EVALUATION OF DIFFERENT SENSING APPROACHES CONCERNING TO NONDESTRUCTIVE ESTIMATION OF LEAF AREA INDEX (LAI) FOR WINTER WHEAT

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Abstract- Different approaches of non-destructive estimation of the LAI in winter wheat were compared. Plant height had weak relation with the LAI, while estimated biomass showed high logarithmic relationship (R^2=0.839). NDRE and REIP were logarithmically well related to the LAI (R^2=0.726 and 0.779 respectively). Saturation effect of NDRE and REIP was less than NDVI. Some RGB-based indices also showed good potential to estimate the LAI. Among the indices, Gm, GMB, RMB, and NRMB were better related to the LAI. The results indicated that digital cameras can be used as an affordable and simple approach for assessment of the LAI of crops.

Index terms: Leaf area index (LAI), plant height, vegetation indices, digital camera, precision agriculture

I.   INTRODUCTION

The concept of leaf area index (LAI) was first introduced by [1] and defined as the ratio of leaf area to a given unit of land area. The LAI is an important variable for analyzing the interactions between plants and atmosphere, for estimating the amount of radiation intercepted by vegetation and plant water requirements, for studying the relationships between plants and environmental pollutants, and for evaluating the photosynthetic activity (CO_2 sequestration) [2]. It can be related to several crop properties such as number of plants, plant height, and biomass [3]. Consequently, it can help to optimize crop management [4-7]. The LAI has also been shown to be useful in precision agriculture, which considers the within-field variability of soils and crops [8-10]. In the framework of precision agriculture, the LAI can be helpful for site-specific adaption of the application rates of N fertilizers, growth regulators, and fungicides [11, 12].

There are two methods of measuring the LAI, direct and indirect. The direct measurements are all based on laboratory methods. They are consist of collection of the leaves and subsequent measurements of their area by using dedicated instruments (e.g., Li-3100 C; Li-Cor, Lincoln, NE, USA) or by acquiring and processing leaf images [13, 14]. The direct methods based on crop harvest provide precise LAI measurements but are destructive, labor and time consuming, and cover only limited areas. Therefore, different indirect methods have been developed, most of them based on the measurement of light transmission through canopies [13, 14]. These methods apply the Beer–Lambert law taking into account the fact that the total amount of radiation intercepted by a canopy layer depends on incident irradiance, canopy structure and optical properties [15].

In recent years, various instruments have been developed to measure either gap fraction or gap size distribution in order to indirectly assess the LAI of plant canopies. Measuring gap fraction, some instruments permit calculating manually, some incorporate canopy image analysis techniques (Digital Plant Canopy Imager (CI-110), and Multiband Vegetation Imager (MVI)), while others such as the AccuPAR (Decagon, Pullman, WA, USA), the DEMON (CSIRO, Canberra, Australia), and the LAI-2000 or LAI-2200 Plant Canopy Analyzers (Li-Cor, Lincoln, NE, USA), calculate LAI by comparing differential light measurements above and below canopy. To study the gap size distribution, the Tracing Radiation and Architecture of Canopies (TRAC) instrument (3rd Wave Engineering, Ontario, Canada) and hemispherical photography can be

used. As demonstrated by different studies, these instruments are very efficient and reliable, where it concerns the measurement of LAI in forest environments [14]. The performance of the indirect instruments for quantifying the LAI of crops proved that they could be good alternatives to destructive methods. However, typical LAI meters have to be operated manually in a stop-and-go mode. Therefore, they are still time-consuming approaches and are not suitable for on-the-go measurements. Another disadvantage of these instruments is that they are expensive.

Considering the limitations of the typical LAI meters mentioned above, some efforts have been made to find alternative methods. Air- or space-borne and ground-based remote sensing have been used for LAI determination [16-19]. Large areas can be covered quickly by images from satellites and aircrafts. However, air- or space-borne remote sensing is affected by weather conditions and may be unable to provide timely information to perform research and crop management tasks [20]. Moreover, the reflectance based indices are only suitable for estimating the LAI of the crop until canopy closure or until the crop has a LAI of 3 or more. With increasing the LAI, the indices become saturated [17].

Some other approaches have also been employed to estimate the LAI, including, ultrasonic sensors [17], a mechanical sensor (the CROP-Meter) [21], digital photography [22], mobile laser scanners [12, 23], smartphone [2].

To estimate crop parameters in precision agriculture, sensing approaches need to be robust and cost-efficient, and it must deliver data in real time. Real-time availability of LAI data is essential because crop protection and N fertilization are time-critical measures in agriculture [12]. In recent years, ground-based sensors have been developed to meet these requirements. Examples are Yara N-Sensor (Yara-GmbH & Co. KG, Germany), GreenSeeker (NTech Industries Inc., USA), MiniVeg N Lasersystem and Isaria (Fritzmeier Umwelttechnik GmbH & Co. KG, Germany), Crop-Circle (Holland Scientific, Inc., NE, USA), and Crop-Meter (agrocom, Muller-Elektronik, Germany) [24]. Digital image processing as a low cost approach has also showed a good potential to determine crop parameters [22, 25]. From such sensor systems not sufficient information are available for an objective comparative assessment in the case of LAI determination. Therefore, the objective of the current study was to compare performance of different crop sensors to assess the LAI of winter wheat. In addition, the potential of vegetation indices derived from digital image processing for this purpose was investigated.

