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DIFFERENCES IN THE SPECTRAL CHARACTERISTICS BETWEEN HEALTHY AND DISEASED CROPS AS DETERMINED FOR SUGAR BEETS AND WINTER BARLEY

PART A: SPECTROPHOTOMETRIC MEASUREMENTS IN THE LABORATORY AND GROUND TRUTH DATA COLLECTION

Abstract

Spectrophotometric reflectance measurements in the 0.5 to 2.5um wavelength interval were conducted at leaves of

- winter barley plants from fungicide-treated and non-treated test plots at two-week intervals between mid-April and the end of June, 1979, and
- healthy and nematode-infested resp. water-stressed sugar beet plants in September and October of the same year.

Ground truth data collected referred to the general phenological conditions of the plants as well as to disease or stress symptoms, biomass, yield, leaf area index, and soil conditions. Differences in the spectral reflectance factors of leaves of healthy and diseased or stressed plants were very slight. Larger differences were observed between the sampling dates, especially for winter barley. The results are compared with the corresponding spectroradiometric in situ measurements and the data of an airborne multispectral scanner (see parts B and C of the joint paper).

Introduction

Considering the fact that vegetation covers large parts of the earth´s solid surface, and thereby contributes to a large extent to the data received by remote sensing systems, comparatively little is known about the spectral reflectance characteristics of plants and plant canopies. This applies for natural features as well as for agricultural cropland. Due to the heterogeneity of natural vegetation, it is difficult to establish basic data with respect to the specific spectral reflectance behaviour of the different ecological and phenological types resp. stages. Up to now, rather rough classifications of those features from remote sensing data are in general sufficiently corresponding to the requirements.
With agricultural vegetation, i.e., cultivated land, it is

different: certain plant species used as human or animal food are grown each one by itself in defined areas. The requirements for the results of remote sensing applications in agriculture are, accordingly, defined much more precisely as to the exact classification of each crop type. This means, that the spectral reflectance pattern of a certain crop must be known for its different growth and development stages throughout the season until harvest time, and, moreover, in order to avoid classification errors as well as to predict yield losses or to detect stress or disease situations, the influence of vitality changes on spectral reflectance must be studied as well.

Thus, in a joint experiment sponsored by the German Research Council, the spectral reflectance of healthy and mildew (Erysiphe graminis f. hordei) -affected winter barley was determined during the growing season of 1979 at three different levels: in a laboratory spectrophotometer, from a ground-based spectroradiometer, and by an airborne multispectral scanner (for the latter two see parts B and C of this paper). Similar measurements were also carried out on healthy and water stress/ nematode/ rizomania-affected sugar beets.

This paper gives an account of the results obtained by the laboratory measurements, and includes the agro-biological ground truth data which were collected in order to enable a thorough understanding of crop spectral behaviour.

Materials and Methods

Test fields for the investigations on winter barley were provided by BASF AG on their agricultural extension station Limburgerhof near Ludwigshafen in the alluvial plains of the Rhine. Süddeutsche Zucker AG made it possible to work on sugar beets in the loess-soil area near Alzey.

