RED EDGE SHIFT AS VITALITY INDICATOR FOR PLANTS ?

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ABSTRACT

The shift of the red edge in the reflection spectra of vegetation targets is a known phenomenon documenting changes in the biological status of plants. In our study we analyzed the variability of red edge reflection in dependency of differently managed field plots. The results indicate that the red edge is not fully described by the shift of the main inflection point, but has to be considered as a collection of several different and possibly independent features, each of them influenced by biological parameters of the plants. Thus, taking all features, the red edge as derived from high resolution spectra may provide enough information to detect small differences in the chemical and morphological status of plants.

INTRODUCTION

Remote sensing techniques in agricultural science help to provide information about crop characteristics. Research aims at interpreting spectral signatures of agricultural targets and quantifying the relationship of reflectivity to plant properties.

The spectral response of a crop canopy correlates with its chemical and morphological status which defines crop vitality. Variations in reflectivity during growing season are a sequence of dynamic processes depending on management practices and environmental factors.

Much research has been done in establishing combinations of reflectance factors in different wavelength bands of spectra to obtain maximum information about crop parameters (TUCKER et al. 1980, AHLRICHS and BAUER 1983, GIOVACCHINI 1986, CLAUSNITZER and TIMOFEEV 1987). As these investigations have shown, however, broad band spectral data are of limited value for detection of plant properties. As improvement, reflectance measurements of high spectral resolution open up new opportunities to find characteristic spectral phenomena which may be highly correlated to the chemical and morphological status of crops. Attention is focused on the slope between 680 and 760 nm, the so called red edge, in the reflectance spectra of vegetation. Shifting to longer or shorter wavelength may document changes in plant vitality. COLLINS (1978) described the spectral position of the red edge as varying with different development stages of certain monocotyledons. He attributed the shift to changes in chlorophyll concentration and polymerization in foliar tissue. HORLER et al. (1983) summarized knowledge about the variation of shape and position of the red edge. In their experiment they performed red edge analysis in spectra of leaves measured in the laboratory and showed the shift to be dependent on chlorophyll content and scattering properties. SCHUTT et al. (1984) reported on a possible physical mechanism for the shift of the red edge in wheat. DEMETRIADES-SHAH and STEVEN (1988) found the shift of the red edge, although in good correlation with leaf chlorophyll content for reflectance data from laboratory, unsuitable for monitoring chlorosis of sugar beet canopies in the field. DOCKTER et al. (1988) showed a distinct shift of the red edge in reflectance spectra of sugar beet crops due to differences in leaf vitality caused by early and late sowing. COLLINS et al. (1983) and CHANG and COLLINS (1983) presented the shift of the red edge as stress indicator. They used airborne reflectance data to detect stress of forest trees and laboratory reflectance data to obtain metal-induced stress of leaves, respectively.

Our investigation aims to monitor the changes in red edge characteristics due to plant development, plant species and management practices using reflection spectra collected under the troublesome conditions in the field. The use of field data is of special interest, because the applicability of red edge attributes needs the prove of their existence under natural growth conditions.

MATERIAL AND METHODS

Data were collected at the experimental farm `DIKOPSHOF' of the University of Bonn during the 1986 growing season. Sugar beets and winter wheat were cultivated according to normal agricultural practices. To produce distinct differences in crop development, chemical and morphological condition of the plants and yield two independent cultivation factors were varied for each species. Sugar beets were established at different sowing dates (T1 = early: 04/17/86 ; T2 = late: 05/09/86) and supplied with nitrogen fertilizer at different levels (N1 = 120 kg N/ha ; N2 = 200 kg N/ha). Two cultivars of winter wheat were chosen (S1 = Okapi ; S2 = General) and grown with different rates of nitrogen fertilization as well (N1 = 60 kg N/ha ; N2 = 170 kg N/ha). The plots were 21 m long and 11 m wide and had a special organization for the collection of agronomic, meteorological and spectral data. A detailed description is presented by BOOCHS (1986).
Daily meteorological data were acquired at a weather station located on the farm. On each day that reflectance were measured additional meteorological data were recorded.