II.   EXPERIMENTAL DESIGN

During the 2012 growing season, a field experiment was conducted at the Bundessortenamt (German Plant Variety Office) Marquardt experimental station which is located in the village of Marquardt about 5 km northwest of Potsdam, Germany (52°27' N, 12°57' E). The soil at the experimental field was a sandy cambisol formed on glacial and post-glacial sediments of the last ice age (approximately 10,000 years ago). Winter wheat (Triticum aestivum L., cv. Cubus) was sown at 380 kernels per square meter with row spacing of 0.14 m. To have different densities of the crop in the trial to have different LAI, an experiment was designed as a randomized split block design with two replications. Treatments consisted of four N fertilization rates (0, 60, 120 and 240 kg N ha^{-1}, in total) and two water regimes (irrigated (Irr) and non-irrigated (NIrr)) in total of 16 plots with dimension of 4.5×9.0 m. Each 16 plots included 18 subplots of 1.25×1.5 m as pseudoreplications (Figure 1). The nitrogen fertilizer application was done at five different dates (Table 1). During the growing season (since sowing until harvesting time), the non-irrigated plots received 272 mm of precipitation, while the irrigated plots received an additional 20 mm of irrigation on two dates (18 April and 29 May).
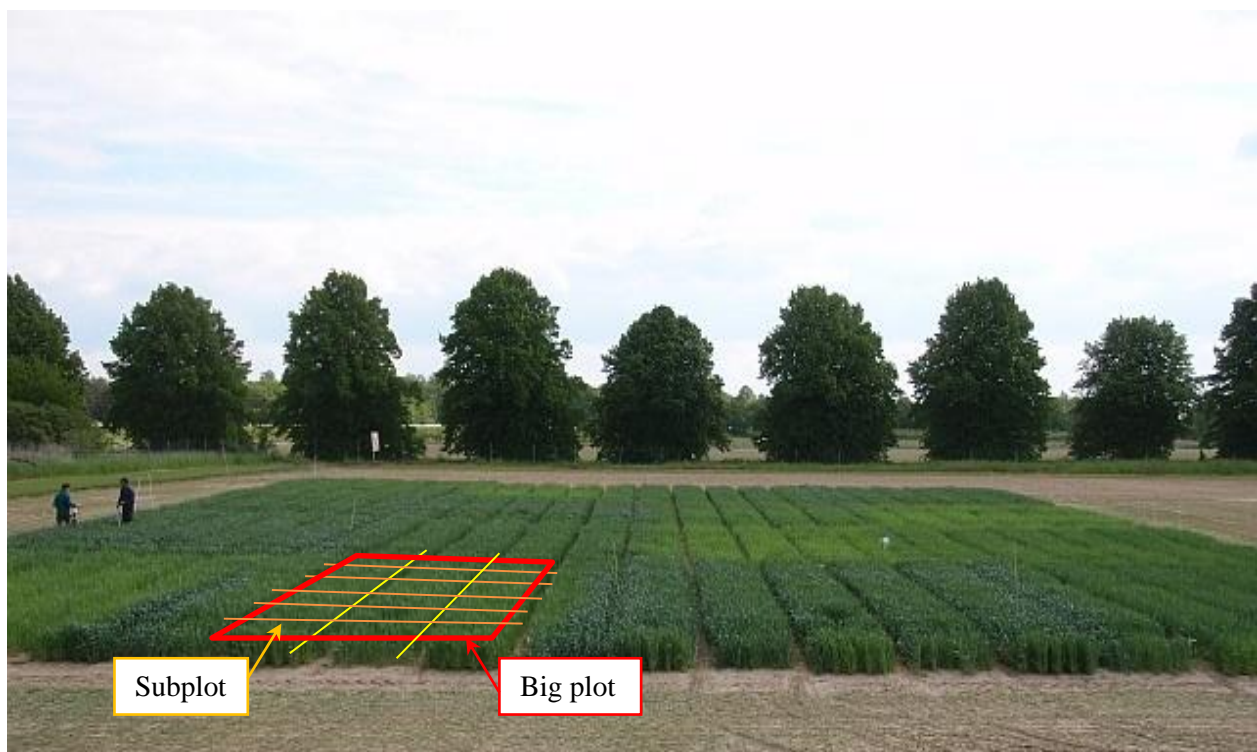

Figure 1. The experimental plots of winter wheat

Table 1: Dates, crop developmental stages, and farming activities of this study (the activities indicated by '×').

Date	DAS[a]	WOY[b]	BBCH[c]	Irrigation	N fertilization	Image acquisition	Height & LAI measurement	Spectral measurement	Biomass sampling	Notes
04.10.2011	0	40								Sowing
13.10.2011	9	41	1							Emergence
13.03.2012	161	11	19		×					First rate[d]
03.04.2012	182	14	29		×					Second rate
17.04.2012	196	16	32		×					Third rate
18.04.2012	197	16	32	×						
25.04.2012	204	17	34			×				
27.04.2012	206	17	35				×	×		
02.05.2012	211	18	36			×	×(only Height)	×		
04.05.2012	213	18	36				×(only LAI)			
08.05.2012	217	19	39-41		×					Fourth rate
09.05.2012	218	19	39-41				×	×		
10.05.2012	219	19	39-41						×	
11.05.2012	220	19	39-41			×				
15.05.2012	224	20	43				×	×		
16.05.2012	225	20	43			×				
21.05.2012	230	21	56-58				×			
22.05.2012	231	21	56-58					×		
24.05.2012	233	21	56-58			×				
25.05.2012	234	21	56-58						×	
29.05.2012	238	22	65-69	×			×(only Height)	×		
30.05.2012	239	22	65-69		×		×(only LAI)			Fifth rate
31.05.2012	240	22	65-69			×				
05.06.2012	245	23	71			×				
07.06.2012	247	23	71				×	×		
08.06.2012	248	23	71						×	
12.06.2012	252	24	73				×	×		
15.06.2012	255	24	73			×				
26.07.2012	296	30	99							Harvest

[a]DAS: days after sowing.
[b]BBCH: a scale used to identify the phonological development stages of the plant [26].
[c]WOY: week of the year.
[d]First rate of N fertilizater: 0, 20, 30, 50 kg ha^{-1}; Second rate: 0, 0, 0, 60 kg ha^{-1}; Third rate: 0, 20, 60, 0 kg ha^{-1}; Fourth rate: 0, 0, 0, 60 kg ha^{-1}; and Fifth rate: 0, 20, 30, 70 kg ha^{-1}, for total fertilizer rates of 0, 60, 120 and 240 kg N ha^{-1}, respectively.

III.   DATA COLLECTION AND PRE-PROCESSING

The dates, the plant growth stages and the activities in this research are presented in Table 1. As

shown, all the experiments were conducted during the growing season in different plant growth stages including: stem elongation (weeks 16, 17, 18, and 19 of the year; BBCH=32-41), booting stage (week 20 of the year; BBCH=43), Inflorescence emergence, heading (week 21 of the year; BBCH=56-58), flowering (week 22 of the year; BBCH=65-69), and development of fruit (weeks 23 and 24 of the year; BBCH=71).

a. Soil parameters

Soil moisture was measured using TDR soil moisture probes (ECH$_2$O, Decagon Devices, Inc., Pullman, WA, USA). The sensors were positioned at a depth of 15 cm in irrigated and non-irrigated soils with and without vegetation. The TDR probes measure the dielectric constant of the soil in order to find its volumetric water content.

b. Destructive crop parameters

Fresh and dry biomasses, and plant N content were measured during the growing season. Crop yield and final biomass were also recorded at the harvesting time. Aboveground biomass sampling was performed three times (Table 1). For each time, area of 1 square meter from each of 16 plots was manually cut using grass shears. The fresh biomass was put into plastic bags, immediately weighed, and then oven dried at 75 ℃ for 24 h. The shoot fresh biomass (FB) and the shoot dry biomass (DB) (g m^{-2}) were recorded. The plant samples were chopped and the N content (% dry weight) was measured by the standard Kjeldahl method in laboratory.

c. LAI measurements

The reference LAI was obtained by a SunScan SS1 LAI meter (Delta-T Devices Ltd, Cambridge, UK) (Figure 2). The LAI measurements were replicated two times per each subplot. Then, the measurements of 6 subplots of each column (12 measurements) were averaged (Figure 1). The SunScan meter consists of the 1-m long SunScan probe with 64 photodiodes for the below canopy radiation in the wavelength range 400–700 nm and a beam fraction sensor for the above canopy radiation. The above and below canopy measurements were performed simultaneously.