As for winter barley, two adjacent plots of 10 x $10m^2$ size were marked in each of three fields. Both plots had been cultivated equally with respect to fertilizing and herbicide treatment before plant emergence. Between April 27 and May 7, after the beginning of shoot elongation up to the emergence of the terminal leaf (stages 31 to 37), two systemic fungicides (Cercobin M (R) and Calixin (R))as well as a growth regulator (Terpal (R)) were applied to one of the plots in each field at application rates of 0.5 kg/ha, 0.75 l/ha, and 2.5 l/ha, respectively. As barley mildew regularly occurs in this region due to microclimatic conditions, its outbreak in the untreated plots was ensured. Starting from 23rd April onwards, data collection was begun at about two-week intervals up to June 27. Harvest date was at July 4. At each measurement date (23.04., 09.05., 16.05., 29.05., 14.06. and 27.06., respectively) ten leaves were collected from each plot, wrapped airtight in plastic bags and stored in an ice box in order to prevent moisture loss for a maximum for a maximum of three hours until measurement in the laboratory. the leaves collected at the respective dates were all from the same nodes of different plants, and each time those primarily contributing to the plant canopy reflectance as viewed vertically from above were taken in order to provide the possibility of correlations to the ground-based spectroradiometric and aircraft measurements. Spectral reflectance of four out of the ten leaves was determined by measurements on the Zeiss PMQ II spectrophotometer with attached RA3 d/0^{o} diffuse reflectance attachment in the wavelength interval 500 to 2 500 nanometers at selected wavelengths of 500, 550, 600, 650, 680, 720, 800, 850, 900, 950, 1 100, 1 450, 1 650, 1 950, 2 250, and 2 500 nm. Sample illumination was diffuse, and reflectance was measured normal to the sample surface. The average of the four parallel measurements and the standard deviation was calculated.

At each date, biological parameters (plant height, growth stage, leaf area index, and disease symptoms) were collected. In order to enable correlations to the spectroradiometric measurements, data collection and sampling was concentrated upon the two measured plots.

As for sugar beets, two adjacent sites of non-stressed and stressed areas of the same field were used for data collection. Plant stress was due to limited soil moisture resulting from locally shallow soil, combined with cyst nematode (Heterodera schachtii) infestation. Times of data collection were 19.09., 03.10., and 21.10., 1979. Harvest was conducted at 05.11. The ground truth and reflectance measurement data correspond to those described for winter barley.

Results and Discussion

1. Winter barley

Table 1 contains the biological parameters of the respective measurement dates. Mildew infestation is expressed in percent leaf area of the leaves most affected by the disease. Due to weather conditions, infestations concentrated mainly upon the lower leaves where humidity is higher, and only finally reached to some small extent the upper leaves. In June, when ripening was going on already, some infestation with barley dwarf rust (Puccinia hordei) came up on the upper leaves. The ears were hardly affected by either mildew or rust. - After development of the grains, the ears bend down, and thereby contribute to a large extent to the reflectance of the canopy. They were, therefore, included in the measurements.

Leaf area index (LAI) of the barley plots was found to be changing considerably with the ongoing vegetation period (see table 2). As determined by reflectance measurements of successively stacked leaves, infinite reflectance (R_{∞}) is reached at LAI = 2 in the visible, and at LAI = 6 in the infrared range. As the LAI of the treated or untreated plots does not differ substantially at the respective measurement dates, this factor will not be the cause of probable differences in canopy reflectance of treated or untreated plots as measured in situ or from the airplane. It may, however, be of influence on the reflectance factors in the near infrared from one date to the other. The decrease in LAI from mid-May onwards can be explained by the shrinking and folding of the leaves with ripening.

Harvest data are given in table 3 for all of the three test plots. The differences that can be observed between treated and untreated plots cannot, however, be examined statistically due to limited sample size. Moreover, as only one of the three sites could be considered for the spectroradiometric in situ measurements due to technical restrictions, correlations between the yield differences and canopy reflectance can be established but they may not yet be generalized.

Spectral reflectance factors as determined by the spectrophotometric measurements throughout the vegetation period are presented in table 4 and figures 1 and 2. The wavelengths given in table 4 were reduced to 550 nm (chlorophyll reflectance maximum), 680 nm (chlorophyll absorptance maximum), 850 nm (near IR reflectance plateau), 1 450 and 1 950 nm (water absorption bands), and 1 650 and 2 200 nm (middle IR reflectance maxima). The changes that can be observed in the progress of the vegetation period are expressed most clearly in the chlorophyll and water absorption bands corresponding to chlorophyll degradation and water loss. Stron correlations between water content and reflectance at 1 450 and 1 950 nm can be observed, whereas in the visible and near infrared wavelength bands reflectance increases only during the final ripening stages of the crop. At May 9th, following the treatment with fungicidal and growth regulatory chemicals, an increase in reflectance can be observed in all wavelengths with the exception of 550 nm. This increase, however, occurs with the untreated plants as well but less as compared to the treated ones. Whether this increase is at least partially caused by the influence of the growth regulator, as could be deducted from results by GAUSMAN et al. 1970 and GAUSMAN et al. 1979, who worked with different growth regulators, is to be investigated by further experiments.

