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ASSESSMENT OF WINTER SPELT AND WHEAT GROWTH AND YIELD BY GROUND SPECTRAL MEASUREMENTS

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A b s t r a c t. Information on the physiological state of plant canopies of crops during the growing season is essential for growers in decision-making such as foliar N and plant growth regulator applications for maximum yield. The aim of the study was to determine optimal vegetation indices for discriminating among four winter spelt and wheat varieties cultivated at six different organic and inorganic N fertilizer treatments. The suitability of the vegetation indices to predict yield was investigated as well. The results showed that the MCARI (Modified Chlorophyll Absorption Reflectance Index) was found to be the best for discriminating among spelt and wheat varieties and the most spectrally distinctive spelt variety was Schwabencorn. Among the tested indices, NDVI (Normalized Difference Vegetation Index) and MCARI could be used to most clearly distinguish the N treatments. A relatively high correlation occurred between the vegetation indices and grain yield of spelt and wheat. This relationship is stronger if the spectral data from different measurement dates are taken into consideration. Therefore, the best yield predictions (R^2 = 0.79) were obtained using the cumulative SR index.

K e y w o r d s: spelt, winter wheat, remote sensing, inorganic and organic N fertilizers, ground spectral measurement

INTRODUCTION

Spelt (*Triticum spelta* L.) is a hexaploid species of wheat and the acreage under this crop in Europe is rather small (approximately 18 000 ha). However, a steady increase in the area under this crop is recently observed, mainly on organic farms (Capouchova 2001). Spelt grains contain more easily digestible protein with higher biological value than common wheat (Chrenkova *et al.* 2000).

The application of modern cultivation methods require the collection of a lot of detailed information on the conditions under which the agricultural production takes place. One way of obtaining such information is the use of remote sensing methods which include ground-based spectral measurements as well as aerial and satellite imaging.

Remote sensing sensors, recording reflected radiance in various spectral bands, are able to collect data which can be used for detailed analysis of the vegetation condition. Near-infrared reflectance is sensitive to vegetation structure while red reflectance decreases as chlorophyll absorption increases. On the basis of crop reflectance data at differing wavelengths, vegetation indices can be calculated. Two broad band reflectance indices: simple ratio (SR) and normalized difference vegetation index (NDVI) have been widely used in agricultural remote sensing applications. However, many other indices using simple ratios of any two single wavelengths or including more complicated wavelength combinations have been developed. These indices can be used as indicators of crop growth (Serrano *et al.* 2000, Broge and Leblanc 2000, Zhao *et al.* 2003), nutrient status (Zhao *et al.* 2005), and yield development (Plant *et al.* 2001, Ma *et al.* 2001). Nitrogen fertilization directly or indirectly influences LAI (Leaf area index), degree of soil coverage by plants, chlorophyll content, and other biophysical parameters, which can cause changes in vegetation indices. Evaluation of plant growth and yield forecasting on the basis of the vegetation indices acquired in the early stages of development can significantly help farmers make decisions about irrigation, fertilization and foliar application of growth regulators.

The aim of this study was to determine the suitability of vegetation indices obtained during ground-based hyperspectral measurements to assess the diversity of spectral properties of three spelt and one wheat varieties grown in different N fertilizer treatments. The usefulness of the indices to predict yield was investigated as well.

MATERIALS AND METHODS

At the Experimental Station Swadzim (52°26'N, 16°45'E), branch of the Gorzyń Research and Education Centre of Poznań University of Life Sciences, three winter spelt (*Triticum spelta* L.) varieties (Badengold, Schwabenpel, Schwabenkorn) and one winter wheat variety (*Triticum aestivum* L. – Turkis) were sown. Crop growth stages were determined according to BBCH-Identification keys (Biologische Bundesanstalt, Bundessortenamt and Chemical Industry)(Stauss 1994). The plots were fertilized in the following treatments:

(1) no N applied during the growing season (0 kg N ha^{-1}),

(2) 30 kg N ha^{-1} applied after vegetation onset (12 March 2009),

(3) 30 kg N ha^{-1} applied after vegetation onset and 30 kg N ha^{-1} at stem elongation stage BBCH 35 (29 April 2009),
(4) 30 kg N ha^{-1} applied after vegetation onset, 30 kg N ha^{-1} at stem elongation stage and 30 kgN ha^{-1} at heading stage BBCH 53 (1 June 2009),
(5) 15 t manure/ha applied in autumn (22 September 2008),
(6) 30 t manure/ha applied at the same time as (5).

