ESTIMATION OF WINTER WHEAT GREEN LEAF AREA INDEX FROM FIELD SPECTROSCOPIC MEASUREMENTS USING A SEMI-DETERMINISTIC MODEL

Robert DE WULF and Roland GOOSSENS
Laboratory of Remote Sensing and Forest Management, Gent State University
Coupure 653, B-9000 Gent, Belgium

Georges HOFMAN
Laboratory of Agricultural Soil Science, Gent State University
Coupure 653, B-9000 Gent, Belgium

ABSTRACT

A comprehensive experiment to estimate green Leaf Area Index (LAI) of winter wheat *(Triticum aestivum* L.) from field spectroscopic measurements spanning four growing seasons (1984, 1985, 1986 and 1988) and involving three cultivars was conducted.
Ground-based colour-infrared photography was the field spectroscopic method selected to acquire winter wheat canopy reflectance data.
Seven types of 'vegetation index' were calculated. Correction procedures for solar zenith angle were introduced as experimental variable.
Based on biophysical considerations, the monomolecular function was selected to model the relationship between vegetation indices and winter wheat LAI.
Different models were constructed for pre-senescence and post-senescence data.
Independent test data were used to assess the effectiveness of the prediction equations constructed from the training data.
It is concluded that, despite obvious inaccuracies for large LAI values, the monomolecular function is an appropriate model to describe the relationship between winter wheat green LAI and vegetation indices. Ratio indices are better estimators of LAI than are orthogonal indices. For pre-senescence conditions, the Simple Ratio, Normalized Difference and TSAVI yield accurate and comparable results across cultivars and growing seasons. Post-senescence LAI is more difficult to estimate, and the Simple Ratio is the only valid vegetation index across cultivars and seasons. A correction for solar zenith angle involving the normalisation of LAI yielded consistent good results.

Key Words : Winter wheat Leaf Area Index, Vegetation Index, Semi-deterministic model.

1. INTRODUCTION

The use of leaf area as the description parameter in crop growth analysis was pioneered by Watson (1956) who defined it as "the area of leaf laminae per unit area of land surface ".
The magnitude and duration of LAI is strongly related to the canopy's ability to intercept photosynthetically active radiation (PAR). Therefore, LAI is correlated with canopy photosynthesis and dry matter accumulation in situations where stress does not predominate.
The importance of an accurate estimation of LAI for crop growth studies needs not to be stressed.
Manual field methods involving cutting, sorting and weighing or planimetering are destructive and extremely tedious.
In addition, in view of statistical considerations, they are not necessarily more accurate. For instance, Curran and Williamson (1985) showed that errors in ground data collection are likely to exceed the error in the remotely sensed data. Paradoxically, this would make remotely sensed data more accurate than the ground data used to check its accuracy.

The rationale behind the use of multispectral reflectance data in general, and of vegetation indices (VI) in particular, to estimate crop LAI has been established for some time.
Canopy reflectance patterns in single bands lead to an explanation for the usefulness of VI's as estimators of LAI.
High absorption in the green and red wavebands causes rapid saturation in function of increasing LAI and occurs around LAI values of 2.
On the other hand, near infrared (NIR) reflectance initially continues to increase at higher LAI levels due to multiple scattering between vegetative layers before eventually reaching an asymptotic level termed infinite reflectance, coinciding with a LAI value of about 8 (Wiegand *et al.* 1979).
From these considerations it follows that the relationships between LAI and VI's are basically non-linear.
A multitude of empirical relationships between LAI and VI's have been documented in literature. In view of a more operational use of these relationships, an investigation of a single model that would be valid across growing seasons and cultivars appears to be justified. For this type of exercise, field spectroscopy methods are eminently suited (Milton 1987).

