POLISH JOURNAL OF ECOLOGY (Pol. J. Ecol.)	53	1	105–111	2005

Short research contribution

Jan PIEKARCZYK

Institute of Physical Geography and Environmental Planning, Adam Mickiewicz University in Poznań, Dzięgielowa 27, 61-680 Poznań, Poland, e-mail: piekjan@amu.edu.pl.

SPECTRAL DISCRIMINATION OF ARABLE FROM FALLOW FIELDS AS LANDSCAPE COMPONENTS

ABSTRACT: Remote sensing methods, including aerial photography and satellite images, could be successfully used for detecting and acreage assessing of landscape components like fallow fields. The objective of the present study was to characterize the reflectance of fallow fields situated in various soil conditions and of different age and compare them with spectral characteristics of main arable crops: winter rye, spring oat, winter oilseed rape, corn, potatoes and meadow. Field spectral reflectance measurements were made with the CIMEL CE313 luminancemeter and five vegetation indices (*NDVI*, *STVI*, *MSI*, *MNDVI* and *GRVI*) were developed by combining the reflectance factors in the five wavebands (450, 550, 650, 850 and 1650 nm). In the second part of May, when seasonal biomass peak of winter crops and meadows occurs and spring crops partly covers the soil, significant differences were observed in the spectral properties of fallow and cultivated fields. Results showed that among the analyzed vegetation indices *MSI* index (R_{1650}/R_{850}) was found to be the best for discriminating among the fallow fields and *GRVI* (R_{550}/R_{650}) and *NDVI* ($(R_{850}-R_{650})/(R_{850}+R_{650})$), were the best discriminators between the fallow fields and arable crops.

KEY WORDS: remote sensing, landscape changes, field spectrometry, reflectance, fallow fields, vegetation indices

1. INTRODUCTION

Significant changes in land use structure follow the structural transformation of agriculture in Poland that has been occurring since 1989. In this year a new economic system with free-market rules was initiated by the parliament democratically elected. From the beginning of the transition, reduced production and an unfavourable development of the terms of trade caused agricultural recession. A great part of plough-land remains uncultivated and lies fallow as abandoned lands (Balcerkiewicz 1997). According to the Polish Central Statistical Office (GUS), there are two categories of fallow grounds. The first are grounds uncropped for the current year. The second are grounds left uncropped for at least two years and vegetation growing on these fields does not yield. In Poland in 2003 the acreage in both of these categories amounted to 1.8 million ha, which is almost 14% of the total ploughed grounds area. The greatest acreage of fallow fields lies in the north-western parts of Poland, in the Lubuskie and Śląskie voivodeships and in the north-eastern part, in the Podkarpackie voivodship, where the share of abandoned fields in the total ploughed area was 31, 28 and 27%, respectively (GUS 2004). In the four years period, between 1999 and 2003, the total acreage of fallow fields in Poland increased by about 300 000 ha. In the future the acreage of abandoned grounds probably will rise and monitoring and forecasting of this process will acquire greater importance. Accurate forecasting facilitates proper management of rural regions and correct decisions about their development in the new economic situation. Inappropriately managing abandoned lands can lead to decrease of the natural environment. Remote sensing methods, including aerial photography and satellite images, could be successfully used for monitoring these changes.

Remote sensing can provide quantitative and timely information essential in landscape ecology and in environmental management (Phinn *et al.* 2003, Jorge and Garcia 1997) as well as in agricultural planning and policy making (Lelong *et al.* 1998, Seelan *et al.* 2003) at both national and regional level. During the past three decades a great amount of research has been dedicated to agricultural land cover classification and acreage estimation using remote sensing techniques (Lillesand and Kiefer 2000). Interpretation of remotely sensed data from aircraft and satellite sensors requires an understanding of the spectral behaviour of arable crops through ground-based reflectance measurements. Much research has been dedicated to describe the spectral properties of different agricultural crops, (Kuusk 1991, Ridao *et al.* 1996, Daughtry *et al.* 2000, Vaesen *et al.* 2001, Piekarczyk 2001) and grasslands (Purevdorj *et al.* 1998, Price *et al.* 2002). However, little information is available on the spectral characteristics of abandoned fields. The spectral behavior of grassland vegetation may be similar to that of fallow field vegetation since they are both comprised of a mixture of "green" and "nonphotosynthetic" vegetation. In the remote sensing literature live, chlorophyll-rich plants are termed as "green" vegetation while dry, senescent and dead fragments of plants as well as standing litter or debris are termed as "nonphotosynthetic" vegetation – NPV (Asner *et al.* 1998, Numata *et al.* 2003).

