ASSESSMENT OF CROP VITALITY THROUGH ANALYSIS OF COMBINED FIELD AND LABORATORY MEASUREMENTS OF BIOPHYSICAL AND BIOCHEMICAL PARAMETERS

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ABSTRACT

Remote sensing bears the potential to provide quantitative information of agricultural crops instantaneously and of a certain regional extent. Estimates of crop growth which are used for crop yield prediction, and timing of forthcoming harvest are important in agricultural planning and policy making. For non-optimal growing conditions, estimates of crop growth may be inaccurate. Crop monitoring during the growing season by means of optical remote sensing can provide information on plant variables that describe the actual status of agricultural crops during the growing season.

In this paper, the assessment of crop vitality through analysis of both field and laboratory measurements of biophysical and biochemical parameters is investigated for wheat and barley, two main crops grown in Switzerland, be it by yield or by area. Leaf area index (LAI), fraction of absorbed photosynthetically active radiation (FAPAR), water content and chlorophyll content are defined as the main parameters defining plant vitality.

1 INTRODUCTION

Between April and August 1999 periodic observations of a summer wheat and a winter barley field have been performed in an intensively cultivated agricultural area, the Limpach Valley (470 m a.s.l.) located in Western Switzerland. Data collection included spectroradiometric measurements of the crop canopy, determination of leaf area index (LAI), fraction of absorbed photosynthetically active radiation (FAPAR), plant-, leaf- and grain-water content and chlorophyll content. The plant growth stage was characterized using a decimal code (DC) for the growth stages of cereals [16]. Spectroradiometric data was collected using an ASD-Field Spectrometer covering the wavelength range from 0.4 μm to 2.5 μm. Leaf area index is determined using a LICOR LAI2000 meter [16] and the fraction of absorbed photosynthetically active radiation is determined using a ceptometer [9]. Chlorophyll a and b content was determined from samples in the laboratory using the equations of Lichtenthaler [14]. Plant-, leaf- and grain-water content are measured by oven-drying of the samples.

LAI is a key variable frequently used by agronomists, crop physiologists and crop modelers. Both LAI and the primary plant pigments chlorophyll a and b control the amount of intercepted solar radiation (FAPAR), which is the driving force for crop growth. Water content as a fourth key variable describing vitality influences the amount of green leaves, plant pigments and therefore the ability of efficient photosynthesis.

2 METHODOLOGY

The phenological development of crops can be divided into a vegetative, a reproductive and a senescing phase. The vegetative phase consists of the growth stages *seedling growth* (DC 10-19), *tillering* (DC 20-29), and *stem elongation* (DC 30-39), the reproductive phase of *booting* (40-49), *inflorescence emergence* (DC 50-59), and *anthesis* (DC 60-69), the senescing phase of milk development (DC 70-79), *dough development* (DC 80-89) and *ripening* (DC 90-99). Data takes were aimed to representatively cover all these phenological stages.

2.1 Measurement plan

Field and laboratory measurements consisted of:

- Spectroradiometric measurements of the vegetation canopy using an ASD-Field Spectrometer.To characterize the spectral variability within the crop fields satisfactorily, a transsect was defined, representing the variations in the crop stand. Each measurement taken was visually described as being of dense, medium or low vegetation cover.

- Determination of leaf chlorophyll content. Leaf samples were collected in the field and taken to the laboratory for chlorophyll extraction. The photometric determination of chlorophyll a and b was performed with a CADAS-100 Spectralphotometer [13] in 100% acetone using the equations of Lichtenthaler [14]:

  $$\begin{aligned} C_a &= 11.24 \cdot A_{661.6} - 2.04 \cdot A_{644.8} \\ C_b &= 20.13 \cdot A_{644.8} - 4.19 \cdot A_{661.6} \\ C_{a+b} &= 7.05 \cdot A_{661.6} + 18.09 \cdot A_{644.8}, \end{aligned}$$

  where A is the measured absorbance value.
  The leaf area of each leaf is determined using a LICOR LI-3100 Leaf Area Meter [15].