2. MATERIALS AND METHODS

2.1. Agronomic data

The study area was located in the Laureinepolder in Watervliet, close to the border with the Netherlands. The geographical coordinates are 51°17' N and 3°40' E. The soil is a fertile Aquic Udifluvent .
The winter wheat cultivars included in the experiments were 'Granta' in 1984, 'Castell' in 1985, 'Sarno' in 1986 and 'Castell' in 1988.
In 1984 and 1985 the experiments were carried out on commercial fields, and the crops received normal amounts of fertilizer. In 1986 and 1988 the experiments were conducted on experimental test plots which received different amounts of N-fertilizer: 0 kg, 200 kg and 275 kg in 1986, 0 kg, 100 kg, 150 kg, 250 kg and 325 kg in 1988. Green (1987) showed that increased nitrogen application causes an increase of the leaf area without changing leaf properties and leaf angle. Hence a wider range of biomass data were available allowing for more accurate reflectance/LAI relationship modelling.
For each day that field measurements took place in 1984 and 1985, three random colour infrared (CIR) photographic and LAI samples were taken. Samples measuring 20 cm x 40 cm were randomly harvested in the area covered by colour infrared photography. Harvested green leaf blades were spread out on a matt-black painted surface (60 cm x 80 cm) and recorded on black-and-white film.
In the dark room, after development of the negatives, a transparent dot grid (dot dimension 1.13 mm^2, each dot representing .14 cm^2) was placed directly on the light-sensitive paper (18 cm x 24 cm) during exposure.
The actual dot counting was facilitated by an in-house developed electro-mechanical counting device. Knowing the total amount of dots falling on leaves, LAI could be computed as dimensions of black background and sample plot were known.

In 1986 and 1988, one (CIR) photographic and LAI sample was taken of each test plot per field day. In 1986 and 1988 leaves of 10 and 25 plants were photocopied on a well-tuned photocopier. The data collected in 1986 were counted using a transparent dot grid overlay. The data collected in 1988 were digitized with a CCD camera. Density slicing of a videodigitized photocopy allowed for the calculation of white (non-leaf) and black (leaf) areas. The LAI could be calculated from the average plant density of the experimental plots.

2.2. Field spectroscopic data

Ground-based multispectral photography was chosen as the field spectroscopy method to obtain multispectral reflectance data of agricultural crops. The used method is described in detail by De Wulf and Goossens (1988).
Field spectroscopic data were collected 10 times during the growing season with approximately 10 days intervals, starting at the end of April and ending at harvest around mid August. Hence the phenological stages between stem-elongation and maturity were covered.
The camera-to-ground distance was kept constant at 2.30 m. The covered ground area measured 2.1 m^2.
The Kodak neutral test card (20 cm x 25 cm) was used throughout the experiments as reflectance standard. For each recording it was positioned at the height of the crop canopy and covered approximately 2.5 % of the photographed area.
A few exceptions notwithstanding, measurements were taken close to solar noon in nadir viewing position.
Due to the latitude of the test area, the solar zenith angles ranged between 28° and 52°.
To obtain consistency in azimuthal position, as recommended by Milton (1987), all measurements were taken with the sun either left or right of the operator (azimuth angles of 90° and 270°). This symmetrical configuration had the additional effect that the target and the grey card were never shaded by the recording platform.

The extraction of relative reflectance from CIR transparencies has also been described in detail by De Wulf and Goossens (1988).
Following vegetation indices were calculated from green (G), red (R) and infrared (IR) reflectance.

1. Simple ratio (SR) (Rouse *et al.*, cit. Bariou *et al.* 1985)

   $SR = IR / R$

2. Ratio Infrared/Visible (RIV)

   $RIV = IR/VIS$

   with VIS = average reflectance in the covered visible part of the E.M. spectrum
   $= (G+R)/2$

3. Normalized Difference (ND) (Rouse *et al.*, cit. Bariou *et al.* 1985)

   $ND = (IR-R)/(IR+R)$

4. Normalized Difference of Infrared and Visible (NDIV)

   $NDIV = (IR-VIS)/(IR+VIS)$

The calculation of the indices 1 to 4 is straightforward and they are site-independent.

The RIV and NDIV indices are amendments of the well-known SR and ND. Their construction was proposed to investigate the information value of the green waveband in a ratio index. This choice is also to some extent influenced by the work of Sellers (1989), who suggested that ideally a ratio VI should be close to 2. Hence the replacement of R by the average reflectance in the PAR wavelenghts could yield values closer to 2.

In the formulae of SR and ND, R has been replaced by (G+R)/2, which is the closest approximation of PAR reflectance with the data available.

The other indices included in this study, PVI, TSAVI and Tasseled Cap-like transformations are site-dependent, as they include bare soil reflectance components.

Calculation of PVI and TSAVI require knowledge of the R and IR values for bare soil.