The presence of NPV can significantly affect the spectral properties of vegetation (Asner 1998). Senescence of plant components cause a breakdown of all pigments and changes in intercellular leaf space, thus the reflectance from dried plant material is often greater than from "green" vegetation at nearly all wavelengths (Woolley 1971). According to Numata (2003) the proportion of NPV to "green" vegetation biomass in the pastures depends on soil conditions and age, and in well-grazed pasture is smaller than in ungrazed pasture (van Leeuwen and Huete 1996). Rychnowska (1976) found that in meadow vegetation on poor and dry soil, the proportion of the NPV was 60% while on the better, wet soils it amounted to only 30%. On the fallow fields during the course of the season, senescence of plant components occurs and proportions of NPV and "green" vegetation change. Jensen (2000) suggested that the optimum time to separate spectrally one vegetation type from another is early in the growing season, when vegetation cover and biomass of various crops differ significantly. Piekarczyk (2004) showed that the most suitable time for separating the cereal crops from fallow fields on the basis of spectral data was in the second half of May. According to Bochenek (1999), at this time in Wielkopolska region (Central Poland) the peak annual *NDVI* occurs – the vegetation index which is directly related to the vegetation biomass.

In vegetation monitoring typically, reflectance measurements in the near-infrared (NIR 700–1500 nm) and visible (VIS 400–700 nm), usually red, wavebands are used (Steven *et al.* 2003). However, reflectance in the shortwave infrared (SWIR 1500 nm–1 cm) waveband, heavily influenced by the water in the plant tissue (Baret and Fourty 1997), seems to be useful in discriminating fallow fields containing dry NPV from crop fields consisting of green, "wet" plants.

The objective of the present study was to characterize the reflectance of three fallow fields and six arable crops, and determine whether the fallow fields of different age, situated in different soil conditions could be separated and then distinguished spectrally from the crop fields. The usefulness of reflectance data obtained in the SWIR waveband for discriminating fallow from crop fields was assessed.

2. METHODS

The study area was located approximately 20 km southwest of Poznań in the Wielkopolska voivodship (Central Poland) with an annual rainfall of 528 mm. Spectral measurements, as well as soil and vegetation samples were taken on three dates: 10 and 22 May and 19 June 2002 at farm fields surrounding a village (52°16' N, 17°01' E). Five field sites (area of 10 m^2) were randomly located within each of the arable crops: winter oilseed rape, winter rye, spring oat, corn, potatoes, natural meadow (Table 1) and three fallow fields (Table 2). At each site three spectral measurements were taken. The fallow fields were chosen to represent various soil conditions and age. The two fallows were situated on degraded black earth (Abruptia Argiaquolls according to US Soil Taxonomy (1975)) formed with a loamy sand texture and the third was on rusty soil (Typic udipsamments, Arents) formed with sand. Soil texture data were obtained from the soil maps 1:5000. For estimating organic matter content in soil samples, dry-ashing method was employed (Carter 1993). On each fallow field, in five sites, vegetation biomas was sampled immediately after the spectral measurements. Plants were cut off at ground level from the area of 0.16 m^2 (40 cm × 40 cm) and taken to the laboratory, where the green parts were separated from dead components, weighed and then all plant material desiccated in an oven at 105°C for 24 hours, until a constant weight was obtained. Similarly, the biomass samples were collected from five points at each of five arable fields, as well as the meadow. Crop growth stages were determined according to BBCH-Identification keys (Biologishe Bundesanstalt, Bundessortenamt und Chemical Industry)(Adamczewski and Matysiak 2002). At the spring oat, corn and potato fields the percentage of "green" vegetation cover at each measurement point was estimated from the photographs taken with a digital camera.