- Determination of plant-, leaf- and grain-water content. Plant-, leaf- and grain-samples of a mean vegetation stand were collected and placed in a drying oven at 85° C for 48 hours. The weight and leaf area of the fresh samples were measured before drying to determine water content from weight loss.

- Determination of leaf area index using a LICOR LAI-2000 Meter. For representative LAI measurements, the datatakes were performed along a transsect and described as being of high, medium or low vegetation cover. Since LAI data strongly depend on the canopy architecture, which itself varies during the day, the measurements were carried out around solar noon, weather permitting.

- Determination of the fraction of absorbed photosynthetically active radiation (FAPAR) by the canopy. FAPAR measurements were carried out using a ceptometer based on the following equation [10]:

  $$FAPAR = 1 - \frac{PAR_r + (PAR_t - PAR_s)}{PAR_o},$$

  where PAR_r is the upward radiation at the top of the canopy
  PAR_t is the downward radiation at the bottom of the canopy
  PAR_s is the radiation reflected at soil surface
  PAR_o is the incoming radiation at the top of the canopy

  To measure FAPAR in the field, the abovementioned radiation fluxes must be measured independently.

- Characterization of the growth stage of each measurement day using a decimal code for growth stages of cereals.

2.2 Data analysis

Each of the four parameters chosen to desribe the vitality status of a crop stand (LAI, FAPAR, water content, chlorophyll content) is related to the spectral data following the methods described below. A visual quality control is applied to every spectrum taken. For each measurement day, a representative mean spectrum of the three classes dense, medium and low vegetation cover is computed.

2.2.1 Estimating LAI

LAI estimation is based on a semi-empirical reflectance model that calculates LAI of a green canopy based on the WDVI (weighted difference vegetation index) and the inverse of an exponential function [5], [6]. The WDVI is a weighted difference between the measured reflectances $\rho(\lambda_{NIR})$ and $\rho(\lambda_{RED})$, assuming that the ratio of these two reflectances is constant for a certain type of bare soil. In this way, the influence of soil background is corrected:

$$WDVI = \rho(\lambda_{NIR}) - C \cdot \rho(\lambda_{RED}),$$

where $C = \dfrac{\rho_{SOIL}(\lambda_{NIR})}{\rho_{SOIL}(\lambda_{RED})}$

The LAI is then calculated as:

$$LAI = \frac{-1}{\alpha} \cdot \ln\left(1 - \frac{WDVI}{\rho_{\infty}(\lambda_{NIR})}\right),$$

where α describes with which rate the above function runs to its asymptotic value and $\rho_{\infty}(\lambda_{NIR})$ is the asymptotic limiting value for the $WDVI$. Parameters α and $\rho_{\infty}(\lambda_{NIR})$ must be estimated empirically from a training set.

2.2.2 Estimating FAPAR

The fraction of photosynthetically active radiation is often expressed as an exponential function of LAI [1]:

$$FAPAR = A \cdot [1 - B \cdot \exp(-C \cdot LAI)],$$

where A, B, C must be estimated empirically from a training set
LAI was both determined from WDVI and SAVI (soil adjusted vegetation index ,[11]) to test the suitability of the two indices.

2.2.3 Estimating water content

Laboratory studies have demonstrated that there is a negative linear relationship between leaf water content and leaf reflectance in the near- and middle-infrared region [3], [17]. DANSON [8] performed a linear correlation analysis of all wavebands of a fresh leaf spectrum and found a statistically significant relationship between leaf water content and leaf reflectance for several wavelengths.
Since a hyperspectral sensor, be it air- or spaceborne, acquires spectroradiometric data of a vegetation canopy and not of single leaves, the extraction of plant water content is investigated here. In addition, grain-water content is closely related to plant-water content (Figure 4), which is not the case for leaf-water. To make use of the information content of several wavebands, multiple linear regression analysis is applied. Because the

position of the inflexion point is highly correlated to plant vitality, the inflexion point wavelength is also taken into account.