R-IR data sets of bare soil were prepared by random sampling of all available CIR transparencies. Eventually 100 R-IR data pairs were obtained which allowed for the construction of the soil line of the test area. All soil moisture conditions were covered in order to yield a valid soil line.

5. Perpendicular Vegetation Index (PVI) (Richardson and Wiegand 1977)

$$PVI = (-1.134 \times R - IR - .674) / 1.319$$

6. Transformed Soil-Adjusted Vegetation Index (TSAVI) (Baret *et al.* 1989)

$$TSAVI = \frac{1.134 \times (IR - 1.134 \times R - .674)}{(R + IR \times 1.134 - .764)}$$

Tasseled Cap-like transformations were obtained according to a procedure for calculation of coefficients of n-space indices as proposed by Jackson (1983). Only the linear combination corresponding to the Tasseled Cap 'greenness' (Kauth and Thomas, cit. Bariou *et al.* 1985) was retained.

7. Greenness (GRS)

$$GRS = -.183 * G - .723 * R + .665 * IR$$

In addition to the investigation of several VI types, four types of normalisation of the spectral data for the effect of solar zenith angle (Θ) were considered:

1. No correction, i.e. assuming that the precaution of taking field spectroscopic measurements close to solar noon is sufficient ('nocor').
2. Blanket normalisation of all vegetation indices by multiplication with cos (Θ). This method is equivalent to data normalization to a standard sun elevation, such as implemented by Pinter *et al.* (1983) and Tueller and Oleson (1989) ('bcor').
3. Normalisation with cos (Θ) of visible wavelength bands only, considering experimental evidence that IR reflectance is usually less influenced by solar zenith angle than reflectance in the visible wavebands, especially in the case of incomplete canopies (e.g. Ranson *et al.* 1985) ('vcor')
4. Normalisation of LAI with the cosine of the solar zenith angle as proposed by Wiegand and Hatfield (1988). Hence, in contrast to alternatives 2. and 3., the causal variable in the LAI/VI relationship is normalized ('lcor').

3. MODELLING

3.1. Model construction

The fact that different authors propose different LAI/VI models for the same crop leads to the assumption that probably no unique index for all locations or crops exist. A possible explanation can be found in the use of different field spectroscopy instrumentation and the use of different wavebands to construct a VI. In addition, different sampling procedures are prone to seriously influence calibration relationships.

Linear empirical models have been suggested to characterize the relationship between winter wheat LAI and VI's (e.g. Hinzman *et al.* 1986, Major *et al.* 1986).

However these authors based their models on LAI data generally lower than 3. Still, a linear model was found to provide better estimates of spring wheat LAI than a leaf area simulation model (Kanemasu *et al.* 1985).

However, in search of a model type describing the LAI-VI relationship, the asymptotic behaviour between both parameters cannot be ignored on theoretical and experimental grounds (e.g. Asrar *et al.* 1985).

Earlier proposed non-linear statistical models include exponential regressions (Hinzman *et al.* 1986) and second degree polynomials (Bauer *et al.* 1981)

In addition, Asrar *et al.* (1985) and Hatfield *et al.* (1985) showed that empirical relations were different for the pre- and post-senescence period. A hysteresis-like functional relationship should be assumed for the complete growth cycle of winter wheat. This can be explained by the fact that radiation phenomena are different for green and senescing canopies.

Adoption of a semi-deterministic model can only be justified if a physical relationship between a VI and LAI exists.

An appropriate choice seems to be the monomolecular curve (Hunt 1982) formally expressed as

$$VI = a * (1 - b * e^{-c*LAI})$$

In the monomolecular function the three parameters determine a physical relationship between a VI and LAI.

- Parameter a is the asymptote.
- Parameter b controls the value of the VI if LAI=0.
- Parameter c controls the rate of ascent of the asymptotic relationship. Low c values point to a better suited model.

Non-linear regression procedures involve the use of arbitrary starting values to estimate the parameter values from the set of observational data.

However, since the parameters of the monomolecular function do have a physical meaning, appropriate starting values can easily be selected.

The largest VI value of the training set can serve as initial estimate of a. Parameter b can be understood as an approximate of ($1 - VI_{soil}$) (Wiegand and Hatfield 1988). Parameter c is a scattering/absorption coefficient and is smaller than 1.