Canopy reflectance measurements were made on sunny days between 11.00 and 13.00 h above all plots on three dates: 16 April when plants were at a continued tillering stage (BBCH 23) and 1 and 13 May at the stem elongation stage (BBCH 32 and BBCH 36 respectively). Reflectance spectra of the spelt and wheat plots were collected by a portable ASD FieldSpec FR spectroradiometer (Analytical Spectral Devices Inc., Boulder, CO, USA). Reflectance was measured at wavelengths ranging from 350 to 2500 nm. The distance between the optical head of the spectroradiometer and the upper plant leaves was 2 m and the radiometer had a 25 field of view. A calibrated reflectance panel (Spectralon, Labsphere, North Sutton, NH, USA) was used as reference prior to each measurement, and reflectance factors for canopy were calculated as the ratio of the canopy reflectance to the panel reflectance. The three spectral reflectance measurements in each plot at each sampling date were averaged, and the mean values were used in analysis.

From the reflectance data four vegetation indices were calculated based on the following equations:

$NDVI = (R_{918} – R_{675}) / (R_{918} + R_{675})$ Rouse *et al.* (1974), (1)
$SR = R_{918} / R_{675}$ Rouse *et al.* (1974), (2)
$MCARI = [(R_{700}–R_{675}) – 0.2*(R_{700}–R_{550})]*(R_{700}/R_{675})$ Daughtry *et al.* (2000), (3)
TCARI (Transformed Chlorophyll Absorption in Reflectance Index) =
$3[(R_{800}-R_{675}) – 0.2*(R_{800}-R_{550}*(R_{700}/R_{670})]$ Haboudane *et al.* (2002). (4)
where: R_{550}, R_{675}, R_{700}, R_{800}, R_{918} are reflectance factors and the subindex indicates the wavelength (nm).

In the statistical analysis Tukey's pair-wise comparisons were used to contrast mean values for significant differences.

RESULTS

Differences in vegetation indices between the spelt and winter wheat varieties

The rapid growth of plants at the beginning of the season caused significant changes in spectral response of plots. As a result of increase of plant biomass, pigment concentration and soil cover, a gradual decrease of the reflectance in the red wavelenghts and increase in the near-infrared and, in consequence, an increase of the NDVI and SR values were observed (Fig. 1).

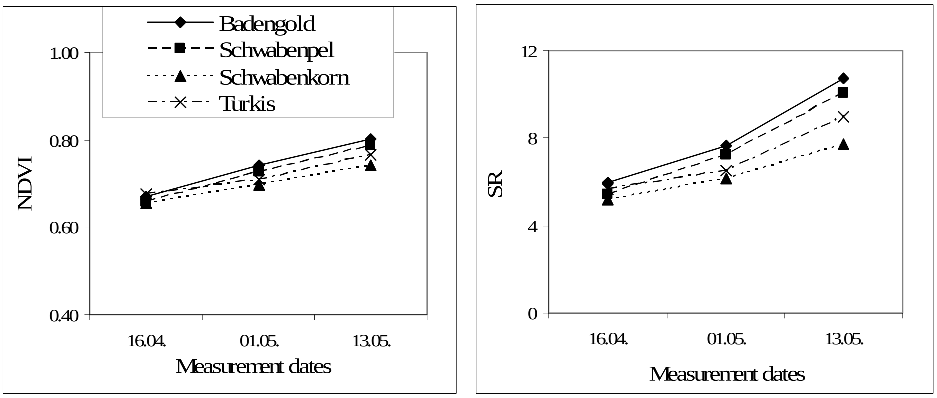

Fig. 1. Time course of the vegetation indices NDVI and SR of three spelt and one wheat varieties on the three measurement dates in 2009

Temporal dynamics of plants of the four studied varieties, assessed on the basis of the vegetation indices NDVI and SR, was similar. During the period of four weeks, between 16 April and 13 May, a greater rate of growth was observed in the case of varieties Badengold and Schwabenpel. The NDVI of both varieties increased by 20% while the NDVI of two remaining varieties increased only by 13%. Plants of varieties Badengold and Schwabenpel gave the highest grain yield of 4.3 and 3.5 t/ha, respectively, while two remaining varieties, Schwabenkorn and Turkis, gave only 3.1 and 3.0 t/ha, respectively.