The linear equation determined by the regression has the form [12]:

$$c = a_0 + \sum_{i=1}^{n} a_i \cdot \rho_i + a_{n+1} \cdot P_{inflex} ,$$

where c is the plant water content, n is the number of wavelengths used in the correlation model, $(a_0, a_{i=1,N+1})$ are the coefficients of the regression, ρ_i are the reflectances at the specified wavelengths and P_{inflex} is the position of the inflexion point

2.2.4 Estimating chlorophyll content

Most non-destructive techniques for the determination of chlorophyll relate the leaf reflectance at about 675nm to the concentration of the total chlorophyll. Chappelle [4] used ratio spectra that allow the identification of reflectance bands corresponding to the absorption bands of specific pigments. The developed *ratio analysis of reflectance spectra* (RARS) *algorithm* allows estimation of the conentrations of chlorophyll a and b per unit mass solvent using a linear relationship. Blackburn [2] describes the relationship of $RARS_a$ with canopy chlorophyll a concentration per unit area using a power model. $RARS_b$ is reported to have no relationship with chlorophyll b.

The algorithms for chlorophyll a and b are defined as follows:

$$RARS_a = \frac{\rho_{675}}{\rho_{700}} \text{ and}$$

$$RARS_b = \frac{\rho_{675}}{\rho_{650}} \cdot \rho_{700}$$

Blackburn developed the *pigment specific simple ratio* (PSSR) *algorithm.* A power model best describes the relationship of PSSR and chlorophyll a and b concentration. $PSSR_a$ and $PSSR_b$ are defined as follows [2]:

$$PSSR_a = \frac{\rho_{800}}{\rho_{680}} \text{ and}$$

$$PSSR_b = \frac{\rho_{800}}{\rho_{635}}$$

3 RESULTS AND CONCLUSIONS

3.1 LAI

The concept of estimating LAI from WDVI was developed for green vegetation [5], [6]. It is most suitable for the vegetative phase and the *booting* and *inflorescence emergence* phases of the reproductive phase. Subsequently, LAI and photosynthetic activity decrease [7].

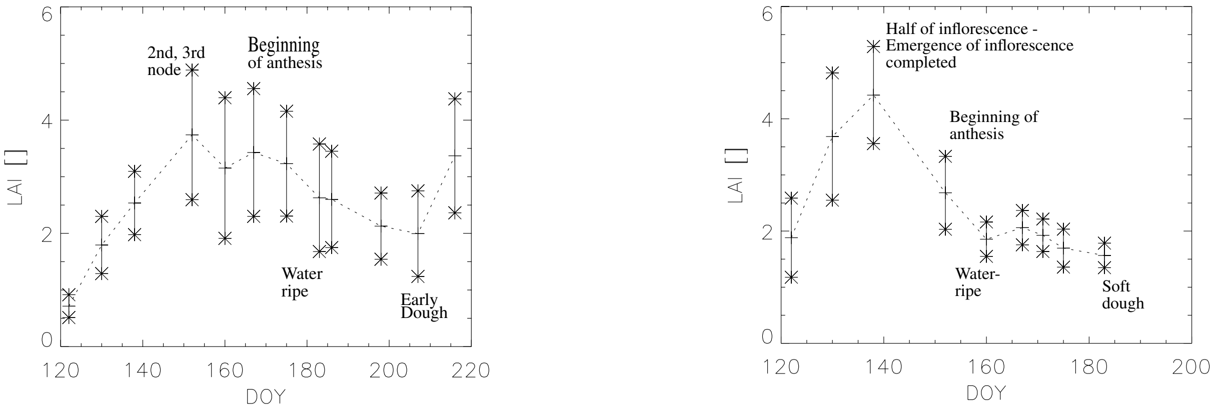

Figure 1: Measured LAI values of summer wheat (left) and winter barley (right) over a vegetation period, representing mean values and one standard deviation.