Ear reflectance as determined in the laboratory was not much different from leaf reflectance; however, due to specular reflectance behaviour of the awns as observed in the field, this factor may possibly influence ground-based and airborne radiometric in situ measurements considerably, especially in the visible range.

Soil spectral reflectance was approximately the same for treated and untreated plots. Furthermore, it is largely governed by soil moisture content, especially in the visible and middle IR wavelength bands. Therefore, it was lowest at the beginning of the season, when soil humidity was high (fig.2).

2. Sugar beets

The investigations on sugar beets were undertaken at the end of the growing season. As their leaves are fully developed from June onwards, and are still green at harvest time, phenological influences on leaf reflectance were rather small during our working period.

Table 5 contains the biological ground truth data. Due to the combined influences of soil moisture lack and nematode attack, the leaves of the stressed plants are less turgid than those of the non-stressed plants; i.e. they are slack but still retain their green colour. Therefore, plant height is less than that of the healthy ones. Moreover, the leaf area of the stressed plants is smaller, whereby the ground is not fully covered. In the area not covered by sugar beet leaves, a few single weeds had grown up. Leaf area index is, consequently, considerably smaller for the stressed as compared to the healthy plots (table 6). As R_∞ was determined to be 1 in the visible, and 7 in the near infrared (SANWALD 1979), the differences observed with the in situ radiometric measurements may be partly caused by LAI differences, in addition to soil and petiole reflectance and less shadow spaces of the stressed plot.

Sugar beet yield was considerably lower in the stressed plot, as only small beets can be developed. Relative sugar content is approximately the same (table 7).

Spectral reflectance data are given in table 8 and figure 3. In the green band, significant differences could be observed for all sampling dates. The differences found in the water absorption bands are difficult to understand, as reflectance values do not correspond to the respective leaf water content as compared for eachsampling date seperately. Moreover, it is quite surprising that the % water content of the stressed plants is not much different from the non-stressed ones. Further investigations are planned to elucidate this phenomenon.

Soil spectral reflectance is shown in fig. 3 for two of the sampling dates. due to humidity changes, rather large differences can be observed. They have to be taken into consideration for the in situ measurement results, especially with the stressed plot, and probably for the healthy plot as well, because in the near infrared where retro-reflectance of the light transmitted by the leaves may be influenced.

Conclusions

The joint experiment (see parts B and C of this paper) has shown that the collection of biological ground truth data is essential for the understanding of plant spectral reflectance behaviour. The laboratory reflectance measurements for the collection of basic data was found to be of considerable value, as this technique adds the missing link to ground-based and airborne radiometric measurements and contributes to the final understanding from the biologist´s and the physicist´s point of view.

Acknowledgements

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Table 1 Biological parameters of winter barley plots

Date	Treat-ment	Growth Stage	Plant height (cm)	Mildew (%leaf area)	Leaf measured	Condition of measured leaf
23.4.	treated	tiller-	35	0	1st leaf	healthy
	un "	ing	40	0		
9.5.	treated	tiller-	45	0	2nd leaf	healthy
	un "	ed	65	0		
16.5.	treated	2nd node	75	0	3rd leaf	healthy
	un "		90	10		
29.5.	treated	earing	120	0	4th leaf	healthy
	un "	complete	150	25	+ ears	
14.6.	treated	flower-	100	0	flag leaf	healthy
	un "	ing	120	35	+ ears	5% mildew + 5% rust
27.6.	treated	yellow	100	0	4th leaf	10% rust
	un "	ripeness	120	35	+ ears	10% mildew + 20% rust
4.7.	h a r v e s t					