The monomolecular function has also been used by others (e.g. Baret and Major 1988) and has been proposed as a standard function in the SAMMA project (Wiegand and Hatfield 1988).

3.2. Calibration results and discussion

A randomly selected 50 % subsample of the 1986 winter wheat data was retained for the calibration of the model. The training data were *a priori* divided in pre-senescence data and post-senescence data. The time boundary taken was Feekes stage 10.5 (all ears out of sheath).

The estimation of the monomolecular parameters was different for both data sets: the asymptotic value a from the estimation of the pre-senescence data was assumed to be valid for the post-senescence data case, leaving only b and c to be estimated. This approach makes the choice of the time boundary to separate both data sets less critical.

This rationale is based on experimental evidence reported by Asrar *et al.* (1984), whereby the VI/LAI relationship reaches an asymptotic value at maximum LAI and migrates back, according to different b and c values.

In the pre-senescence regressions, for each Julian date, a data pair for bare soil was included to tune the model for the boundary condition LAI=0, i.e. properly estimate the b parameter.

From the model calibration following results can be highlighted:

1. The higher rate of ascent of the ND and TSAVI with increasing LAI, as often reported in literature is mirrored by the large c values (approximately .7, as opposed to .4 for SR). NDIV follows the same pattern. However, this trend is less differentiated for the post-senescence data.

2. The values for parameter b effectively control the model for the situation LAI=0, both for bare soil situations as for completely senesced vegetation. For instance, for the models PVI/LAI and GRS/LAI, the b values are approximately equal to 1.

3. R^2 values, indicating how close the calibration data fit to the proposed model are larger than .84. In all cases there is a lower R^2 value for the post-senescence models as compared to the pre-senescence data. The ND, NDIV and TSAVI indices display the least scatter around the model, which is probably due to their strong asymptotic behaviour with respect to LAI.

4. As for the corrections for solar zenith angle, the blanket corrected VI's (bcor) show higher R^2 and is followed consistently by 'lcor', 'nocor' and 'vocor'. This is the case for pre-senescence data as well as for post-senescence data.

It can be concluded at this stage that the proposed monomolecular model appears to provide a suitable description of VI's and winter wheat LAI.

The differences of the b and c parameters between the pre-senescence and post-senescence models warrant the use of two different models during the winter wheat growth cycle.

3.3. Validation results and discussion

In order to test how effective a model is as a predictive tool, it is necessary to subject an independent test data set to the obtained prediction equations. All data from 1984, 1985 and 1988, as well as the remaining 50% of the 1986 data served as test data.

The model validation exercise was expected to provide answers to the following questions:

- Are the VI/LAI relationships stable, i.e. do they apply to several cultivars and growing seasons?
- Which VI is the best estimator of LAI?
- Is a correction for solar zenith angle necessary, and if so, which correction type is the best?

All calibration models were inverted, to yield, after input of measured VI, estimated winter wheat LAI (LAI_{est}).

The general form of the inverted model is

$$LAI_{est} = \ln((1 - (VI/a))/b)/-c$$

The limitations of an inverted monomolecular model are obvious:

1. If VI values are larger than the model asymptote a, there is no solution for LAI_{est}. If VI values are only slightly smaller than a, unrealistically high LAI_{est} values may result. In both cases this problem was met by replacing the LAI_{est} value by

10. This is in agreement with the highest recorded LAI values for winter wheat mentioned in literature (Watson 1971, Langer and Hill 1982).

2. Negative LAI_{est} values may occur. In these cases LAI_{est} was set to zero.

After feeding the measured VI's into the respective models, a comparison was made between the measured LAI's and estimated LAI's.
This was initially done by application of the Wilcoxon signed ranks test (Siegel and Castellan 1988). This distribution-free test is somewhat less powerful than Student's T-test for paired samples, but requires no assumptions regarding normality and homogeneity of variances.
The models yielding significant differences between measured LAI and LAI_{est} were dropped from further analysis.
As Wilcoxon's test does not indicate whether the remaining models accurately predict LAI, normalized averaged deviations (DEV_{norm}) of LAI_{est} from measured LAI were calculated as:

$$DEV_{norm} = \frac{\text{average deviation from the the 1:1 line}}{\text{average measured LAI}}$$