The LAI was calculated by the data collection terminal connecting the SunScan probe and the beam fraction sensor using a numerical canopy analysis equation by Wood [27].
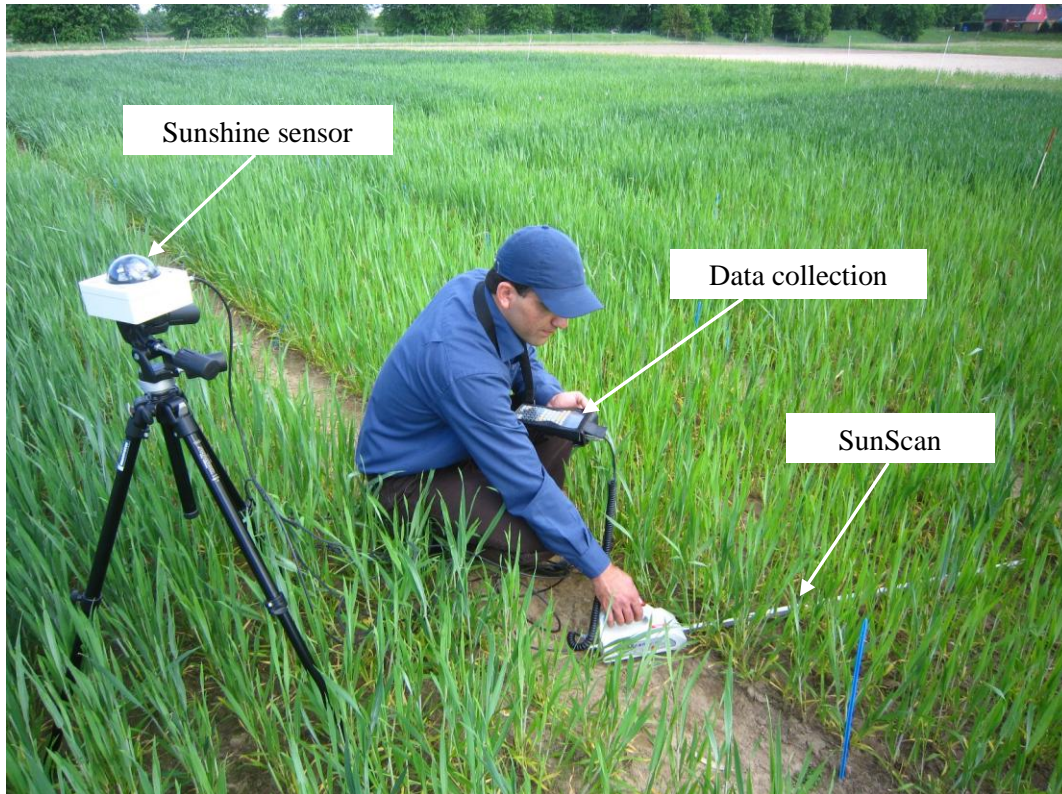

Figure 2. Indirect measurement of the leaf area index (LAI) with the SunScan SS1 (Delta-T Devices, Cambridge, UK) equipment.

c. Crop height

A plate meter was also used for direct measurement of the plant height. The device consists of a rectangular plastic sheet of 100×70 cm dimensions which a scaled wood rod crosses through its middle. The sheet can slide over the rod. As the meter is placed over a canopy, the canopy is compressed until it will support the plate's weight and the rod passes through the plant to the ground. The distance from the point where the rod contacts the ground and the plate is the plate height or average plant height. The average plant height of each subplot was measured with the described procedure.

d. Vegetation indices from spectral spot measurements

To obtain vegetation indices used in commercial crop sensors a spectroradiometer made of tec5 components, was employed (tec5 AG, Oberursel, Germany) (Figure 3). The main parts were two "Zeiss MMS1 nir enh" diode-array sensors with a nominal range of 300 to 1150 nm at < 10 nm resolution and an effective range of 400 to 1000 nm (Carl Zeiss MicroImaging GmbH, Jena, Germany). A tec5 LOE-2 USB CT electronics and SDACQ32MP dynamic linkage library provided the interface to a mobile computer on which a self-developed software was ran. One fiber optics was pointing to the ground while the other, pointing to the sky, collected global radiation. By this arrangement it is possible to compensate for fluctuations in illuminations conditions, e.g., due to clouds. At the beginning of each campaign the sensor was ran for at least 10 min (warm-up phase) before collecting spectra from a white reference plate. These spectra were then used for calculating the reflectance (R) as the ratio the light reflected from the ground (canopy and soil) the white reference. Measurements were repeated 10 times on each sub-plot. Based on the full spectra form the visible and near-infrared proportion of the light, common vegetation indices used in commercial optical crop sensing systems were calculated [28]. These vegetation indices and the respective crop sensors are listed in Table 2.

Figure 3. The spectroradiometer used for spectral spot measurements

Table 2: Spectroradiometer based vegetation indices [28]

Abbreviation	Full name	Calculation	Commercial crop sensor
NDVI	Normalized difference vegetation index	$(R_{780} - R_{670})/(R_{780} + R_{670})^*$	GreenSeeker (Trimble, Boulder, CO, USA)
REIP	Red edge inflection point	$700 + 40*(0.5*(R_{670} + R_{780}) - R_{700})/(R_{740} - R_{700})$	Isaria (Fritzmeier Umwelt-technik GmbH & Co. KG, Germany)
NDRE	Normalized difference red edge index	$(R_{780} - R_{720})/(R_{780} + R_{720})$	N-Sensor (YARA GmbH & Co. KG, Germany), Crop Circle (Holland Scientific, Inc., NE, USA)
$^*R_{xxx}$: Reflectance at xxx nm			

e. Vegetation indices from digital image analysis

Digital images of winter wheat canopy were acquired by a Canon camera model EOS 550D with resolution of 18.0 megapixels. Medium resolution of the camera was used. The resulting images

had a size of 3456 × 2304 pixels at Program AE shooting mode of the camera. The camera was set to automatically adjust f-stop and shutter speed. Focus was set manually. The colour images were recorded in JPEG format and downloaded to a desktop computer for subsequent processing. The images were taken looking vertically downward from a height of 1.8 m, which resulted in a rectangular area of 1.5 × 1.0 m on the ground. The photos were recorded for each subplot at different dates (Table 1). A setup was built to install the camera on it for keeping constant height for all the subplots and dates as well as capturing photo from the same area at each date.