As basis for investigations onto the red edge in the reflection of plant targets measurements of incoming and reflected electromagnetic radiation are necessary. Actually these are collected by a two channel spectroradiometer equipment which is positioned vertically over the field plots about 8 meters apart from the plants. One optical channel of the instrument is directed down onto the plants, the second one is aimed to measure the incoming energy by means of a near Lambertian reflectance panel with BaSO4 coating. Both channels are measured almost simultaneously to allow the operation of the equipment even by changing weather conditions without weakening the reflection values. The spectral resolution of the measuring device amounts to 2nm, guaranteed by the use of a grating monochrometer. The instrument registrates 679 spectral channels in the region of 404-2190 nm out of which 90 channels ranging from 623-802 nm here are used for the analysis of the red edge characteristics.
Each set of reflection values is derived from independent measurements of three different targets from one field plot. The readings first were calibrated followed by an averaging to reduce the influence of stochastic variations in the spectral data. Furthermore the so gained reflection values are fed into a low pass filter process to eliminate the effect of a fluttering last digit in the instrument recordings. As filter served a moving average of length three, which obviously has a limited smoothing effect. This is done intentional in order to save most of all other high frequent information components possibly originating from characteristics in the plant reflection.
After preprocessing, the spectrum of the first derivative is calculated. According to the quantification of the reflection in discrete steps of 2 nm the derivative has to be calculated using:

$$dr(i) = r(i)-r(i-1) \qquad \text{with : } i = 1 \rightarrow 90;\ \lambda(r(1)) = 623 \text{ nm};\ \lambda(r(90)) = 802 \text{ nm}$$

The resulting derivative spectrum has to be considered as an information onto the reflection change per spectral channel. Due to the fact that this part of the spectrum which is labeled as

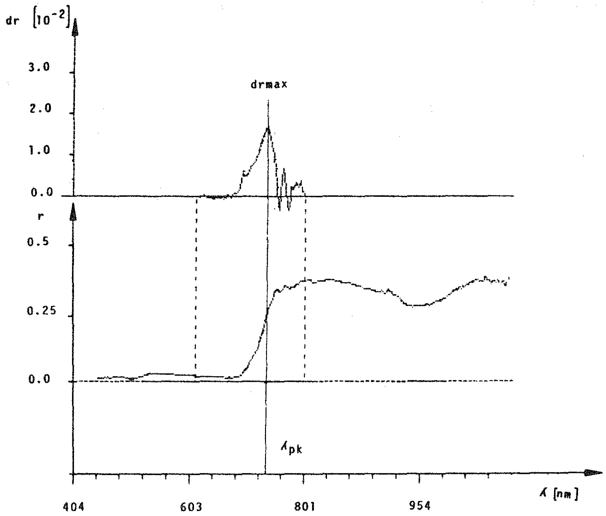

Fig. 1 Reflection curve for a wheat field plot together with calculated derivative spectrum between 623 and 802 nm.