Table 2 Leaf area index of winter barley plots

		23.4.	9.5.	16.5.	29.5.	14.6.	27.6.
Ø leaf area	treated	54,1	93,7	117,7	89,9	61,8	33,0
per plant (cm^2)	un "	55,7	98,2	129,9	73,0	70,2	43,2
leaf area	treated	2,76	4,78	6,00	4,59	3,15	1,68
per m^2 (m^2)	un "	2,67	4,71	6,23	3,51	3,37	2,07
leaf area	treated	3	5	6	4,5	3	2
index (LAI)	un "	3	5	6	3,5	3	2

Table 3 Harvest data of winter barley plots

Plot	kg Biomass (straw+grains)	Straw kg	Grains kg	%H_2O of grains	1 000 grains weight (g)
I treated	16,10	11,93	4,17	17,4	33,8
I un "	25,90 (lodging dampness)	19,25	6,65	17,3	27,2
II treated	16,50	10,00	6,50	13,8	26,7
II un "	15,8	8,20	7,60	19,3	25,0
III treated	18,7	10,05	8,65	11,8	24,3
III un "	15,8	8,65	7,15	11,9	21,6

Table 4 Spectral reflectance factors of winter barley leaves and ears as determined in the Zeiss PMQ II + RA3 d/0° laboratory spectrophotometer. Underlined are differences significant at p=.05. Percent water content of the leaves is mainly for comparison with water absorption band data.

Date	λ (nm)	550	680	850	1 450	1 650	1 950	2 200	% water content
23.4.	treated	12,0	4,4	47,2	16,1	34,8	7,2	19,8	83,8
	un "	12,3	4,5	47,6	16,6	35,4	7,4	21,4	83,7
9.5.	treated	12,6	<u>4,9</u>	51,5	21,4	39,3	<u>8,6</u>	23,8	74,9
	un "	11,4	<u>4,3</u>	49,9	19,9	38,2	<u>7,8</u>	23,2	76,3
16.5.	treated	10,5	5,8	44,7	20,4	34,6	10,7	22,4	76,5
	un "	10,9	5,6	44,6	20,8	34,7	10,6	23,0	78,8
29.5.	treated	11,4	6,5	44,6	21,0	35,6	9,8	22,5	75,2
	un "	10,4	6,6	43,8	22,0	36,0	10,2	24,6	75,8
14.6.	treated	12,3	8,5	47,8	30,0	42,2	15,7	30,7	63,0
	un "	12,4	8,9	49,4	33,2	44,6	17,6	33,8	60,2
27.6.	treated	<u>15,8</u>	<u>21,3</u>	<u>53,5</u>	56,4	59,0	53,7	<u>57,1</u>	14,5
	un "	<u>12,4</u>	<u>18,8</u>	<u>51,3</u>	56,2	58,0	52,6	<u>54,6</u>	14,6
E A R S									
29.5.		9,2	6,8	47,6	19,8	34,0	11,0	22,0	n.n.
15.6.		11,0	8,6	45,3	16,1	24,6	10,0	17,1	n.n.
27.6.	treated	13,5	15,8	49,1	32,6	34,7	28,4	31,9	4,4
	un "	12,8	15,6	48,6	32,1	34,6	28,4	30,8	5,0

Table 5 Biological parameters of sugar beet plots

Date	Status	Plant height (cm)	Ground cover
19.9.	healthy	45	100%
	stressed	30	60% + weeds
3.10.	healthy	45	100%
	stressed	20	60% + weeds
21.10.	healthy	45	100%
	stressed	25	60% + weeds
5.11.	h a r v e s t		