Image processing for extraction of crop coverage and RGB-based vegetation indices from the digital images was performed using MATLAB software (Version 7.13, R2011b, Mathworks Company). The digital camera recorded visible images with red, green, and blue channels. Each channel is 8-bit (256 levels of intensity). Leaf reflectance is greater in the green than in the red parts of the spectrum [29]. Therefore, for segmentation of the green plant against background, a by a mask (M) (binary image) was derived from the difference between green (G) and the red (R) band of each image together with the threshold t:

$$M = \begin{cases} 1 & for \quad (G-R) \geq t \\ 0 & for \quad (G-R) < t \end{cases} \tag{1}$$

Crop coverage (CC) was defined as the proportion of plant pixels in an image:

$$CC = \frac{\sum M}{n \cdot m} \tag{2}$$

where n and m are number of rows and columns of pixels.

Various RGB-based vegetation indices were obtained from plant part of the images defined by the mask M:

$$Rm = R*M \tag{3}$$

$$Gm = G*M \tag{4}$$

$$Bm = B*M \tag{5}$$

$$GMR = Gm - Rm \tag{6}$$

$$GMB = Gm - Bm \tag{7}$$

$$RMB = Rm - Bm \tag{8}$$

$$NGMR = (Gm - Rm)/(Gm + Rm) \tag{9}$$

$$NGMB = (Gm - Bm)/(Gm + Bm) \tag{10}$$

$$NRMB = (Rm - Bm)/(Rm + Bm) \tag{11}$$

where R, G and B are the intensity levels of the red, green and blue channels, respectively. The values were then averaged for each image.

An estimated plant biomass index (EB) was calculated by multiplying the crop coverage (CC) derived from the digital image analysis and the plant height (H) measured by the plate meter:

$$EB = CC*H \tag{12}$$

IV.   STATISTICAL ANALYSES

The data obtained from the measurements and the image processing were analyzed using analysis of variance (ANOVA) and the means were compared at 5% level of significance using the Tukey range test in SAS software (version 9.3, SAS Institute, Inc., Cary, N.C.). Regression and correlation analysis were done using MATLAB software (Version 7.13, R2011b, Mathworks Company).

V.   RESULT AND DISCUSSION

Based on the statistical analysis results, there were strong significant differences among the N supply levels and between the irrigation regimes in the case of crop yield and final straw of the crop ($P<0.01$). For all three times of biomass sampling, the differences of N supply levels for fresh and dry biomasses and also plant N content were highly significant ($P<0.01$). However, the differences of irrigation regimes for the crop properties were mostly insignificant ($P>0.05$).

Analysis of variance (ANOVA) results showed that the effect of N supply on LAI was significant ($P<0.01$) for all the growth stages considered, while the effect of water supply was significant ($P<0.05$) for all the stages except the stage development of fruit (week 23 of the year).

The results confirm that the experimental design was working well and the results obtained from indirect measurements are presented below.
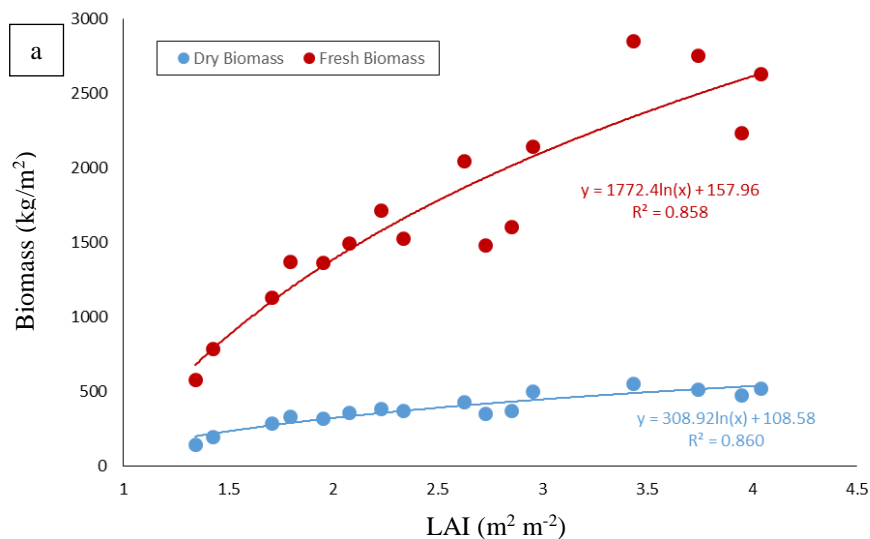
a. Relationships between LAI and destructive measurements of plant parameters

Spearman's rank correlation coefficients were calculated for relationships between the destructive measurements of plant parameters (fresh and dry biomasses, and plant N content) and the LAI. The results are summarized in Table 3. As seen, there were high correlations between the LAI and the parameters for all three times of biomass sampling. The *rho* values for the relationships ranged from 0.753 to 0.953. The highest values were between the LAI and the plant biomasses. Therefore, regression models used to relate LAI and the plant biomasses. There were a logarithmic relationship between them as presented in Figure 4.

Table 3: Spearman's rho for correlation between the destructive measurements of winter wheat properties and the LAI in different dates of biomass sampling

Variable	10.05.2012			25.05.2012			08.06.2012		
	N content (%)	FB (g m^{-2})	DB (g m^{-2})	N content (%)	FB (g m^{-2})	DB (g m^{-2})	N content (%)	FB (g m^{-2})	DB (g m^{-2})
N content	1	0.915**	0.897**	1	0.594*	0.591*	–	–	–
FB	0.915**	1	0.994**	0.594*	1	0.979**	–	1	0.994**
DB	0.897**	0.994**	1	0.591*	0.979**	1	–	0.996**	1
LAI	0.824**	0.921**	0.918**	0.753**	0.909**	0.874**	–	0.953**	0.932**