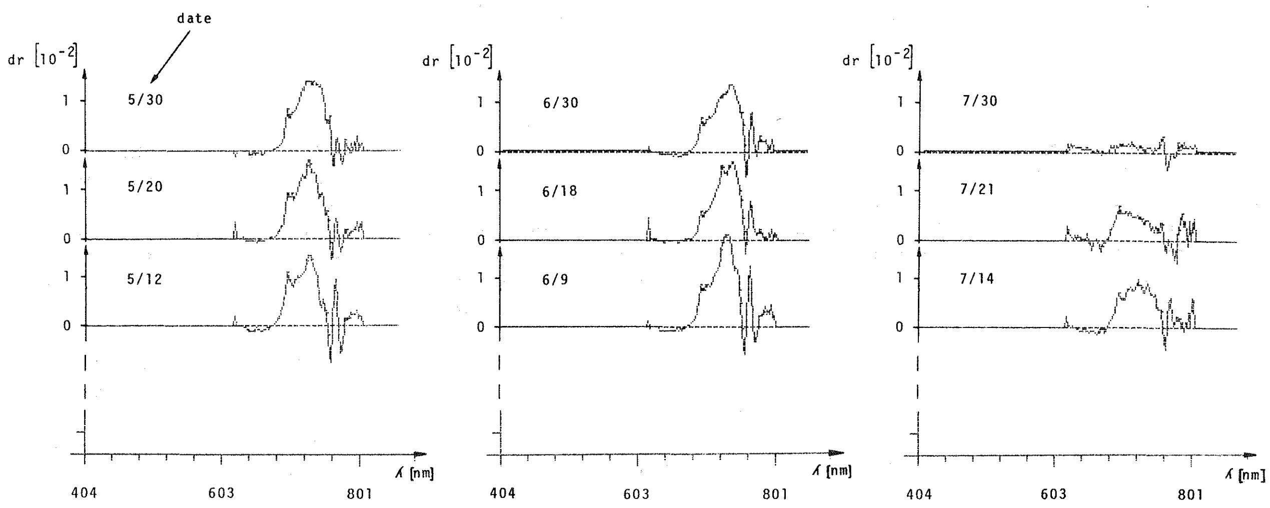
derivative spectra for a wheat plot during growing season

Fig. 2 A set of derivative spectra for a wheat field plot covering the whole growing season. The graphic shows derivation vs. wavelength curves for 9 measuring dates.

red edge consists of a steep transition from the region of high energy absorption (r≈1%) to the domain of relative high reflection (r≈40%) the derivative spectrum shows a typical shape dominated by a peak at a certain wavelength λ(pk) (cf. Fig.1).
As previous investigations have shown (HORLER et al., 1983; COLLINS et al., 1983) the position of maximum slope λ(pk) is varying with certain chemical and morphological parameters in plants and may be used for monitoring purposes.
Besides the peak wavelength a high resolution derivative spectrum provides information to the shape of the transition from red to infrared reflection and might help to prove for common structures therein.

RESULTS

- Attributes of a derivative spectrum

First of all some derivative spectra of wheat field plots will be considered in order to find typical features, if present, and to focus the attention onto the most useful parts of the curves. To emphasize typical attributes a complete set of spectra covering a whole growing season will be used for analysis (cf. Fig.2).

Regarding at the curves in the left column originating from early measuring dates which might be grasped as typical for green vegetation we find a derivative spectrum with a generalized shape similar to a parable. This is due to the nature of steep transitions which in general show first increasing slopes culminating in the inflection point followed by decreasing slopes until the transition has reached the end level. Therefore the parabolic outline has to be considered as an inevitable attribute for a red edge transition (ranging from about 680nm to about 760nm). Accordingly this parabolic form disappears as wheat plants mature and the red edge degenerates to a line of continuously increasing reflection (cf. Fig.2, top right curve). This demonstrates that the derivative spectrum shows characteristic variations corresponding to the phenological development of plants and for this reason is of equal value for monitoring the growth stage as original reflection spectrum.

Looking at the curves in more detail we find further characteristics :

1. Besides the main peak at about 735nm there is a small second one in the fore part of the curve at 703nm. This peak remains notifyable for almost the complete growing period and is still existing when the red edge has started the degeneration process, documented in the lost of the parabolic shape.
The qualitative information of the first peak therefore differs from that of the longer wavelength parts of the curve and might be useful as additional indicator.
2. The outline of the parabolic part between 700nm and 760nm is in continuous development during growing season. At the beginning of growth (cf. Fig.2, bottom left curve) we find a