Field spectral reflectance measurements were made with the CIMEL CE313 luminancemeter, the head of which was mounted on a hand-held boom, elevated approximately 2.5 meters above the canopy. Measurements were made only at clear sky conditions. The luminancemeter's sensor with a field-of-view (FOV) of 10°, covers an area of 0.15 m^2. The three spectra were obtained for each measurement point at the nadir direction and were then averaged. Reference panel (Spectralon) measurements were collected immediately before the luminance measurements. Reflectance factors were calculated as the ratio of the reflected radiance from crop and fallow fields to that reflected from a reference panel in five wavebands: 450, 550, 650, 850 and 1650 nm. A sum, difference, ratio or other linear combination of reflectance factors from two or more wavelength intervals produce various spectral vegetation indices (Wiegand *et al.* 1991). Vegetation indices are commonly used in remote sensing since they are relatively independent of illumination intensity and reduce errors introduced by the presence of the soil background (Pinter *et al.* 1983). In this study five vegetation indices were calculated by combining the reflectance factors:

$$NDVI=(R_{850}-R_{650})/(R_{850}+R_{650}) \quad (1)$$

(acc. to Rouse *et al.* 1973),

$$STVI=(R_{1650}*R_{650})/R_{850} \quad (2)$$

(acc. to Ridao *et al.* 1998),

$$MSI=R_{1650}/R_{850} \quad (3)$$

(acc. to Rock *et al.* 1985),

$$MNDVI=(1+0.03H_2)(NDVI)/(1+0.6H_1) \quad (4)$$

where:

$$H1 = (0.55*R_{650}-R_{450}+0.12)/(R_{8502}-R_{6502})$$

$$H2 = 1/(0.55*R650- R450+0.12),$$

(acc. to van Leeuwen and Huete 1996)

$GRVI=R_{550}/R_{650}$ (5)

where: R_{450}, R_{550}, R_{650}, R_{850}, R_{1650}: reflectance factors in the 450, 550, 650, 850 and 1650 nm bands, respectively.

An analysis of variance was conducted to determine significant differences among the mean reflectance factors and vegetation indices of fallow fields and between fallow and crop fields. The means were separated by the least significant difference (LSD) method according to the Tukey test at the *P* <0.01 level.

3. RESULTS AND DISCUSSION

3.1. Spectral variation among fallow fields

The aboveground biomass values were different on the three fallow fields F1, F2 and F3 due to various soil conditions and the period when they were uncultivated. The soil characteristics and species composition of the fallow fields are listed in Table 1. Both, "green" and "NPV" vegetation biomass on the F1 field, were greatest due to relatively good soil conditions (loamy sand) and a long period of noncultivation (five years). This resulted in higher soil organic matter content (Strączyńska and Rola, 1998, Niedźwiecki *et al.* 1998) and thus more nutrient absorption and release through the decomposition of organic matter. Although on the F2 and F1, the soil texture was similar, the shorter period of noncultivation on the F2 meant that its total aboveground biomass was about twice lower than on the F1 field. The field F3 represented the lowest vegetation biomass due to poor soil condition. The total aboveground biomass on the F3 field was almost fivefold lower than on the F1 field. The greatest proportion of the NPV, (60% of the total aboveground biomass), occurred on 22 May on F3, while the lowest was 29% on the F1 on the same date (Table 2).

The variation in the aboveground biomass and proportion of its "green" and NPV components on the fallow fields affects their spectral properties. A comparision of the three dates of the reflectance factors is presented in Figure 1 and shows that the variation in spectral reflectance between three fallow fields was smaller in the VIS wavebands (R_{450}, R_{550} and R_{650}) than in NIR (R_{850}) and SWIR (R_{1650}) wavebands. The greatest differences in reflectance among the fallow fields as well as between the fallow and crop fields were found on 22 May (Fig. 1).

Absorption of incident sunlight in the red portion of the spectrum decreases as "green" leaves lose pigments (Jensen 1996), thus with increasing proportion of NPV in the vegetation of the fallow fields red reflectance increases. F3, with 60% NPV and the lowest share of "green" biomass among fallow fields, showed the highest reflectance in the red wavelengths (Fig. 2). However, differences between the red band reflectance factors of the three fallow fields were small and statistically nonsignificant (Fig. 2).