*. Correlation is significant at the 0.05 level
**. Correlation is significant at the 0.01 level
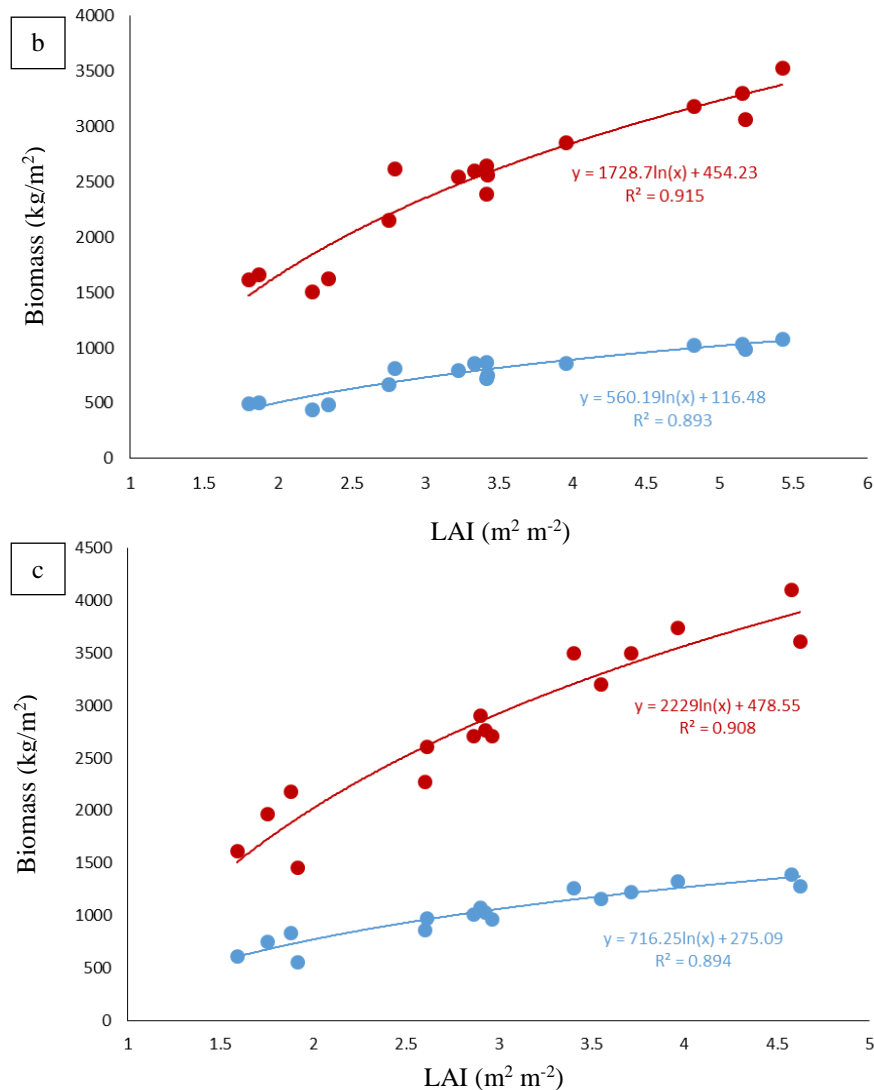The data for the blank cells is not available

Figure 4. Relationships between the destructive dry and fresh biomasses measurements and the LAI for a) first sampling, b) second sampling, and c) third sampling

b. Plant height and estimated biomass

Based on regression analysis results, plant height had weak relation with the LAI for all the growth stages considered.

The biomass of the crop was estimated by multiplying the height and the crop coverage derived from the digital image analysis. The estimated biomass (EB) showed a strong logarithmic relation with the LAI (Table 4 and Figure 5a). The R^2 value for the relation between the EB and the LAI

considering whole the growing season was 0.839 (Table 4). The logarithmic relations between the EB and the LAI for each of the growth stages of winter wheat are presented in Figure 5a. As observed, the EB was highly related with the LAI for each of the growth stages with R^2 in the range of 0.863 to 0.954. In the weeks 20, 21 and 24 the strongest relations were observed; but the EB showed a little saturation for the higher values of the LAI in the stages. The saturation effect was much less in the last stages of the plant growth (week 22, 23 and 24: flowering and development of fruit stages).

Very limited researches for estimation of the LAI using plant height were found in the literature. Scotford and Miller [17] conducted a 2-year (2001/2002 and 2002/2003 growing seasons) study in which tractor-mounted radiometer and ultrasonic sensing systems were evaluated to determine if the combined arrangement could be used to estimate tiller numbers (tillers m^{-2}) and the leaf area index (LAI) of winter wheat. Using a relationship identified in the 2001/2002 growing season for estimating tillers numbers, and a crop height estimate from the ultrasonic sensors, they derived a compound vegetation index (CVI):

$$CVI = \frac{\text{number of tillers}\,(m^{-2})}{600} \times \frac{\text{crop height}\,(m)}{1.0} \tag{13}$$

which could be used to estimate the leaf area index, in the 2002/2003 growing season, to an accuracy of ± 0.47 when compared to leaf area index measurements obtained using a commercially available light interception instrument.

Dammer, et al. [21] used the following simple model for estimating the LAI of cereal crops:

$$LAI = \frac{\text{crop height}\,(m) \times \text{number of tillers}\,(m^{-2})}{100} \tag{14}$$

They compared the estimated LAI with the measured LAI for the four growth stage classes shooting, ear emergence, flowering and ripeness. The values of Pearson's correlation coefficient r ranged from 0.64 to 0.91. The best estimation was achieved in growth stage class 2 during ear emergence (r = 0.91), followed by growth stage class 3 flowering (r = 0.80), growth stage class 1 shooting (r = 0.71) and growth stage class 4 ripeness (r = 0.64).

Table 4: Selected regression models for the LAI and the indices using the data of whole the growing season

Variable	Regression model[*]	R^2	RMSE
EB	y = 26.88ln(x) + 1.67	0.839	4.626
NDVI	y = 0.13ln(x) + 0.69	0.327	0.072
NDRE	y = 0.15ln(x) + 0.08	0.726	0.035
REIP	y = 8.37ln(x) + 715.08	0.779	1.749
CC	y = 0.23ln(x) + 0.45	0.546	0.082
Gm	y = -23.7ln(x) + 171.26	0.473	9.823
GMB	y = -34.46ln(x) + 76.77	0.677	9.341
RMB	y = -25.63ln(x) + 51.65	0.619	7.893
NRMB	y = -0.15ln(x) + 0.26	0.582	0.049
[*]y: the variable; x: LAI.			

c. Vegetation indices calculated from the Spectroradiometer readings

Regression analysis results for vegetation indices NDVI, NDRE, and REIP are presented in Table 4 and Figure 5b, c and d. NDRE and REIP had strong logarithmic relations with LAI, while the relation between NDVI and LAI was not so strong. The R^2 values for the relations of NDVI, NDRE and REIP with LAI, considering whole the growing season were 0.327, 0.726, and 0.779, respectively (Table 4). In addition, there were strong logarithmic relations between the vegetation indices and the LAI for each of the stages of the plant growth; the R^2 for the relations were in the range of 0.760 to 0.858, 0.853 to 0.942, and 0.839 to 0.938, for the relation of the NDVI, NDRE, and REIP with the LAI, respectively (Figure 5b, c and d).