Therefore, LAI estimates of the vegetative stage were treated separately from estimates of the generative stage (starting at *beginning of anthesis*). The relationship between WDVI and LAI can be described by the inverse of an exponential function both for summer wheat and winter barley. The data consists of measurements of dense, medium and low crop stands up to *beginning of anthesis*. Because the curves of the data fit for summer wheat and winter barley look almost similar, the two data sets can be combined. The relative root mean square for the combined dataset is 22%.

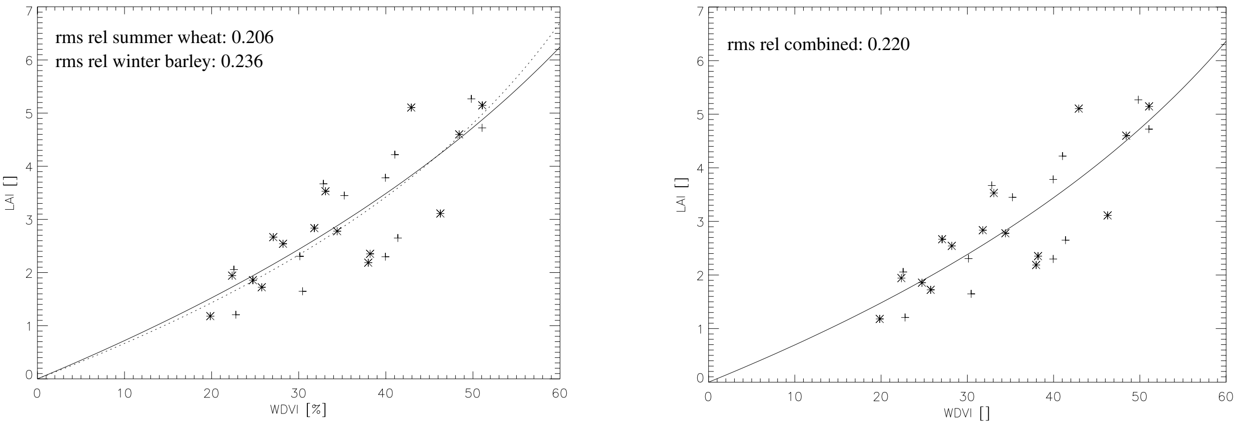

Figure 2: Left: Fitted relationship between WDVI and LAI for summer wheat (solid line) and winter barley (dotted line). The crosses denote WDVI values and measured LAI for summer wheat, the asterisks WDVI values and measured LAI for winter barley. Right: combined data sets of summer wheat (crosses) and winter barley (asterisks).

During senescence, reflectance in the visible part of the spectrum increases, whereas the infrared reflectance decreases. This situation is comparable with an increasing contribution from bare soil [7]. The parameter set of the fitted curve for LAI estimates of the reproductive and senescing phase (rms rel. for summer wheat:

18.4%) differed from the one of the growing phase. Therefore, vegetative and generative stages were treated separately.

A sensitivity analysis involving measured and estimated LAI values for summer wheat and winter barley was performed. The error to be expected in estimated LAI, the minimum detectable LAI changes and the number of detectable LAI changes over time was investigated, based on the assumptions of the WDVI concept for estimating LAI [5], [6], [7] and the collected data sets.

Table 1. Sensitivity analysis for estimating LAI from WDVI for the vegetative phase up to *beginning of anthesis*

crop	**LAI min**	**LAI max**	**LAI max-min**	**RMS abs**	**Sensitivity** $(LAI_{max}-LAI_{min})/RMS_{abs}$	**RMS rel**
summer wheat	1.723	5.146	3.423	**0.647**	**5.290**	**0.206**
winter barley	1.207	5.268	4.061	**0.669**	**6.070**	**0.236**
summer wheat and winter barley	1.207	5.268	4.061	**0.658**	**6.172**	**0.220**

As Table 1 shows, expected errors in estimating LAI from WDVI lie around 20%. The *absolute root mean square error* denotes a minimal detectable change in LAI which is not caused by inadequate model assumptions, technical reasons of the instruments used or the measurement plan. *Sensitivity* is the amount of contrast detectable in the observed period. Five to six classes of LAI can be detected. To track LAI development of summer wheat from the *3 leaves unfolded stage* (DOY 122) until *beginning of anthesis* (DOY 167) LAI measurements should be made every 8 to 10 days. To track LAI of winter barley from *stem erection* (DOY 122) to *beginning of anthesis* (DOY 152), measurements should be carried out every 4 to 5 days!