Table 6 Leaf area index of sugar beet plots

		19.9.	3.10.	21.10.
∅ leaf area per plant (cm^2)	healthy	4 888	3 606	3 250
	stressed	1 967	1 573	1 312
leaf area per m^2 (m^2)	healthy	35,2	26,0	23,4
	stressed	15,3	12,3	10,2
leaf area index (LAI)	healthy	3,5	2,5	2,5
	stressed	1,5	1	1

Table 7 Harvest data of sugar beet plots

Plot	Sugar beet yield (kg/10m^2)	Ø weight per beet (g)	% polarisation (for sugar content)
healthy	59,2	822,2	19,5
stressed	43,2	553,8	19,3

Table 8 Spectral reflectance factors of leaves of healthy and stressed (nematode-affected and water deficient) sugar beet plants as determined in the laboratory spectrophotometer. Underlined are differences significant at p = .05.

Date	λ (nm)	550	680	850	1 450	1 650	1 950	2 200	% water content
19.9.	healthy	14,9	11,5	48,6	14,3	32,0	7,9	16,9	84,4
	stressed	17,3	12,1	48,8	12,8	29,8	7,6	14,8	83,2
3.10.	healthy	13,5	10,4	48,6	13,8	31,6	7,7	15,7	81,3
	stressed	15,0	10,9	50,7	13,8	31,7	7,3	15,9	79,2
21.10.	healthy	12,3	8,2	47,5	13,2	30,6	6,1	15,2	82,3
	stressed	13,4	8,8	47,1	10,4	27,0	5,6	12,3	82,0