The normalisation by average measured LAI facilitates comparison between data from different seasons as the range of LAI values was different between normally fertilized plots (1984, 1985) and the plots receiving a wide range of N-fertilizer (1986, 1988).
Figure 1 summarizes the results of the model validation exercise. Following conclusions can be drawn:

1. The SR, ND and TSAVI are valid estimators across cultivars and growing seasons for pre-senescence LAI of winter wheat if no correction for solar zenith angle is made. However, the accuracy of LAI estimation may vary and errors range from 15% to as much as 50% of the average LAI.
2. The SR and TSAVI are valid estimators across cultivars and growing seasons for pre-senescence LAI of winter wheat if the causing variable of the model (LAI) is corrected for solar zenith angle. The accuracies are similar compared with the 'nocor'-models.
3. The 'bcor'- and 'vcor'-models are no valid estimators of LAI.
4. SR is the only vegetation index that yields valid estimations of post-senescence LAI of winter wheat. This applies only to the 'nocor'-model.
5. The accuracy of LAI estimation is much lower in the post-senescence period.

Remarkably, the LAI of 1986 are not more accurately estimated than the LAI of the other cultivars, although half of the 1986 data served as calibration data.
In general the orthogonal VI's perform poorly. This might be attributed to slight architectural differences between wheat cultivars for which GRS and PVI are more sensitive (Jackson and Pinter 1986). The bad performance of PVI apparently corresponds with results obtained by Wiegand *et al.* (1979) who found good relationships between PVI and LAI, but concluded that the slopes differed unexplainably from field to field. These differences were thought to be caused by complex interactions of shadow effects and canopy architecture.
TSAVI, which is labeled as a hybrid between a ratio index and an orthogonal index, seems to behave as a ratio index.
The proposed RIV and NDIV indices have a worse performance than the established vegetation indices.

4. CONCLUSIONS

The monomolecular model offers an appropriate description of the relationship between LAI of winter wheat and some vegetation indices.
The simple ratio (SR) is the only vegetation index that can be used across cultivars and growing seasons to accurately estimate LAI, both in the pre-senescence as in the post-senesence period. Correcting LAI for solar zenith angle or neglecting its effect completely in the model yield equal results. Other corrections of the VI's for the effect of solar zenith angle yield poor results. The ND and the TSAVI are equally accurate estimators of LAI in the pre-senescence stage.
Large errors may result from LAI estimation of a yellowing wheat canopy.
It is a fortunate implication for any exercise using LAI as an input in yield prediction, that the best LAI estimation is possible in the vegetative stage.

ACKNOWLEDGEMENTS

Mr. Peter Haelvoet, Mr. Dirk Tietens and Mr. Rik Standaert offered valuable assistance for the LAI measurements. There was a most pleasant cooperation with Mr. Etienne Vanderschueren, owner of the farm where the test fields were located.
This research was supported in part by IWONL (Comittee for Applied Pedology) and NFWO, the Belgian National Fund for Scientific Research.

LITERATURE

Asrar, G., Fuchs, M., Kanemasu, E.T. and Hatfield, J.L., 1984. Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. Agronomy Journal, 76 (2): 300-306.

Asrar, G., Kanemasu, E.T. and Yoshida, M., 1985. Estimates of leaf area index from spectral reflectance of wheat under different cultural practices and solar angle. Remote Sensing of Environment, 17 (1): 1-11.

Baret, F., Guyot, G. and Major, D.J., 1989. TSAVI : A vegetation index which minimizes soil brightness effects on LAI and APAR estimation. In : Proceedings of the IGARRSS'89 Symposium, Vancouver-Canada, pp. 1355-1358.

Baret,F. and Major, D., 1988, Significance of the normalized difference. In: Proceedings of the Workshop on "Vegetation indices and their interpretation", The Remote Sensing Society, Nottingham-Great Britain (in press).

Bariou, R., Lecamus, D. and Le Henaff, F., 1985. Indices de Végétation. Dossiers de Télédétection, Centre Régional de Télédétection, Rennes.

Bauer, M.E., Daughtry, C.S. and Vanderbilt, V.C., 1981. Spectral-agronomic relationships of maize, soybean and wheat canopies. In: Proceedings of the International Colloquium on Spectral Signatures of Objects, INRA, Avignon-France, pp. 261-272.