The variation in plant development between the four varieties caused statistically significant differences among the average values of the four vegetation indices (Tab. 1). In mid-April there were no statistically significant differences between the values of four vegetation indices of all studied varieties. Very rapid development of plants observed in Badengold variety caused that on the first day of May the values of all indices of this variety were significantly higher than the indices of the variety Schwabencorn. The greatest variety differences occurred in the values of the MCARI index. On the third date (13 May), this index showed significant differences between all the varieties except Badengold and Schwabenpel, while significant differences in NDVI and SR were only noted between Badengold and Schwabenkorn as well as between Schwabenpel and Schwabenkorn.

Table 1. Mean values of the four vegetation indices of three spelt and one wheat varieties on three measurement dates in 2009 and values of the least significant differences (LSD) between the varieties

Varieties	NDVI			SR		
	16 Apr	1 May	13 May	16 Apr	1 May	13 May
Badengold	0.67^{a}	0.74^{a}	0.80^{a}	7.26^{a}	7.68^{a}	10.76^{a}
Schwabenpel	0.66^{a}	0.73^{ab}	0.79^{a}	5.44^{a}	7.26^{ab}	10.09^{a}
Schwabenkorn	0.66^{a}	0.70^{b}	0.74^{b}	7.66^{a}	6.14^{b}	7.73^{b}
Turkis	0.68^{a}	0.71^{ab}	0.77^{ab}	5.68^{a}	6.50^{ab}	8.97^{ab}
0.1% LSD	0.042	0.036	0.037	2.34	1.18	1.88
Varieties	MCARI			TCARI		
	16 Apr	1 May	13 May	16 Apr	1 May	13 May
Badengold	5.03^{ab}	5.95^{a}	4.82^{a}	64.0^{a}	79.2^{a}	73.2^{a}
Schwabenpel	5.32^{a}	6.13^{ab}	4.80^{a}	57.8^{b}	76.9^{a}	68.6^{a}
Schwabenkorn	5.21^{ab}	5.39^{c}	4.11^{b}	61.4^{ab}	71.2^{b}	61.5^{b}
Turkis	4.75^{b}	5.64^{dc}	4.54^{c}	59.9^{ab}	75.0^{ab}	67.8^{ca}
0.1% LSD	0.53	0.35	0.24	6.1	5.5	4.8

Treatment means within a column followed by the same letter are not significant different (P>0.05).

Differences in vegetation indices between the fertilizer treatments

Comparison of spectral signatures of five various fertilizer treatments acquired on 13 May showed lower visible (380-780 nm) and shortwave (1300-2500 nm) reflectance and higher near-infrared (780-1300 nm) reflectance of 0N and both manure treatments than of three inorganic N treatments (Fig. 2). Deficit of nitrogen in plants causes a small increase in LAI and biomass (Fernandez *et al.* 1996, Zhao and Oosterhuis 2000, Reddy *et al.* 2003) and reduces the concentration of photosynthetically active plant pigments (Zhao and Oosterhuis 2000, Zhao *et al.* 2005), thus the plant reflectance in the visible and shortwave wavelength region increases and in the near-infrared region decreases. Symptoms of N deficiency stress were evident for plants in the 0N treatment which had, on all three measurement dates, significantly lower values for all four vegetation indices than the remaining treatments (Tab. 2).

Slower rate of growth of plants on the plots fertilized with manure resulted in lower values of all analysed indices compared to the plots fertilized with inorganic N. The differences were statistically significant in the case of NDVI and SR on the second and third measurement dates. Nitrogen applied on 29 April at the (3) and (4) fertilizer treatments at the rate of 30 kg N ha^{-1} accelerated plant growth and the vegetation indices of these treatments had the highest values on the last measurement date. However, spectral differences between the inorganic N treatments (2), (3) and (4) were insignificant for all three dates.