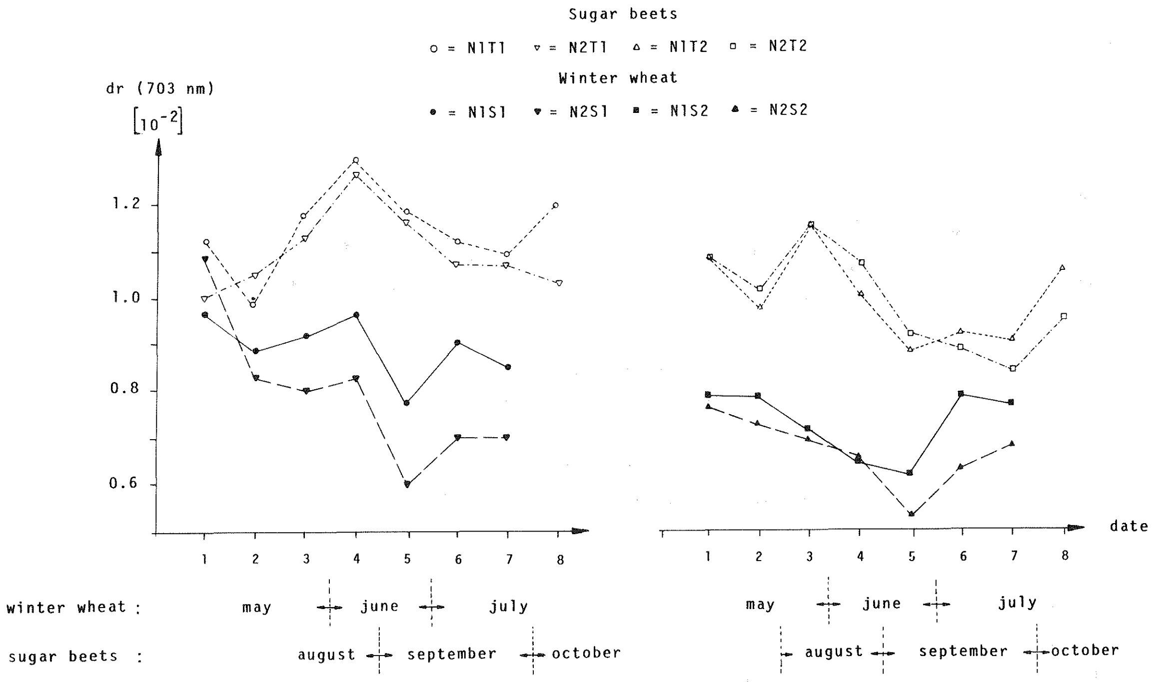

Fig. 3 The plot shows the amplitude of the slope at the first peak (dr(703nm)) varying with measuring date and different species (sugar beet - winter wheat, high - low nitrogen level (N2-N1), early - late sowing date (T1-T2), plant cultivar 1 (Okapi) - plant cultivar 2 (General) (S1-S2))

small shape with an acute peak of moderate amplitude. During the growth phase the amplitude increases considerably, sometimes accompanied by a broadened peak. The phase of senescence is attributed by a rapid decrease of the amplitude and by a lost of the small shape. When the plants are close to maturity the parabolic form is destroyed completely.
This behaviour gives opportunity for the use of the peak amplitude and, if applicable, of the form of the curve to trace the development stage of the plants.
3. Considering the peak at about 735nm it seems to vary in form and position. The form allows to distinguish between dates of a small and acute peak, dates with a broad peak and a date with two peaks. The case of two peaks originates from a measurement during flowering. This may lead to the assumption, that the outline of the peak is in dependence of certain phenological stages.
In regard to the wavelength position of the peak a shift to longer wavelengths can be observed until flowering, followed by a backshift to the blue end of the spectrum in parallel with senescence.

In summary of all these observations the derivative spectrum supplies several independent informations possibly helpful for monitoring purposes. Furthermore it indicates, that the red edge phenomenon is not fully described by the shift of the main inflection point but has to be considered as a collection of several different and possibly independent parts, each of them influenced by biological components of the plants.
In order to prove the dependencies of plant structures and chemical status in the derivative spectrum, differently cultivated plots (variation in : plant species, plant cultivars, nitrogen fertilization, sowing date) will be analyzed together with some descriptors for the derivative spectrum. As descriptor will serve

1. Amplitude of the first peak (dr(703nm))
2. Amplitude ratio for the first peak and the peak with maximum slope (=main inflection point) rat(dr)=dr(703nm)/dr(infpt))
3. Wavelength position of dominant peaks (λ(pk))

The values for each descriptor are calculated for all reflection data sets and plotted vs. measuring date (cf. Fig. 3,4,5).