As observed in Figure 5b, the NDVI values tended to be saturated when the LAI values increased. Conforming results for saturation of NDVI with increasing plant biomass were reported by many researchers such as: for wheat [30] and for maize [31]. They concluded that visible- and red light-based indices, such as the NDVI, tended to be saturated with increasing crop stand density due to a decreased sensitivity of the spectral signal. Therefore, the red edge inflection point (REIP) and several NIR/NIR indices have been proven to offer more reliable signals in high biomass-producing areas like Europe [32, 33].

The results obtained in the current study confirm their conclusion. As shown in Figure 5c and d, the NDRE and REIP had less saturation effect; they also were better related to the LAI than the
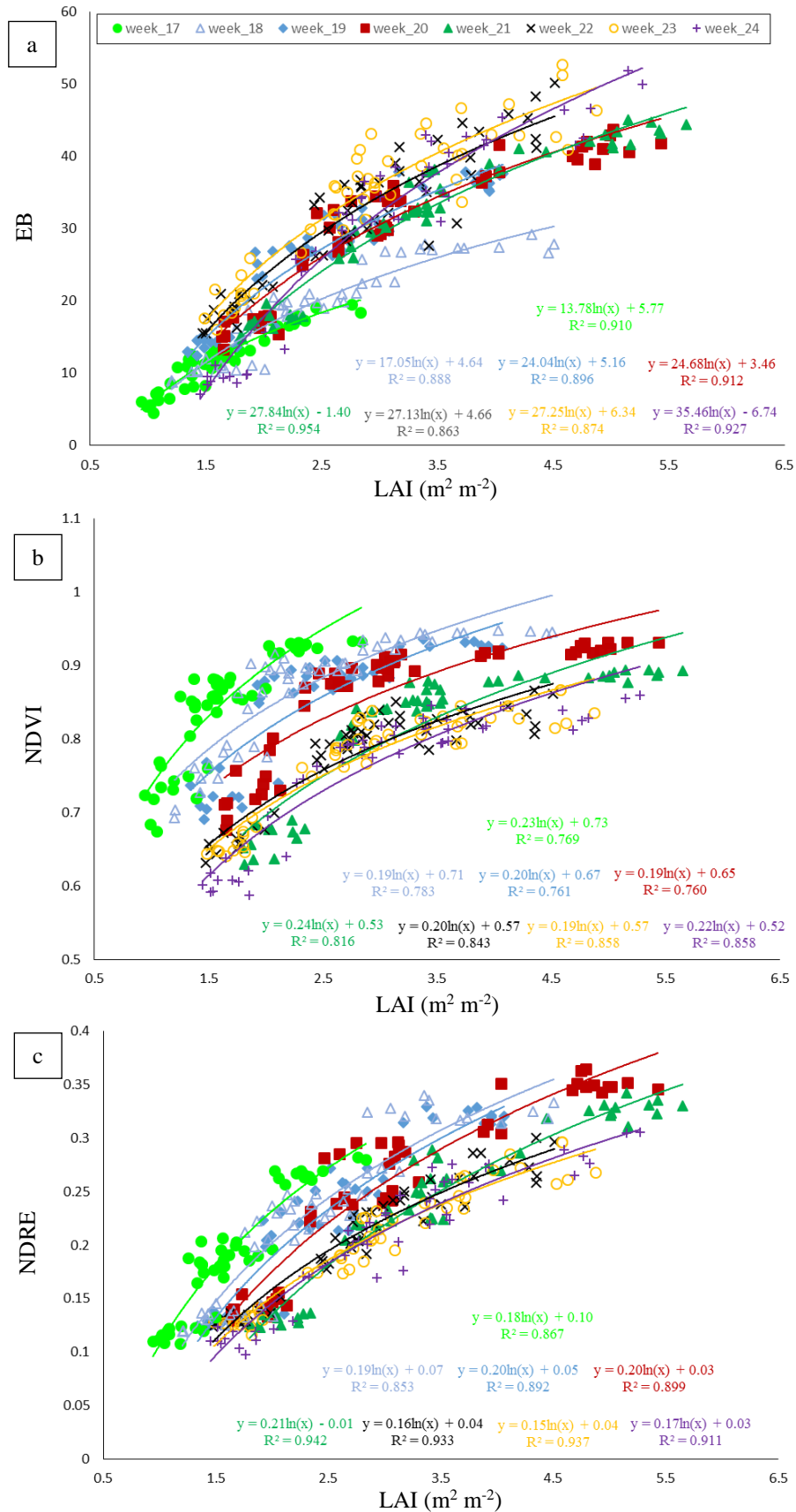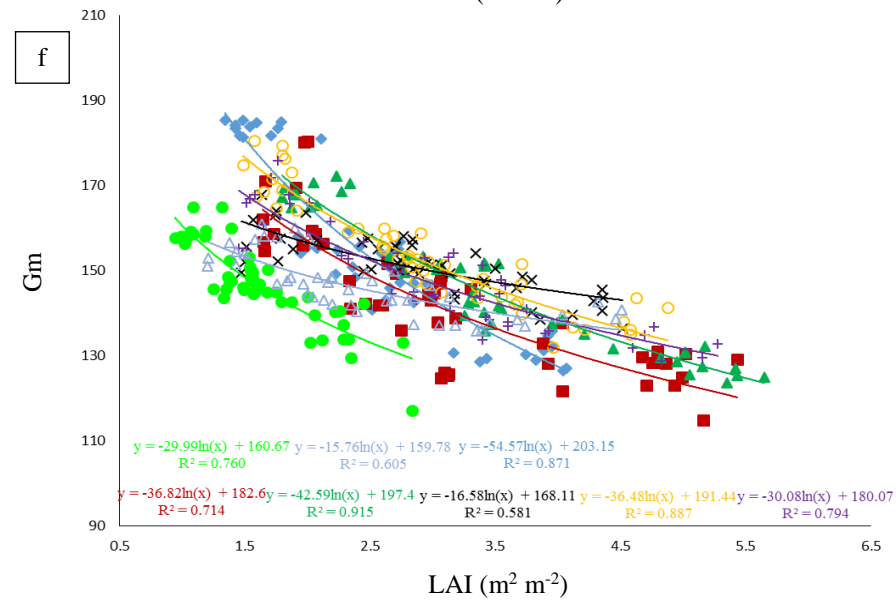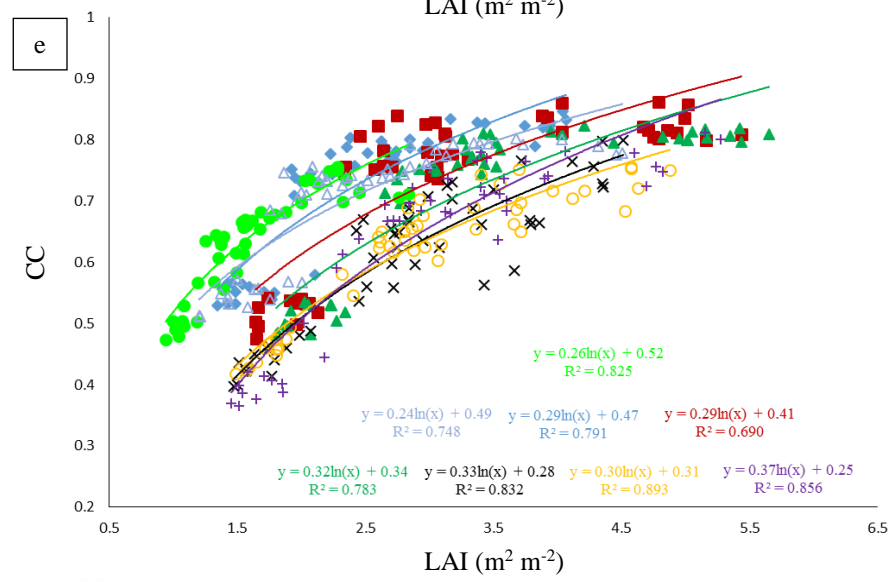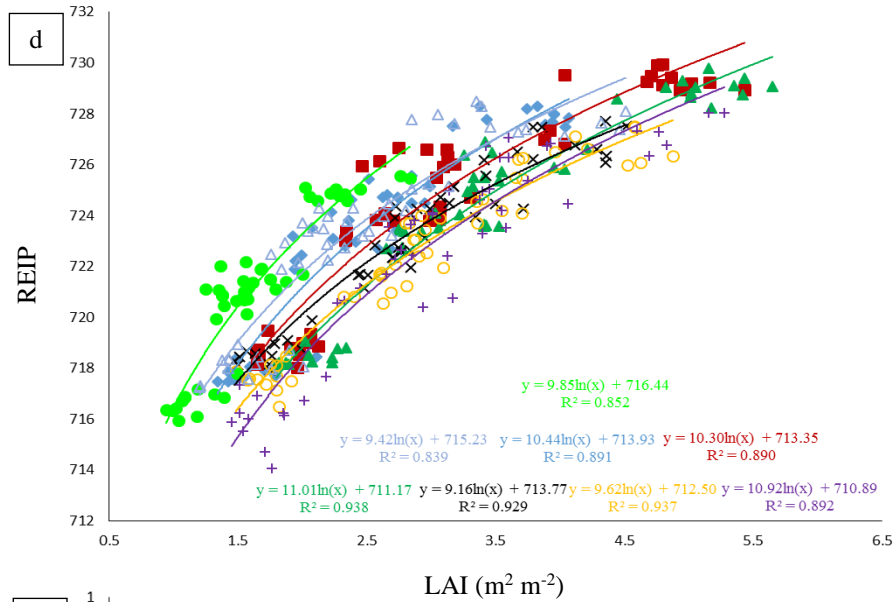
NDVI.