3.2 FAPAR

Estimation of FAPAR is based on an exponential relationship with LAI. In this work, LAI was both estimated from WDVI and from SAVI.

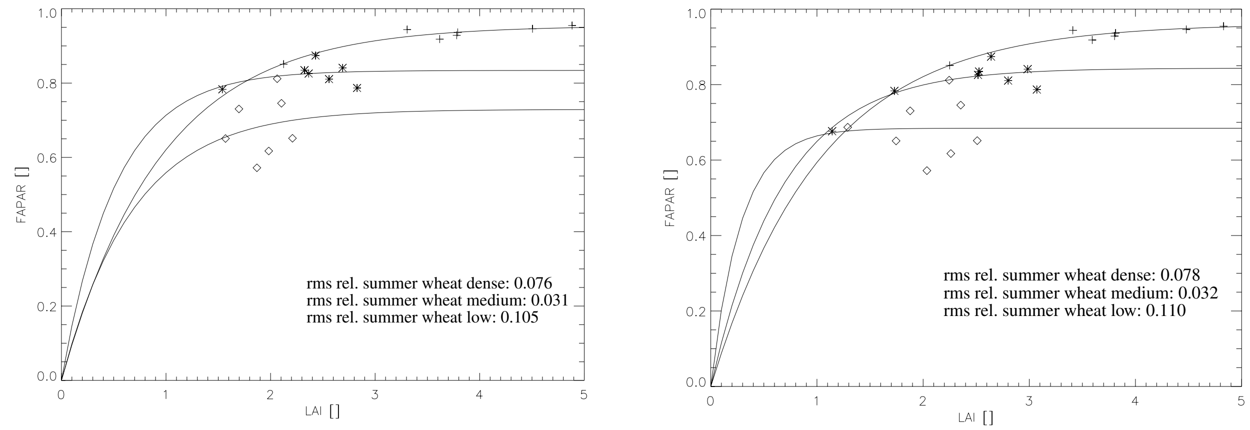

Figure 3: Estimating FAPAR of summer wheat from LAI using an exponential relationship. Left: LAI estimation based on WDVI, right: LAI estimation based on SAVI. Crosses are LAI values and measured FAPAR values for a dense canopy, asterisks denote a medium canopy and squares a low density canopy.

FAPAR measurements in the field were taken for both summer wheat and winter barley during the vegetative, reproductive and senescing phase. Figure 3 shows a limited variation of FAPAR values, especially for medium and low density canopies. The best fit is perfomed for dense crop stands. The exponential relationship described in the literature [1] is not visible for medium and low density canopies. A joint data set of all density classes of summer wheat results in a relative root mean square error of 11.5% for FAPAR estimation from LAI based on WDVI.

3.3 Water content

Water content of summer wheat and winter barley was determined for plant-, leaf- and grain-samples. Whereas plant- and grain-water content decrease steadily towards the end of the senescing phase, leaf-water content decreases abruptly from the *water ripe* stage.