- Influence of the plant species

Using Fig. 3,4 and 5 there are a lot of informations for separation of sugar beets and winter wheat.
The peak ratio (Fig.4) exhibits a plant typical development during growth. The values for sugar

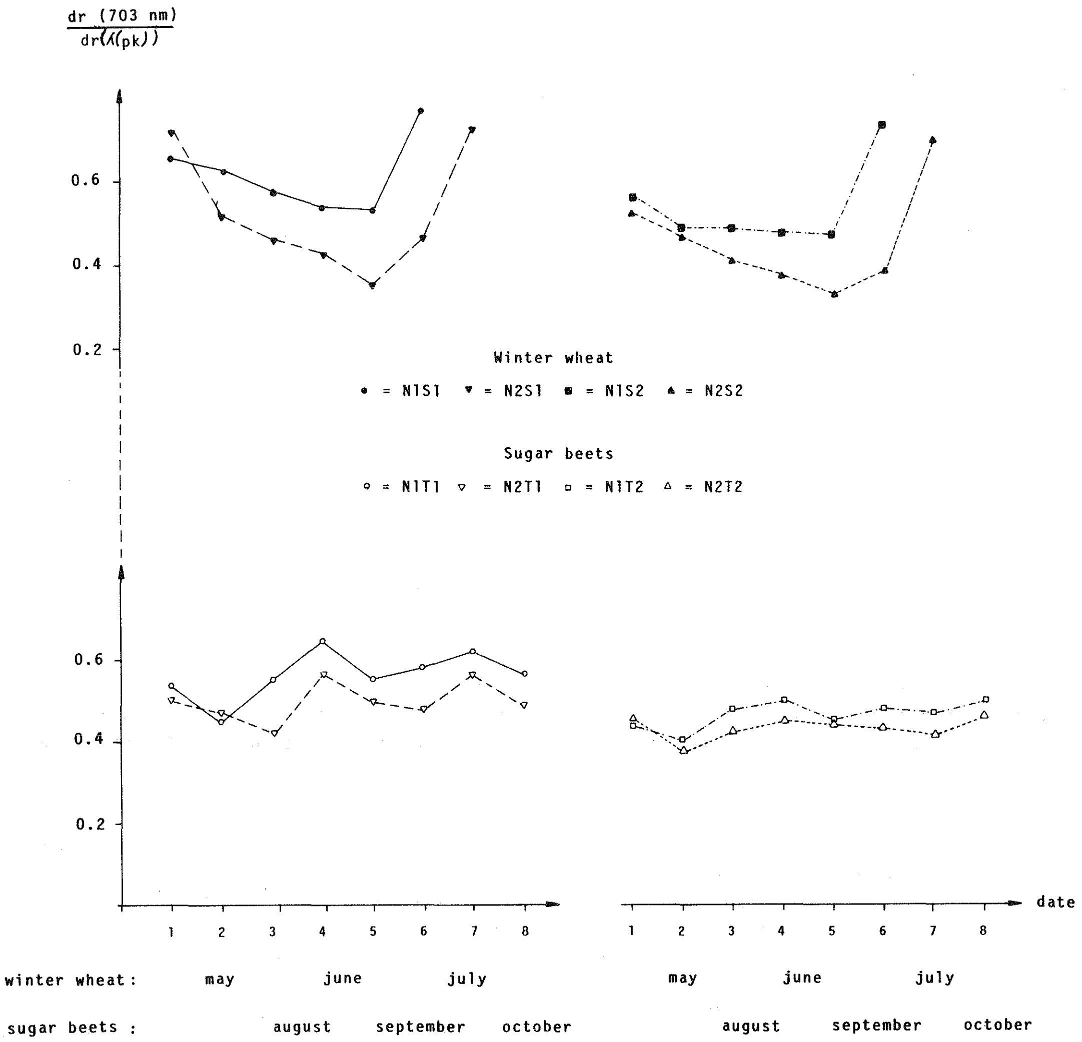

Fig. 4 The plot shows the ratio of the slopes at the first peak and the main inflection point (rat(dr)) varying with measuring date and different species (sugar beet - winter wheat, high - low nitrogen level (N2-N1), early - late sowing date (T1-T2), plant cultivar 1 (Okapi) - plant cultivar 2 (General) (S1-S2))

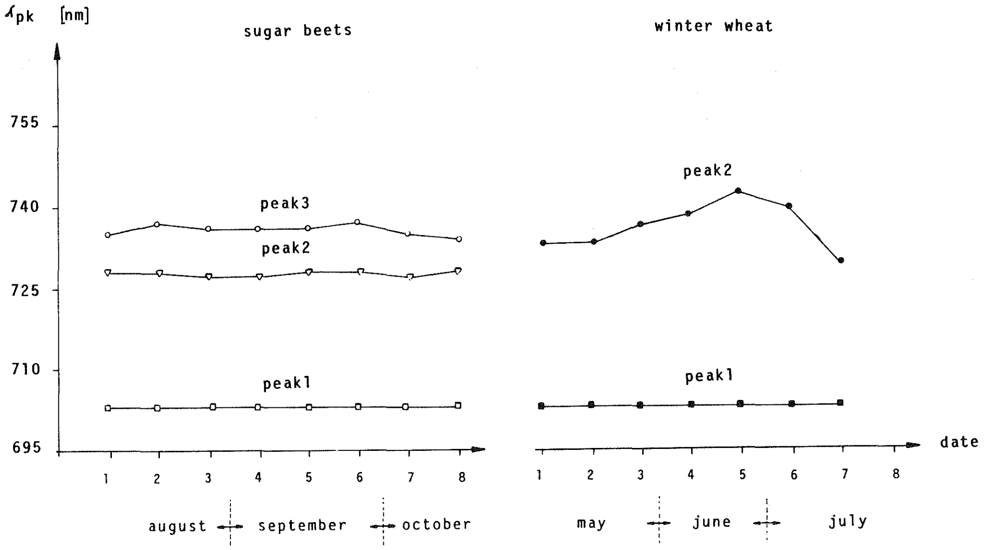

Fig.5 The plot shows the wavelength positions of dominant peaks (°(pk)) varying with measuring date and plant species (sugar beet - winter wheat). The values are averaged out of all plots of each plant type.

beets are oscillating in conformity but without a general trend what leads to the assumption to find herein the influence of growth conditions. In opposite to that, wheat shows a typical development. The first 5 values are continuously decreasing what corresponds to the accumulation of biomass and chlorophyll, followed by a steep increase for the ratios going in parallel with the maturity process. Therefore the values for rat(dr) of wheat seem to be in close accordance to the well known growth cycle.
Secondly sugar beets and wheat may be distinguished by the location and the number of dominant peaks (cf. Fig.5). Wheat has two peaks out of which the second one, standing for the inflection point, exhibits the typical red and blue shift variations. Sugar beets have three peaks all located at fix wavelengths (703nm, 728nm, 736nm) with a minimal red and blue shift for the inflection point (Rpeak3).
The amplitude of the slope at 703nm gives the most significant information (cf. Fig.3) and allows to separate the plant species alone with one value for dr(703nm). Furthermore the curves for each plant species are again in very close accordance, an additional prove for the significance of the information provided by dr(703nm).

- Influence of nitrogen treatment

Analysing for nitrogen effects we find similar trends with different magnitudes for the two plant species. In general, a higher nitrogen level leads to smaller values for dr(703nm) and rat(dr) (cf. Fig. 3,4). This is in good correspondence to the greater vitality of plants with higher nitrogen supply. The only difference between wheat and sugar beets is visible in the distinct magnitude for the parameter values, with a higher influence of nitrogen for wheat plants. But using the peak ratios rat(dr) the significance of the data is still good enough even to recognize the small differences for the two nitrogen levels in sugar beets.