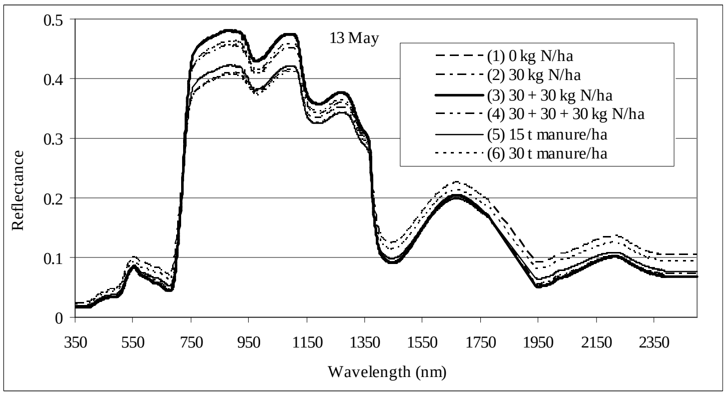

Fig. 2. Spectral signatures for the six fertilizer treatments of spelt and wheat recorded on 13 May 2009

Table 2. Average values of the four vegetation indices of the six N fertilizer treatments of spelt and wheat recorded on the three dates in 2009 and values of the least significant differences (LSD) between the treatments

Fertilizer treatment	NDVI			SR		
	16 April	1 May	13 May	16 April	1 May	13 May
(1)	0.59^{a}	0.63^{a}	0.7^{a}	4.0^{a}	4.7^{a}	6.5^{a}
(2)	0.77^{bc}	0.77^{b}	0.81^{b}	8.2^{b}	6.8bd	10.8^{b}
(3)	0.75^{bc}	0.78^{b}	0.83^{b}	7.9^{b}	8.6^{c}	11.6^{b}
(4)	0.78^{b}	0.76^{b}	0.82^{b}	8.3^{b}	7.7^{bc}	11.1^{b}
(5)	0.66^{ac}	0.69^{c}	0.76^{c}	5.3^{ab}	6.2^{ab}	9.2^{bc}
(6)	0.67^{ab}	0.68^{c}	0.72^{ac}	5.3^{ab}	5.5^{ad}	7.1^{ac}
0.1% LSD	0.11	0.04	5.26	3.2	1.6	2.4
Fertilizer treatment	MCARI			TCARI		
	16 April	1 May	13 May	16 April	1 May	13 May
(1)	8.1^{a}	10.2^{a}	9.3^{a}	53.4^{a}	66.4^{a}	63.0^{a}
(2)	12.6^{b}	13.7^{b}	11.2^{b}	65.6^{b}	80.7^{b}	70.3^{bcd}
(3)	12.3^{bc}	14.1^{b}	11.3^{b}	62.7b^{c}	82.8^{b}	75.0^{b}
(4)	12.8^{b}	14.1^{b}	11.0^{b}	66.0^{b}	82.1^{b}	71.7^{bc}
(5)	9.1^{ac}	10.6^{a}	9.6^{a}	57.4^{ac}	71.2^{a}	66.1^{ac}
(6)	9.6^{ab}	10.3^{a}	8.8^{a}	59.3^{ab}	70.3^{a}	64.8^{ad}
0.1% LSD	3.5	0.5	1.3	7.9	6.9	6.6

Treatment means within a column followed by the same letter are not significant different (P>0.05)

At the start of the growing season, plots fertilized with manure at the dose of 15 t ha^{-1} (5) had similar values of vegetation indices to those of plots fertilized at the dose of 30 t ha^{-1} (6). However, till the half of May plants in treatment (5) grew more rapidly than those in treatment (6), so that the values of the vegetation indices for treatment (5) were higher than for treatment (6), though the differences were not statistically significant.

The greatest treatment differences occurred on the third measurement date, when plants were at elongation stage. Serrano *et al.* (2002) reported the greatest differences between wheat crops growing under different N supplies in the heading stage. In the present study it was not possible to take spectral measurements at the heading stage due to bad weather conditions, i.e. lack of a cloudless sky.

Relationships between grain yield and reflectance indices

In order to estimate the possibility of predicting spelt yield on the basis of spectral data recorded at the beginning of the growing season, the average values of vegetation indices of all 24 plots obtained on the three dates were compared with the grain yield harvested from these plots. At the beginning of the season, in the tillering stage, NDVI showed a stronger relationship with yield and in the later stages SR was most highly correlated with yield (Tab. 3).