Curran, P.J. and Williamson, H.D., 1985. The accuracy of ground data used in remote sensing investigations. International Journal of Remote Sensing, 6 (10): 181-186.

De Wulf, R.R. and Goossens, R.E., 1988. A method for extracting relative reflectance from 35 mm colour-infrared transparencies. ITC Journal, 3 : 272-277.

Green, C.F., 1987. Nitrogen nutrition and wheat growth in relation to absorbed solar radiation. Agricultural and Forest Meteorology, 41: 207-208

Hatfield, J.L., Kanemasu, E.T., Asrar, G., Jackson, R.D. and Pinter, P.J., 1985. Leaf-area estimates from spectral measurements over various planting dates of wheat. International Journal of Remote Sensing, 6 (1): 167-175.

Hinzman, L.D., Bauer, M.E. and Daughtry, C.S., 1986. Effects of nitrogen fertilization on growth and reflectance characteristics of winter wheat. Remote Sensing of Environment, 19 (1): 47-61.

Hunt, R., 1982. Plant growth curves. Edward Arnold, London.

Jackson, R.D., 1983. Spectral indices in n-space. Remote Sensing of Environment, 13 (5): 409-421.

Jackson, R.D. and Pinter, P.J., 1986. Spectral response of architecturally different wheat canopies. Remote Sensing of Environment, 20 (1): 43-56.

Kanemasu, E.T., Asrar, G., and Fuchs, M., 1985. Application of remotely sensed data in wheat growth modelling. In: Wheat growth and modelling, Day, W. and Atkin, R.K (editors), NATO ASI Series A/86, pp. 357-369.

Langer, R.H. and Hill, G.D., 1982. Agricultural plants. Cambridge University Press, Cambridge.

Major, D.G., Schallje, G.B., Asrar, G. and Kanemasu, E.T., 1986. Estimation of whole-plant biomass and grain yield from spectral reflectance of cereals. Canadian Journal of Remote Sensing, 12 (1): 47-54.

Milton, E.J. 1987. Principles of field spectroscopy, International Journal of Remote Sensing, 8 (12) : 1807-1827.

Pinter, P.J., Jackson, R.D., Ezra, C.E. and Gausman, H.W. 1985. Sun-angle and canopy-architecture effects on the spectral reflectance of six wheat cultivars. International Journal of Remote Sensing, 6 (12): 1813-1825.

Ranson, K.J., Biehl, L.L. and Bauer, M.E., 1985. Variation in spectral response of soybeans with respect to illumination, view and canopy geometry. International Journal of Remote Sensing, 6 (12): 1827-1842.

Richardson, A.J. and Wiegand, C.L., 1977. Distinguishing vegetation from soil background information. Photogrammetric Engineering and Remote Sensing, 43 (12): 1541-1552.

Sellers, P.J., 1989. Vegetation-canopy spectral reflectance and biophysical processes. In : Theory and applications of optical remote sensing. Asrar, G.R. (editor), Wiley, New York, pp. 297-335.

Siegel, S. and Castellan, N.J., 1988. Nonparametric statistics for the behavioral sciences. McGraw-Hill, New York.

Tueller, P.T. and Oleson, S.G., 1989. Diurnal radiance and shadow fluctuations in a cold desert shrub plant community. Remote Sensing of Environment, 29 (1): 1-13.

Watson, D.J., 1956. Leaf growth in relation to crop yield. In : The growth of leaves. Milthorpe, F.L. (editor), Butterworths Scientific Publications, City, London.

Watson, D.J., 1971. Size, structure and activity of the reproductive system of crops. In : Potential crop production. Wareing, P.F. and Cooper, J.P. (editors), Heinemann Educational Books, London.

Wiegand, C.L. and Hatfield, J.L., 1988. The spectral-agronomic multisite-multicrop analyses (SAMMA) project. In: Proceedings of the 16th International Congres of the International Society of Photogrammetry and Remote Sensing, Kyoto-Japan, pp. 676-706.

Wiegand, C.L., Richardson, A.J. and Kanemasu, E.T., 1979. Leaf area index estimates of wheat from LANDSAT and their implications for evapotranspiration and crop modeling. Agronomy Journal, 71 (2) : 336-342.