- Influence of sowing date

A difference in the planting date for sugar beets results in a modification of the growth cycles accompanied with different vitality levels. This is reflected by the peak ratios, rat(dr), and much more pronounced, by the slope amplitude dr(703nm) (cf. Fig. 3). Here the lower values for the late sowing date are documenting a higher vitality, which will be kept by the plant for the whole growing season and accordingly is visible in the dr-values. The same behaviour can be observed for the ratios rat(dr), however with smaller significance.

- Influence of the plant cultivar

Plant cultivars vary in morphological structures and chemical constitution. Regarding at Fig. 4 we find small differences between corresponding plots (N1S1-N1S2; N2S1-N2S2), which are standing for little increase in vitality for cultivar General. In opposite to that the slope values (cf. Fig.3) show a much more remarkable dependence onto the factor cultivar. This is displayed in generally lower values for cultivar General and in differing shapes of the curves. This might be interpreted as a possible influence of chemical parameters which are reflected in the slope values at 703nm.

In summary we have to state that the used management and plant parameter produce significant differences in the structures of the red edge.
In inversion of this context, the red edge seems to provide a lot of informations for the analysis of plant physiology, if it is possible to explain the observed variations in the derivative spectrum in dependence of important internal plant factors like chlorophyll content or biomass.

DISCUSSION

The amount of chlorophyll in plant leaves is one of the factors determining shape and wavelength position of the red edge. COLLINS (1978) described the red edge as near-infrared absorption edge of chlorophyll which shifts up to 20 nm towards the longer wavelengths in some maturing vegetation canopies. The author explained this phenomenon by an increase of chlorophyll and associated establishment of polymerization products which absorb longer wavelength photons. More detailed informations are presented by HORLER et al. (1983). They applied derivative analysis techniques on detection of the red edge shift and identified two peaks in derivative spectra. The first peak at around 700 nm was attributed to the chlorophyll content in plant leaves, the second one at around 725 nm rather to leaf scattering properties than to chlorophyll content. A shift of the peaks to longer wavelengths was shown to be due to an increase in chlorophyll concentration and leaf stacking, respectively.
In contradiction to the results of HORLER et al. (1983), we find the peak at 703 nm in first derivative spectra of sugar beet and winter wheat to remain stable in spectral position. Different chlorophyll concentrations of leaves cause only a variation in peak amplitude. As shown in

Fig.3, a high nitrogen supply, which is equivalent to a high chlorophyll concentration of leaves, is correlated with low values for dr(703nm). Moreover, as can best be noted for winter wheat, an increase in chlorophyll content during growth leads to a decrease in amplitude and vice versa. This coincides with COLLINS (1978) who showed that the region of absorption extends to longer wavelengths as the chlorophyll content increases. This smoothes the slope of the red edge at 703 nm and consequently reduces the amplitude of the peak in derivative spectra.

In good accordance with HORLER et al. (1983) we identified a second peak in the longer wavelength part of the slope at about 735 nm (Fig.5). In winter wheat canopies this peak shifts to longer wavelengths until the stage of flowering (measuring date 5) and reverts during senescence until harvest (measuring date 7). HORLER et al. (1983) described the shifting to longer wavelength mainly to be induced by an increase in leaf scattering. As more leaves were added to a stack scattering increased, accordingly the absorption yield of the existent pigment concentration improved by extending the path length of the light. During the growth period the leaf area index (LAI) and the biomass of wheat crops increase. This causes greater light scattering and consequently a shifting of the peak to longer wavelengths. During senescence the above mentioned parameters decrease and produce a reversion of the shift.