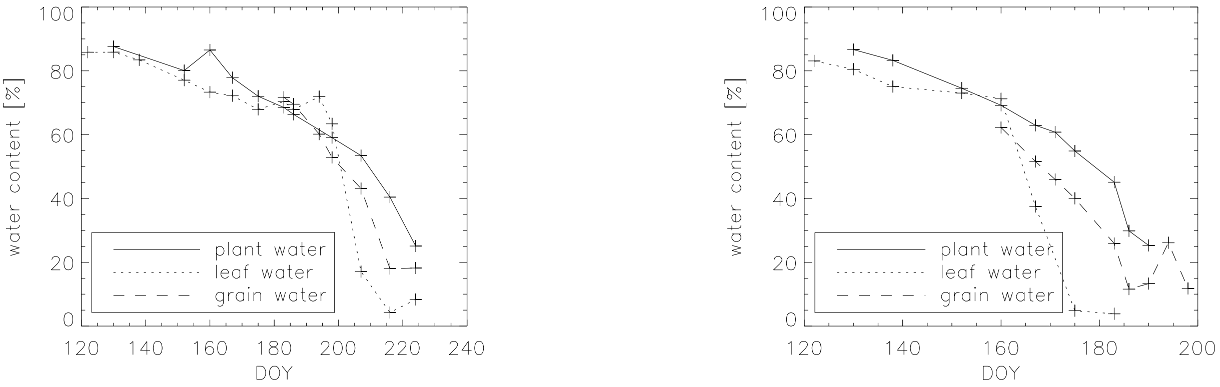

Figure 4: Plant-, leaf- and grain-water content of summer wheat (left) and winter barley (right). Leaf-water content decreases abruptly from the *water ripe* stage. Rain strongly affects the grain-water content during maturity.

Since the decrease of corn-water content is related to the decrease of plant-water content, the extraction of plant-water content from spectroradiometric data is investigated. Furthermore, spectroradiometric measurements of a crop canopy describe a whole plant, not single leaves.

First, multiple linear regression of all available spectral bands of the ASD-spectroradiometer and the position of the inflexion point (independent variables) and measured plant-water content (dependent variable) was performed, resulting in a multiple correlation coefficient R_{mul} for all wavelength bands available. Second, five wavelength bands having highest values for R_{mul} were selected and, together with the inflexion point wavelength again entered into the linear multiple correlation model.

As Figure 5 (left) shows, the wavelength bands around the inflexion point are highly correlated to plant-water content. Mean deviations between measured and modelled plant-water content are 3.1%, with highest deviations around 10% (Figure 5, right).

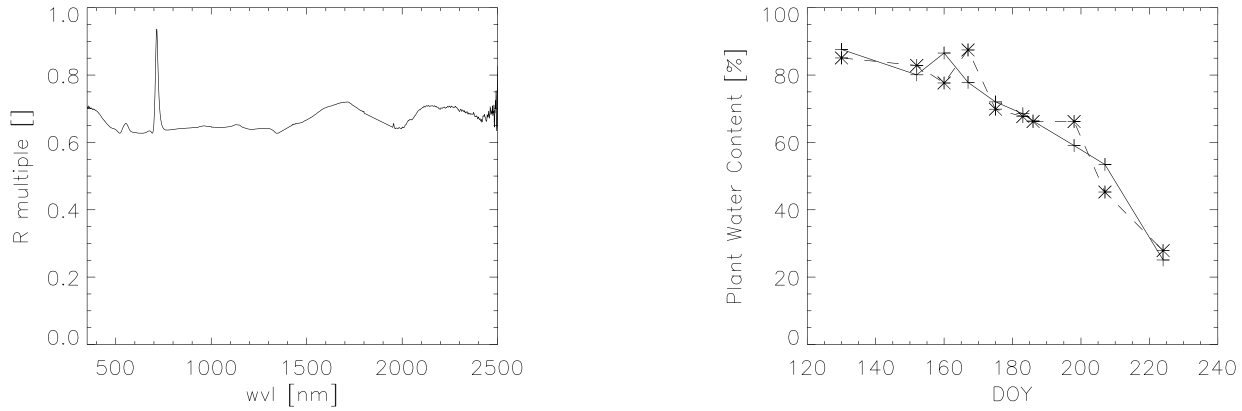

Figure 5: Left: Multiple linear correlation coefficient R_{mul} for all available spectral bands, the position of the inflexion point (independent variables) and measured plant-water content (dependent variable). Right: Measured (solid line) and modelled (dashed line) plant-water content for summer wheat using multiple linear regression of five highly correlated wavebands and the position of the inflexion point.