NIR energy is strongly reflected due to micro-cellular structures in leaf material and responds to the amount of "green" foliage (Vaesen *et al.* 2001), thus the NIR reflectances of the F1 and F2 with the greater "green" biomass per m^2 (1550 g and 755 g, respectively on 22 May), were significantly higher than the reflectance of F3, with 200 g m^{-2} of "green" vegetation. The differences between the NIR band reflectance factors of F1 and F2 were nonsignificant, however F1 showed slightly lower reflectance resulting from a greater amount of "green" vegetation per m^2 (Fig. 2).

The greatest variation among the fallow fields occurred in the SWIR band. On 22 May differences among the 1650 nm reflectance factors of all three fallows were statistically significant. The reflectance in the SWIR band increases as leaves lose water (Jensen 2000) thus with increasing share of NPV on the fallow fields the reflectance in the SWIR wavelengths increased. The highest reflectance in the SWIR was recorded from F3 where NPV share values were near 60% of aboveground biomass (Fig. 2).

The vegetation indices developed from spectral measurements in the five wavelengths, have enlarged spectral variation among fallow fields (Fig. 3). The greatest sensitivity to differences in NPV share to aboveground live biomass showed *MSI* (3), an vegetation index that incorporate the NIR (850 nm) and SWIR (1650 nm) reflec-