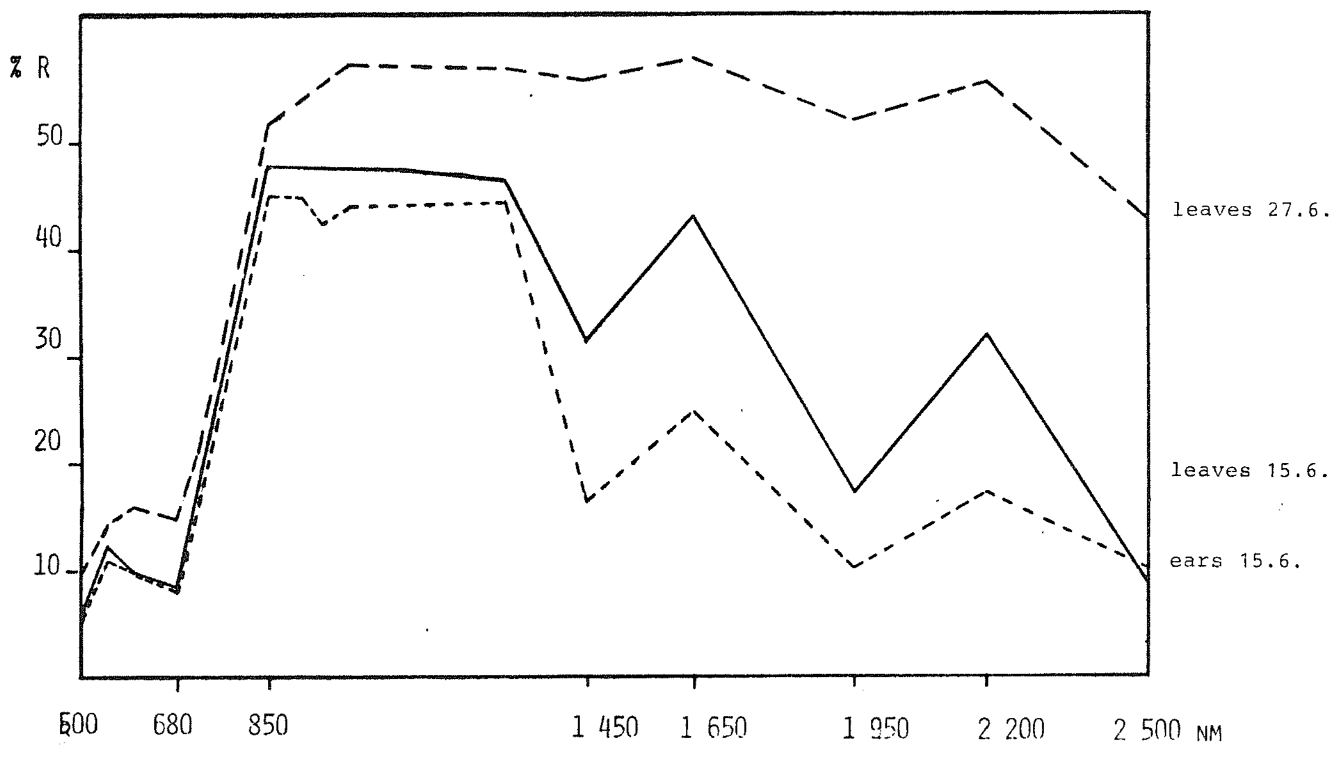

Figure 1: Spectral reflectance pattern of winter barley leaves and ears at the end of the growing season

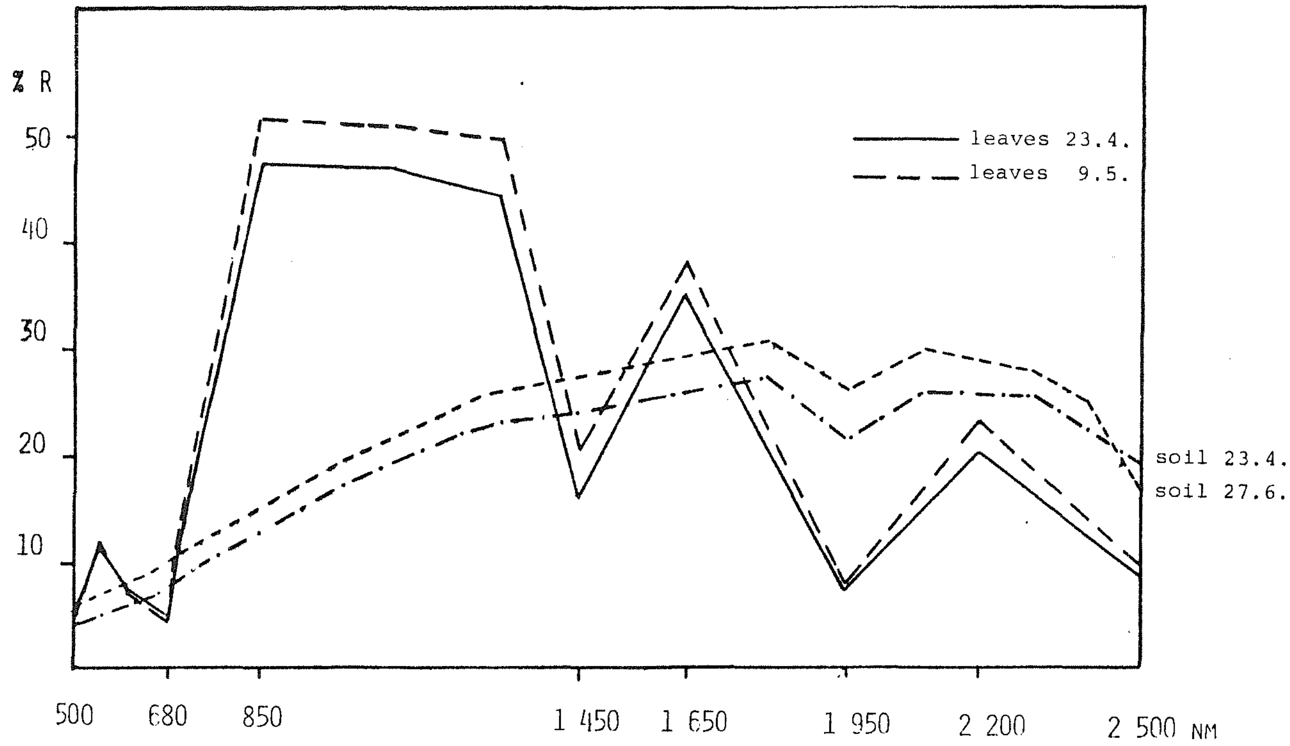

Figure 2: Spectral reflectance pattern of winter barley leaves at the beginning of the season, and of the plots´soil surface at the beginning and at the end of the season