Table 3. Regression equations and determination coefficients (R^2) used to estimate spelt and wheat grain yield from the vegetation indices values

Vegetation index	Equation	R^2
	16 April	
NDVI	$y = 15.86x^2 – 16.0x + 6.92$	0.58
SR	$y = 0.006x^2 + 0.15x + 2.33$	0.54
MCARI	$y = –0.02x^2 + 0.57x – 0.44$	0.52
TCARI	$y = 0.003x^2 – 0.27x + 9.28$	0.50
	1 May	
NDVI	$y = 43.2x^2 – 53.3x + 19.4$	0.58
SR	$y = 0.068x^2 – 0.65x + 4.55$	0.63
MCARI	$y = 0.015x^2 – 0.15x + 3.09$	0.52
TCARI	$y = 0.002x^2 – 0.26x + 11.0$	0.56
	13 May	
NDVI	$y = 43.4x^2 – 58.2x + 22.4$	0.68
SR	$y = 0.016x^2 – 0.11x + 3.07$	0.72
MCARI	$y = 0.057x^2 – 0.85x + 6.06$	0.62
TCARI	$y = 0.003x^2 – 0.28x + 10.6$	0.65

NDVI is more useful for assessing the condition of wheat plants and biomass, at a small LAI, when the plants do not form a dense canopy (Gao 2006, Chen *et al.* 2005, Calera *et al.* 2004). For well developed canopies SR is more suitable for assessing their growth (Serrano 2000). Comparing with SR or NDVI, the vegetation indices MCARI and TCARI did not improve the relationships between reflectance data and grain yield in the present study. This is consistent with the results of research on cotton by Zhao *et al.* (2007) and Zarco-Tejada *et al.* (2005). Scatter plots of grain yield versus SR, NDVI, MCARI and TCARI in different growth stages indicate that the relationships can be expressed as a polynomial function. The strongest relationship between yield and SR values occurred on the last of the three measurement dates (13 May), when the plants were at BBCH 36 growth stage and R^2 calculated for this relationship was 0.72. Moges *et al.* (2004) reported a strong relationship between grain yield and NDVI in winter wheat at BBCH 36 growth stage and the best fit was achieved by using a power or exponential function.

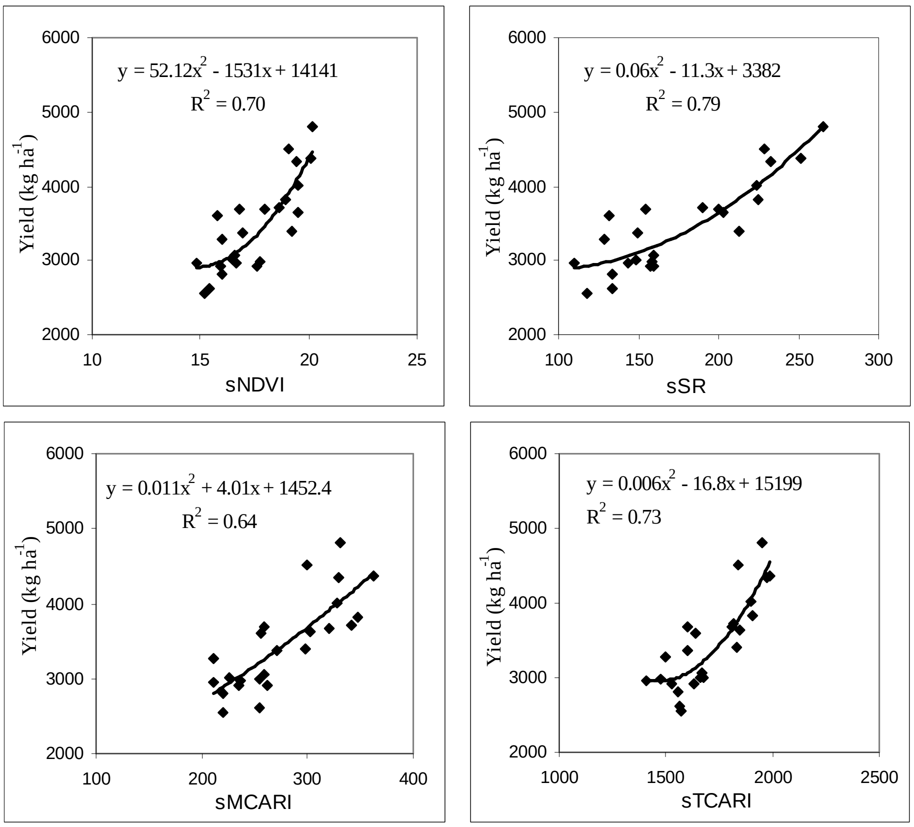

Fig. 3. Relationship between grain yield and the four cumulative vegetation indices (n = 24)