d. Vegetation indices obtained from the digital image analysis

Among the RGB-based indices that were calculated using the image processing in this study, CC, Gm, GMB, RMB, NRMB were better related to the LAI. The regression analysis results showed that logarithmic equations can better relate the indices to the LAI. Table 4 presents the regression models and their R^2 and *RMSE* using the data of whole the growing season for each index. In Figure 5e to j the results from regression analysis for each of the plant growth stages are shown separately. As seen, the indices GMB, RMB, and NRMB had less saturation at higher values of the LAI and stronger relation with the LAI than CC and Gm.

Liu and Pattey [22] estimated leaf area index (LAI) from vertical gap fraction measurements obtained using top-of-canopy digital colour photography over corn, soybean and wheat canopies. They used a histogram-based threshold technique to separate green vegetation tissues from background soil and residue materials in order to derive the canopy vertical gap fraction from the digital photos. The results showed that there was a logarithmic relationship between LAI measured with a LAI-2000 plant canopy analyzer and the vertical gap fraction derived from digital photography (R^2=0.84). They also reported that digital photography was limited by gap saturation when the canopy reached closure.

As it is observed in Figure 5, for most of the indices used in this study (including EB, NDRE, REIP, Gm, GMB, RMB, and NRMB), the strongest relation of the indices with the LAI was achieved at the growth stage heading (week 21 of the year).

Panel d — REIP vs LAI ($m^2\ m^{-2}$):
$y = 9.85\ln(x) + 716.44$, $R^2 = 0.852$
$y = 9.42\ln(x) + 715.23$, $R^2 = 0.839$
$y = 10.44\ln(x) + 713.93$, $R^2 = 0.891$
$y = 10.30\ln(x) + 713.35$, $R^2 = 0.890$
$y = 11.01\ln(x) + 711.17$, $R^2 = 0.938$
$y = 9.16\ln(x) + 713.77$, $R^2 = 0.929$
$y = 9.62\ln(x) + 712.50$, $R^2 = 0.937$
$y = 10.92\ln(x) + 710.89$, $R^2 = 0.892$

Panel e — CC vs LAI ($m^2\ m^{-2}$):
$y = 0.26\ln(x) + 0.52$, $R^2 = 0.825$
$y = 0.24\ln(x) + 0.49$, $R^2 = 0.748$
$y = 0.29\ln(x) + 0.47$, $R^2 = 0.791$
$y = 0.29\ln(x) + 0.41$, $R^2 = 0.690$
$y = 0.32\ln(x) + 0.34$, $R^2 = 0.783$
$y = 0.33\ln(x) + 0.28$, $R^2 = 0.832$
$y = 0.30\ln(x) + 0.31$, $R^2 = 0.893$
$y = 0.37\ln(x) + 0.25$, $R^2 = 0.856$