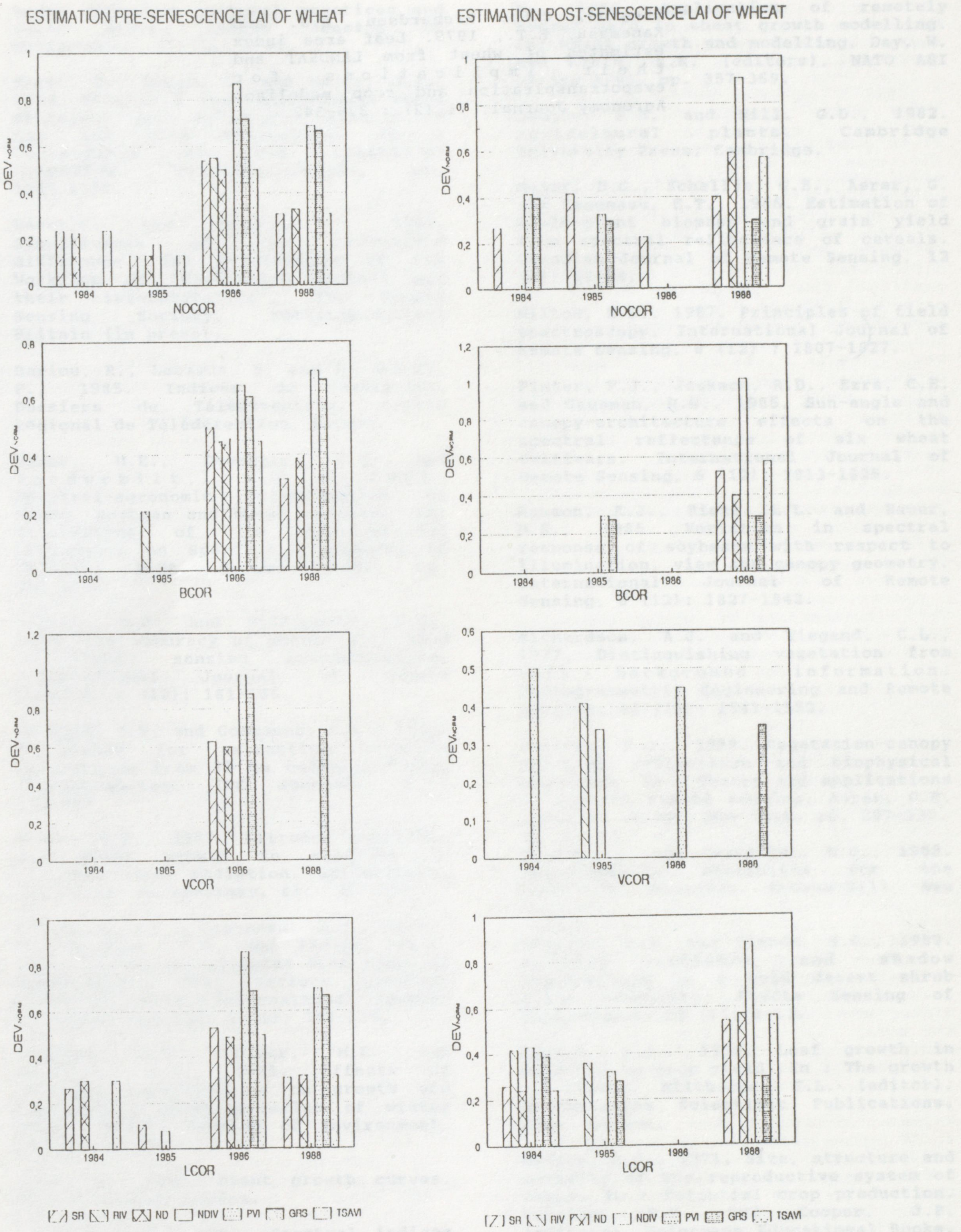

Figure 1. Performance of different vegetation indices (VI's) as winter wheat LAI predictors, using the normalized deviation (DEV_{norm}) from measured LAI as criterion. Results of VI's yielding significant differences between measured and estimated LAI are not displayed. Bar charts on the left and on the right refer to LAI estimation in the pre-senescence and post-senescence period respectively. The rows of bar charts refer to normalisation procedures for solar zenith angle. The reader is referred to the text for the explanation of the acronyms.