3.4 Chlorophyll

The *ratio analysis of reflectance spectra* (RARS) *algorithm* [4] was developed on plants that were allowed to grow a certain time after germination. Unlike the investigated crop stands, these plants do not represent different growth stages. The *pigment specific simple ratio* (PSSR) *algorithm* [2] was made for chlorophyll estimation throughout a growing season.

As Figure 6 shows, both RARS and PSSR have a strong variation in the relationship between reflectance ratio and chlorophyll a and b content per unit area. Both algorithms show a turning point which, for summer wheat, is reached at the stage *flag leaf sheath opening / half of inflorescence emerged* (DOY 160). Nevertheless, the strong relationships between the reflectance ratioes and chlorophyll concentrations using a power model as described in the literature could not be found for this data set. PSSR follows a relationship that could be described by a power model at least from the stage *anthesis complete* towards maturity. It is obvious that the two algorithms are not able to track chlorophyll of plants undergoing such fundamental physiological changes as crop stands do.

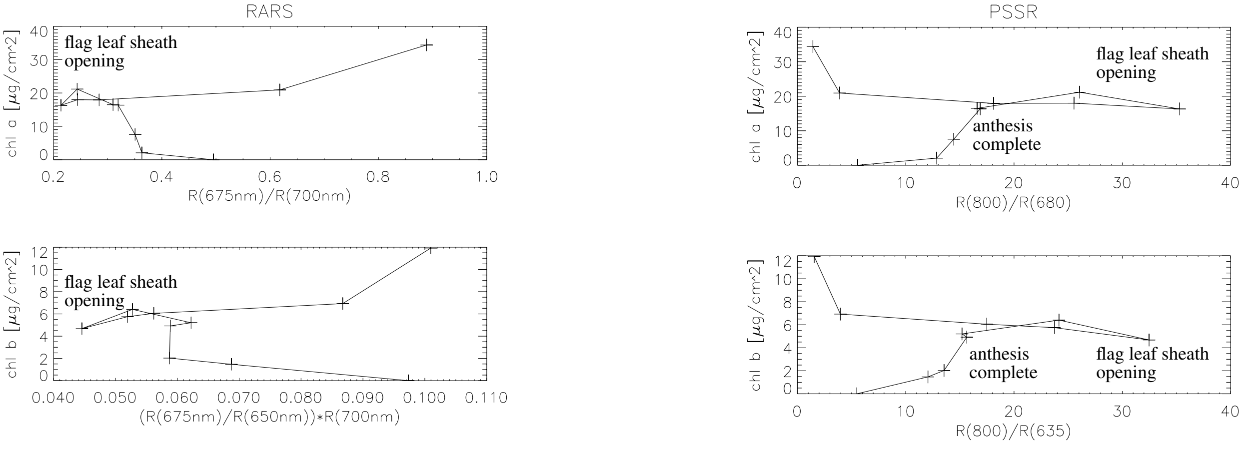

Figure 6: *Ratio analysis of reflectance spectra* (RARS) *algorithm* (left) and *pigment specific simple ratio* (PSSR) *algorithm* (right) for a dense summer wheat canopy both show a strong variation in the relationship between reflectance ratio and chlorophyll a and b content per unit area.

As far as the suitability of the parameters LAI, FAPAR, water content and chlorophyll content is concerned to describe the growth stages, it can be said, that LAI, water content and chlorophyll content have highest variations over the growing season. FAPAR measurements exhibit lowest variations although they represent all three main growing phases. The applied techniques allow retrieval of LAI, FAPAR and plant-water content within the specified accuracies. Chlorophyll a and b retrieval from the RARS and PSSR algorithms could not be parameterized because the parametric models proposed can not handle the plants physiological changes during a vegetation period.

To describe growth stages of crops towards the end of the growing season for monitoring maturity, retrieval of plant-water content (and related to it grain-water content) seems most predictible, since ripe plants have no green leaves anymore and therefore can not absorb any solar radiation for photosynthesis.

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