In sugar beet crops we identified a second peak at 728 nm and a third peak at 736 nm (Fig.5). While the second peak remains almost stable, the third peak varies slightly during the vegetation period except for the final measurements (measuring dates 7 and 8) where we find a shift to shorter wavelength. This matches well with the smaller variations in LAI and biomass of the sugar beet crops during the observed period. The blue shift at the end of the growing season indicates the senescence of plants.

Development monitoring of agricultural crops can be achieved by using 1. the amplitude of the first peak in derivative spectrum at 703 nm, dr(703nm) (Fig.3) or 2. the amplitude ratio for the first peak and the peak with maximum slope, rat(dr), (Fig.4). Regarding our results we assume that dr(703nm) is mainly influenced by chlorophyll concentration of leaves and rat(dr) by chlorophyll concentration and LAI. Chlorophyll concentration and LAI usually show parallel variations during development of plants. For this reason the shapes of the curves in Fig.3 and Fig.4 are very similar, especially for winter wheat. The values of dr(703nm) (Fig.3) for sugar beets show a greater variation during the vegetation period than do the values of rat(dr) (Fig.4). This is due to the development of the crops which is strongly influenced by weather conditions causing not necessarily conform variations in chlorophyll concentration of leaves and LAI.

As has been noted in Fig.3 and Fig.4 the values for winter wheat form an exact inverse profile to the development of chlorophyll content and LAI during the growing season and show the well known growth cycle. This relationship is evident for sugar beets as well when the weather conditions are taken into account.

Several investigators have evaluated vegetation indices from broad band spectral data for development monitoring of crops and growth parameters (TUCKER et al. 1980, AHLRICHS and BAUER 1983, GIOVACCHINI 1986, CLAUSNITZER and TIMOFEEV 1987). In most cases these vegetation indices show sensitivity both to leaf pigmentation and biomass and accordingly reduce detectibility of related parameters. A new opportunity for unambiguous monitoring of agricultural parameters will be provided by use of high spectral resolution data with the assessment of different peaks in derivative spectra and the two indices dr(703nm) and rat(dr).

- Influence of plant species

As shown in Fig.3 the amplitude of the peak at 703 nm is definitely higher for sugar beets than for winter wheat and can be used for distinguishing the two crops. This difference in magnitude cannot be explained with differences in chlorophyll content. We assume that there is a difference in the absorption process of chlorophyll between sugar beets and winter wheat. Further investigations have to be conducted for finding and answer for this phenomenon.

- Influence of nitrogen treatment

High nitrogen nutrition of plants causes a high chlorophyll content of leaves and a high LAI. This effect can be recognized by low values in Fig.3 and Fig.4. The greater difference in magnitude for winter wheat plots than for sugar beet plots is due to an obviously greater variation in chlorophyll concentration and LAI of the canopies in the field. These differences have their reason in the chosen management practices and the response of the crops depending on growth cycle. In opposite to DEMETRIADES-SHAH and STEVEN (1988) who did not record any correlation between leaf chlorophyll content and red edge in canopy spectral measurements, the indices dr(703nm) (Fig.3) and rat(dr) (Fig.4) show a clear dependency on N-treatment.

- Influence of the sowing date

The difference in vitality of sugar beets due to early and late sowing could be observed by DOCKTER et al. (1988) as shift of the largest peak in first derivative spectra. Fig.3 and Fig.4

show these differences as variation in the values of dr(703nm) and rat(dr).

- Influence of the plant cultivar

The cultivar `General' is evaluated as more vigorous than the cultivar `Okapi' (BUNDESSORTENAMT 1984), and consequently exhibits lower values for dr(703nm) in Fig.3. The smaller differences in rat(dr) between `General' and `Okapi' in Fig.4 are probably due to a compensating effect of morphology (plant height, leaf inclination).

CONCLUSIONS

The red edge part of a plant reflection spectrum together with high resolution spectral measurements and the first derivative spectrum allow the detection of small qualitative differences in the chemical and morphological status of field crops. Assuming that a quantitative relationship will be established, the application of remote sensing techniques to the analysis of plant parameters can be improved in future.

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