To improve the relationship between the spectral data and the grain yield, the average values of the four indices acquired on two consecutive measurement dates were multiplied by the number of days between those dates. The obtained values were summarized receiving the cumulative vegetation indices: sNDVI, sSR, sMCARI and sTCARI. The average grain yield was more strongly associated with the values of the cumulative indices than with the values of indices calculated on the basis of reflectance coefficients recorded on the individual measurement dates (Fig. 3). Serrano *et al*. (2000) obtained a slightly lower value of R^2 (0.74) for the relationship between the yield of wheat (variety Soissons) and the values of sSR, which could be explained by the relatively early flag leaf senescence of plants and rust infection (*P. graminis*).

CONCLUSIONS

1. Variations in crop growth in response to varietal properties and N fertilization influenced strongly the spectral response of spelt and winter wheat plots. This indicates a possibility of using aerial photographs and satellite images to identify varieties and to assess the level of nutrition of plants in canopies as well as to estimate the grain yield.
2. The spectral differences between the three spelt and one wheat varieties were the greatest at the stage of stem elongation and the varietal influences were more consistently shown by MCARI than by the other three indices: NDVI, SR and TCARI. Schwaben corn variety demonstrated the most distinctly different values of the vegetation indices. N fertilizer treatment had also a consistent effect on the spectral response of spelt and winter wheat plots. Among the tested indices, NDVI and MCARI could be used to most clearly distinguish the N treatments. Relatively high correlation occurred between the vegetation indices and grain yield of spelt and wheat. This relationship is stronger if spectral data from different measurement dates are taken into consideration. Therefore, the best yield predictions were obtained using the cumulative SR index. Relatively high correlation between the spectral data collected at the beginning of the growing season and yield probably resulted from the relatively favourable weather conditions that occurred in the second part of the growing season when precipitation was higher than the average of many years.
3. The results of this study indicate that the vegetation indices acquired at the beginning of the growing season can be used as input for plant growth models which provide estimates of potential yields.

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OCENA STANU UPRAW ORKISZU I PSZENICY ORAZ PROGNOZOWANIE PLONÓW NA PODSTAWIE POLOWYCH POMIARÓW SPEKTRALNYCH

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Streszczenie. Informacje dotyczące kondycji roślin w uprawie, w sezonie wegetacyjnym, są niezbędne przy podejmowaniu decyzji produkcyjnych dotyczących na przykład nawożenia lub stosowania regulatorów wzrostu. Celem badań było stwierdzenie występowania różnic między właściwościami spektralnymi różnych odmian orkiszu uprawianego w odmiennych wariantach nawożenia oraz określenie przydatności wskaźników roślinnych uzyskanych w trakcie naziemnych pomiarów hiperspektralnych do prognozowania wysokości plonów orkiszu. Największe zróżnicowanie spektralne między trzema odmianami orkiszu ozimego i jedną odmianą pszenicy obserwowano w przypadku wskaźnika MCARI. Wskaźniki NDVI i MCARI były najbardziej przydatne do odróżniania poletek uprawianych w odmiennych wariantach nawożenia. Między wartościami wszystkich analizowanych wskaźników roślinnych i wielkością plonu z poletek występowała istotna zależność. Najsilniejsza zależność występowała, gdy do jej określenia wykorzystano dane spektralne zarejestrowane w trzech terminach na początku sezonu wegetacyjnego. Wówczas wartość współczynnika determinacji obliczonego dla zależności między plonem ziarna i wartościami wskaźnika SR wynosiła $R^2 = 0,79$.

Słowa kluczowe: orkisz ozimy, pszenica, teledetekcja, nawożenie organiczne i mineralne, naziemne pomiary spektralne