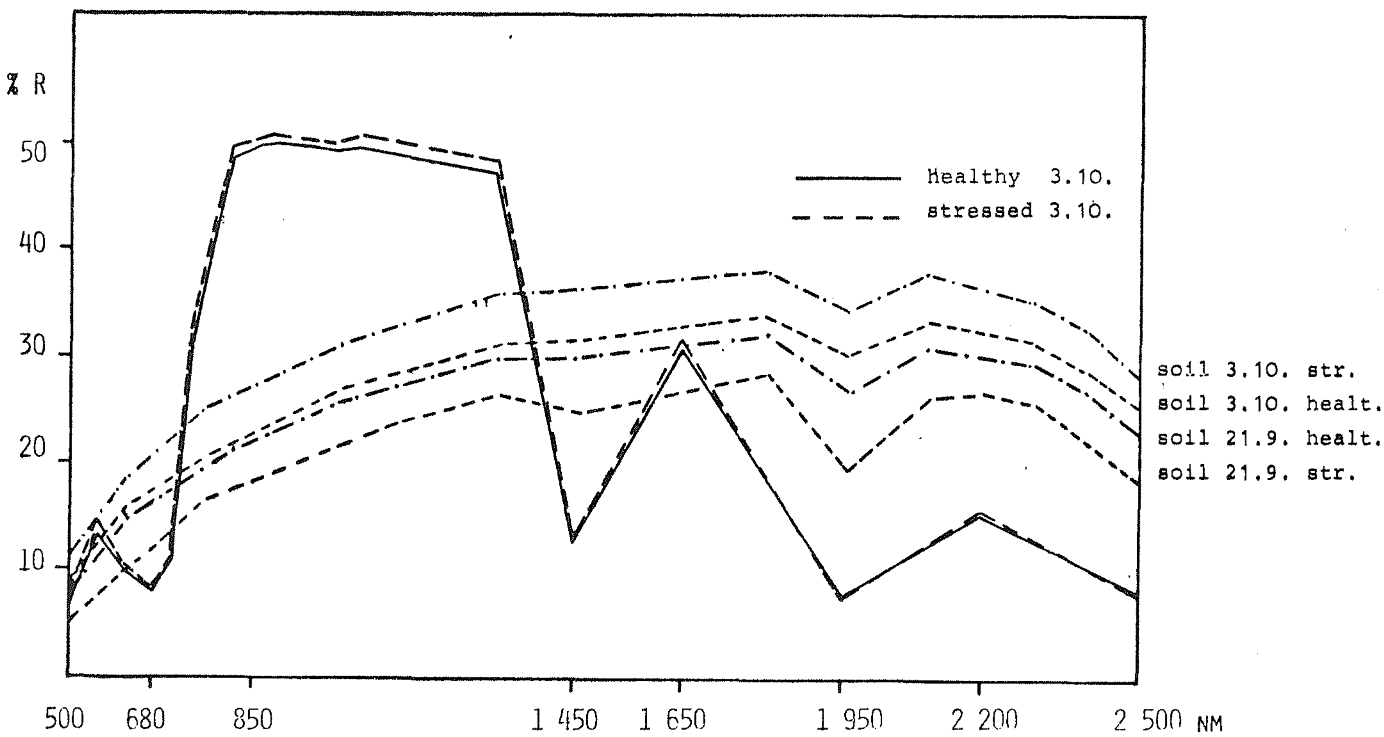

Figure 3: Spectral reflectance pattern of leaves of healthy and stressed sugar beets, and of the plots´soil surface