Panel f — Gm vs LAI ($m^2\ m^{-2}$):
$y = -29.99\ln(x) + 160.67$, $R^2 = 0.760$
$y = -15.76\ln(x) + 159.78$, $R^2 = 0.605$
$y = -54.57\ln(x) + 203.15$, $R^2 = 0.871$
$y = -36.82\ln(x) + 182.6$, $R^2 = 0.714$
$y = -42.59\ln(x) + 197.4$, $R^2 = 0.915$
$y = -16.58\ln(x) + 168.11$, $R^2 = 0.581$
$y = -36.48\ln(x) + 191.44$, $R^2 = 0.887$
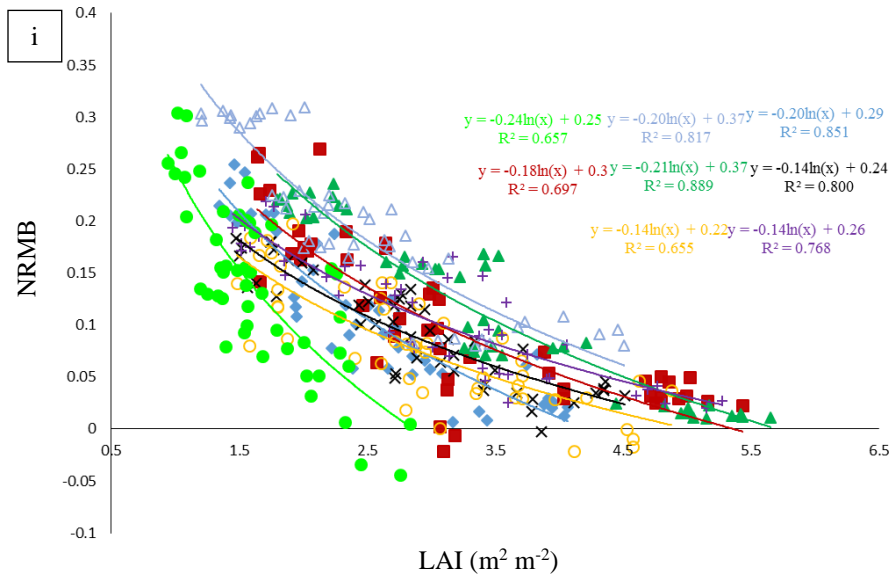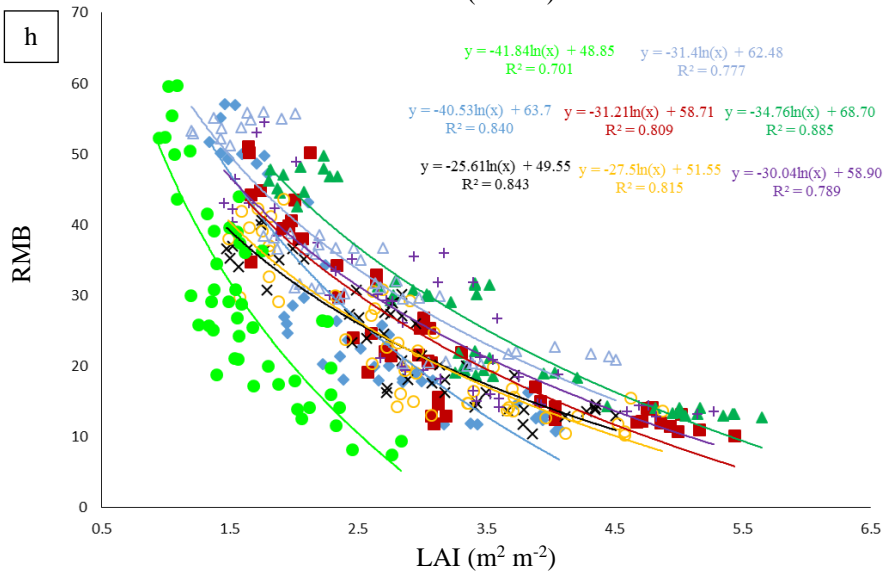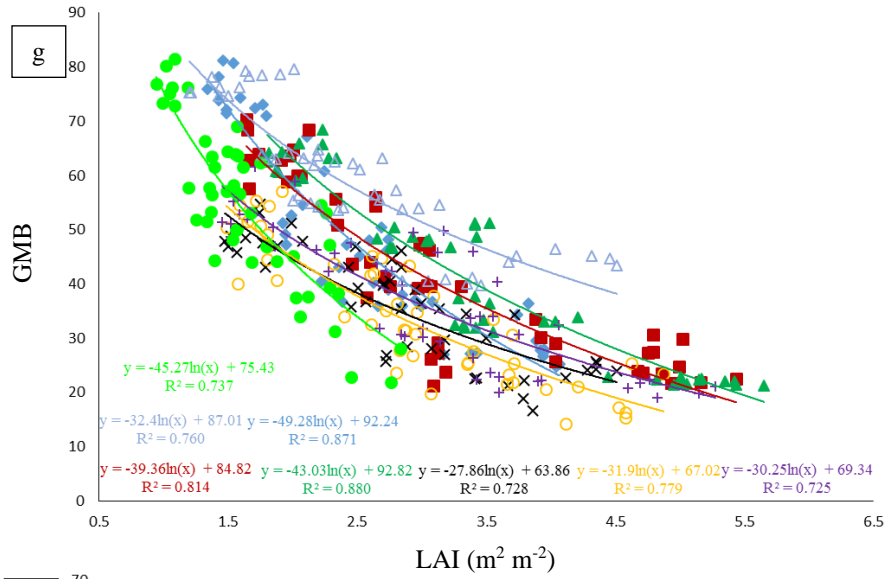$y = -30.08\ln(x) + 180.07$, $R^2 = 0.794$

Figure 5. Relationships of leaf area index (LAI) against (a) EB (Estimated Biomass), (b) NDVI, (c) NDRE, (d) REIP, (e) CC (Crop Coverage), (f) Gm, (g) GMB, (h) RMB, and (i) NRMB for different growth stages of winter wheat

VI.   CONCLUSION

The performance of different sensing approaches for non-distractively estimating leaf area index (LAI) of winter wheat was evaluated in this study as alternatives to conventional equipment in order to meet requirements of precision agriculture. The following results are concluded.

Regression analysis of the plant height and the measured LAI indicated that the height measurements cannot be used to estimate the LAI directly. However, the index Estimated Biomass (EB) which was calculated by multiplying the height and crop coverage derived from image processing showed remarkable relation with LAI. The EB had low saturation for the higher values of the LAI indicating that it can be a good estimator of the plant property. Therefore, a combined sensing approach consist of a sensor system for measuring the plant height (like Ultrasonic sensing systems) and a digital camera can be a real time solution to monitor the LAI in large fields for practical agricultural management.

The vegetation indices which use the red edge region of the electromagnetic spectrum, like NDRE and REIP seems to be convenient predictors of the LAI as proved by their strong logarithmic relation with the LAI. They also had less saturation effect for higher values of the LAI in comparison with the NDVI.

The digital image processing as a low cost approach showed a potential for estimation of the LAI. According to the results obtained, the RGB-based indices GMB, RMB, and NRMB had less saturation at higher LAI values and stronger relation with the LAI than the other indices calculated in this research. Digital cameras present some practical advantages such as: they are affordable devices to acquire field information, the measurement protocol is relatively simple to follow, the processing of digital photographs can be done in an automated manner with relatively little effort, and the recorded images can be stored on a computer for later review. The protocol

can also be used in smartphones to provide a portable, simple and inexpensive approach to estimate the LAI.

The investigations over time showed that for most of the sensing approaches, during the growth stage heading, the strongest relations with the LAI was achieved.

ACKNOWLEDGMENTS

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