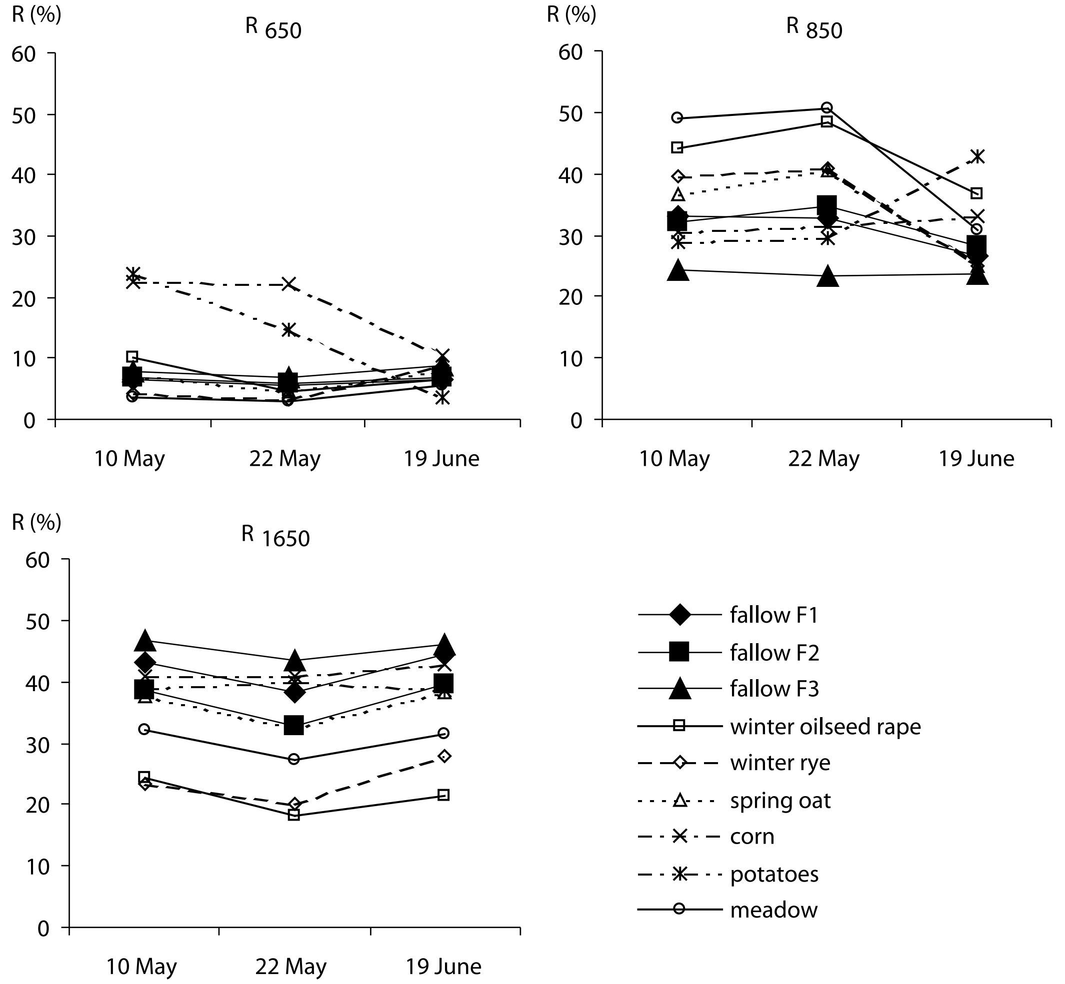

Fig. 1. Reflectance factor (R) for five wavebands (450, 550, 650, 850, 1650 nm) of the three fallow fields (Table 2), the five arable crops and the meadow (Table 1) measured on the three dates.

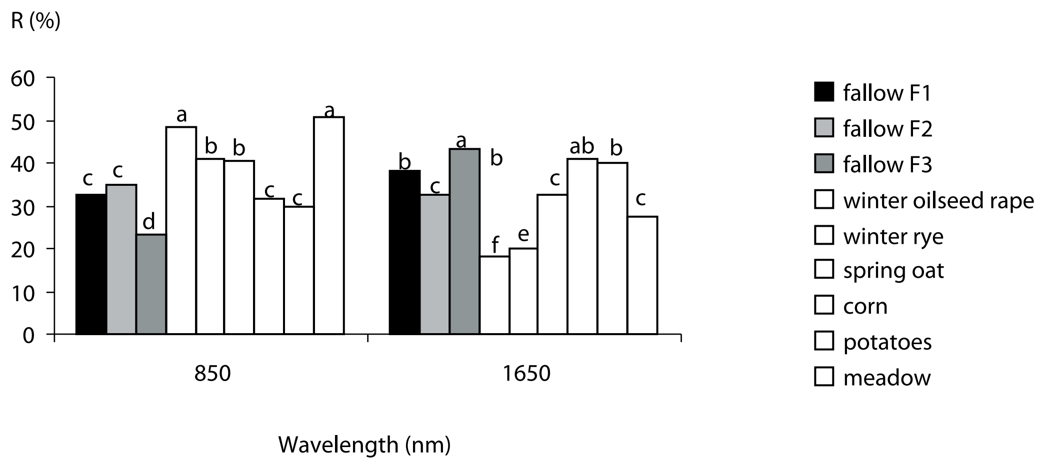

Fig. 2. Spectral variation (R – reflectance factor) in the five wavelengths among three fallow fields (Table 2), five arable crops and the natural meadow (Table 1) on 22 May.

Table 1. Agronomic characteristics of the five arable crops and the natural meadow on the three dates. (CGS – Crop growth stage; GC – Ground cover; AGPM – Aboveground biomass)

		10 May			22 May			19 June		
	Field area (ha)	CGS	GC (%)	AGPM (g m^{-2})	CGS	GC (%)	AGPM (g m^{-2})	CGS	GC (%)	AGPM (g m^{-2})
Winter rye	10.7	Heading	100	2702	Flowering, anthesis	100	3173	Ripening	100	4348
Spring oat	8.0	Stem elongation	64	960	Stem elongation	81	1989	Heading	100	5558
Winter oilseed rape	42.3	Flowering	100	4543	Development of fruit	100	4632	Ripening	100	4662
Corn	26.8	Before germination	0	0	Leaf develop-ment	4	32	Leaf development	42	1962
Potatoes	1.3	Germination	8	142	Leaf develop-ment	26	268	Flowering (begin-ning)	100	3952
Natural meadow	0.9	Species composition: *Vicia hirsuta* (L.), *Lolium perenne* (L.), *Trifolium arvense*(L.)	100	2722		100	2995		100	3185

Table 2. Soil characteristics, age, species composition and vegetation biomass of three fallow fields. Aboveground biomass: „Green" – live, chlorophyll-rich plants; "NPV" – nonphotosynthetic vegetation, i.e. dry leaves, senescent standing litter and woody stems or barks.

