship between NDVI and APAR for the standard crop.

3.7 Influence of Mesophyll Structure

The leaf mesophyll structure (*N* parameter) had hardly any influence on APAR and only a small influence on WDVI (Clevers, 1992). This was explained by the negative correlation between the reflectance and transmittance of a single leaf in the NIR.

The influence of mesophyll structure on the relationship between WDVI and APAR is illustrated in Fig. 13. From this figure it may be concluded in qualitative terms that the mesophyll structure had only a minor influence.

The maximal absolute errors in APAR estimation for the standard crop due to an inaccuracy in the *N* parameter are illustrated in Fig. 14. Errors appeared to be quite small. Largest errors occurred at about 90% APAR (large LAI, see remarks above). For an *N* parameter of 1.0 (monocotyledonous plants) the maximal error reached a value just over 10% APAR. Results for the NDVI were quite similar to the ones for the WDVI.

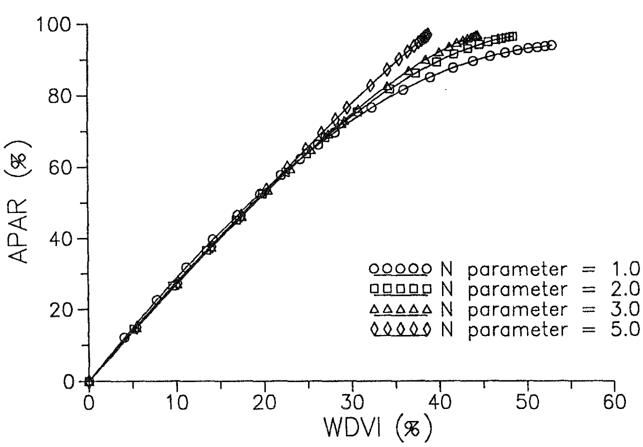

Figure 13: Influence of *N* parameter on the relationship between WDVI and APAR for the standard crop.

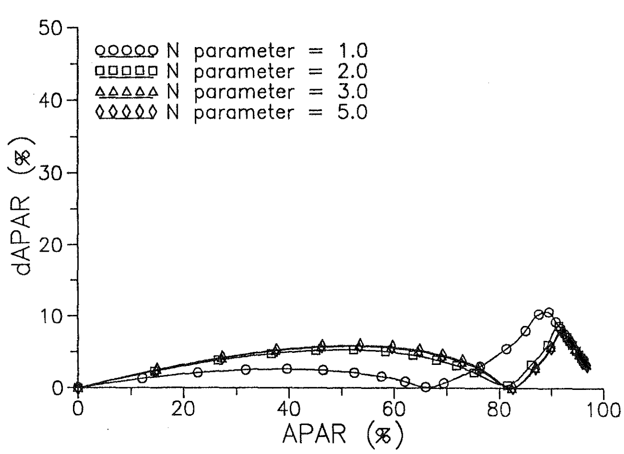

Figure 14: Absolute errors in APAR estimation by means of the WDVI, caused by deviations from Eq. (17) due to *N* parameter variation for the standard crop.

4. CONCLUSIONS

Concerning the estimation of the APAR by means of the WDVI and NDVI, the sensitivity analysis with the combined PROSPECT-SAIL model resulted into the following conclusions (conclusions in this report are restricted by the validity of these models):

- A linear relationship between VI and APAR may be applied as an approximation for estimating APAR from the WDVI or NDVI.

- The influence of **soil background** on the relationship between WDVI and APAR was only minor. Absolute errors in APAR estimate were lower than 10% APAR in absolute units, except for the theoretical case of a soil with 0% reflectance. So, the WDVI does what it is developed for: it corrects satisfactory for the influence of soil background, not only for estimating LAI, but also for estimating APAR. Soil background had a significant influence on the relationship between NDVI and APAR.

- The sensitivity of the relationship between VI and APAR for errors in **solar zenith angle** was quite small, especially for practical circumstances in western Europe. By assuming a solar zenith angle of 45°, the maximum error was about 10% APAR.

- The influence of the **ratio diffuse/total irradiation** on the relationship between VI and APAR was only minor.

- As expected, the **leaf inclination angle** had a huge influence on the relationship between WDVI and APAR. This influence cannot be neglected and is mainly caused by its influence on simulated WDVI. Its influence on the fraction APAR was small near zero APAR (all curves run towards 0% APAR) and at large APAR (all curves run towards about 96% APAR). The influence of the LAD on the relationship between NDVI and APAR was less (maximal error of 10% APAR).

- The influence of the **hot spot size-parameter** on the relationship between VI and APAR for nadir viewing was not very large.

- The influence of the **leaf chlorophyll content** on the relationship between WDVI and APAR was small from a chlorophyll content of 2 $\mu g.cm^{-2}$ onwards. A very large influence only occurred for albino leaves (lacking chlorophyll). Errors larger than 10% APAR occur for the 10 $\mu g.cm^{-2}$ curve between 85-90% APAR. Lower chlorophyll concentrations do not reach such high values for APAR resulting also into smaller errors. It was noticeable, that the chlorophyll content had a significant influence on the relationship between NDVI and APAR.

- The **leaf mesophyll structure** had only a minor influence on the relationship between WDVI and APAR. Largest errors occur at about 90% APAR (large LAI). For an *N* parameter of 1.0 (monocotyledonous plants) the maximal error reaches a value just over 10% APAR. The NDVI yielded similar results as the WDVI.

5. PRACTICAL IMPLICATIONS

Of the external parameters, the influence of soil background on the measured signal at a remote sensing platform could be corrected for satisfactorily by means of the WDVI approach (CLAIR model). The performance of the NDVI in this respect was much worse. The solar zenith angle had only a small influence on the relationship between WDVI and APAR for nadir viewing. Often optical remote sensing measurements are gathered during the growing season of agricultural crops at about the same time during the day, which results into a limited range in solar angles. As a result, one might assume an average solar zenith angle at all dates. The influence of the ratio diffuse/total (or diffuse/direct) irradiation appeared to be only minor. Moreover, optical remote sensing is mostly carried out at sunny days with low (and not very varying) diffuse/total ratios. From the simulations in this report, we may conclude that the external factors will not pose a large problem on the regression of APAR on WDVI.

With the crop parameters, other than the LAI, this is quite different. Particularly, the LAD had a significant influence on the relationship between WDVI and APAR (in this respect the NDVI has some advantages). The influence of leaf properties such as chlorophyll content and mesophyll structure appeared to be quite small for green leaves. The main problem often is that actual information on the LAD is lacking. Clevers & Verhoef (1990) already pointed at the possibility of a constant or a gradually changing LAD (related to a changing LAI) during part of the growing season; with cereals, e.g., a distinction between vegetative and generative (yellowing) stage should be made. In such situations, the effects are caught in the empirical parameters α and $WDVI_{\infty}$ of the CLAIR model. Clevers (1989) described a practical procedure for applying the WDVI, whereby a training set is used for establishing the regression function of LAI on WDVI for a given crop. A similar approach could be applied for establishing the regression function of APAR on WDVI.

Another solution for correcting for LAD may be found in acquiring information on both APAR (or LAI) and LAD by performing measurements at two viewing angles. Such measurements may, e.g., be obtained by using the dual look concept with the CAESAR scanner. In Looyen et al. (1991) the possibilities of acquiring information on both LAI and LAD by means of the dual look concept were illustrated. Goel & Deering (1985) confirmed that two view zenith angles for fixed solar zenith and view azimuth angles are enough to allow estimation of LAI and LAD by the infrared reflectances. Such an approach should be tested more thoroughly.

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