Fallow field	Field area (ha)	Soil type	Soil surface texture	Age (years)	Soil organic matter (%)	Species composition	Aboveground biomass ($g\ m^{-2}$)					
							10 May		22 May		19 June	
							Green	NPV	Green	NPV	Green	NPV
F1	4.2	Degraded Black Earth	loamy sand	5	7.80	*Dactylis glomerata* L.	1100	930	1550	632	1439	840
						Bromus inermis Leyss.						
						Erigeron canadensis L.						
						Artemisia vulgaris L.						
						Agropyron repens (L.) P.Beauv.						
F2	2.4	Degraded Black Earth	loamy sand	2	2.48	*Rumex acetosella* L.	610	620	755	542	952	600
						Apera spica-venti (L.) P.Beauv.						
						Trifolium repens L.						
						Erigeron canadensis L.						
						Capsella bursa-pastoris (L.) Medik.						
F3	1.7	Rusty soil	sand	5	1.75	*Vicia hirsuta* (L.) S.F.Gray	188	210	200	303	190	272
						Agropyron repens (L.) P.Beauv.						
						Potentilla anserina L.						
						Apera spica-venti (L.) P.Beauv.						
						Anthemis arvensis L.						

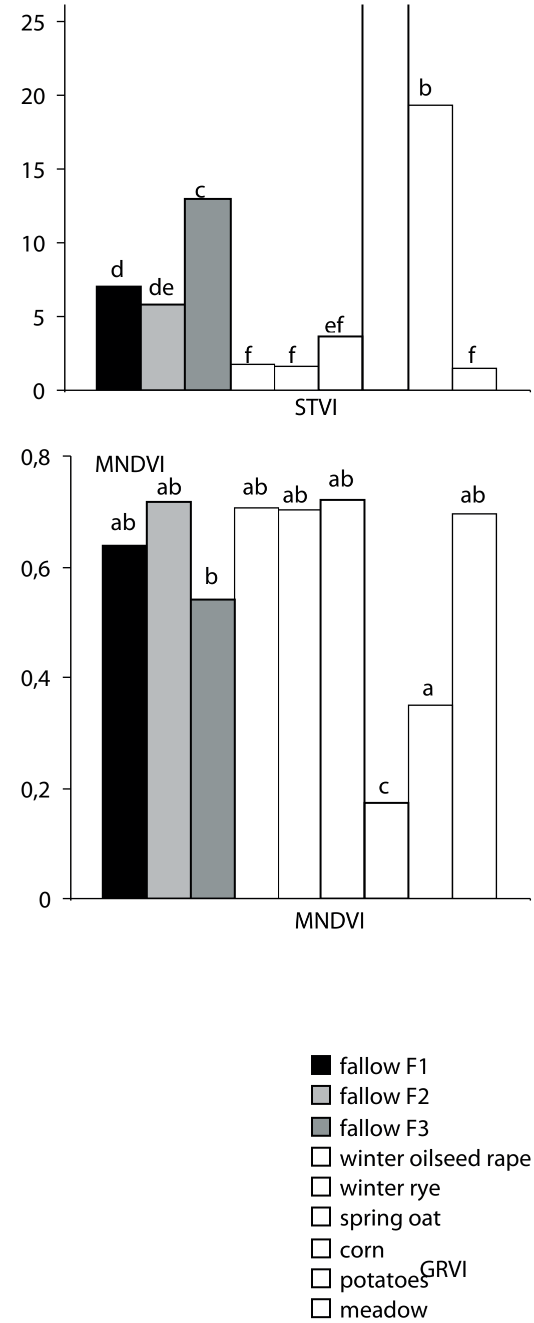

Fig. 3. Five vegetation indices *NDVI* (see (1) in text), *STVI* (2), *MSI* (3), *MNDVI* (4) and *GRVI* (5) for fallow fields (Table 2) and arable crops (Table 1) developed by combining the reflectance factors measured on 22 May.

tance factors. On 22 May the differences in *MSI* (3) values of the three fallow fields were significant, while in *NDVI* (1) and *STVI* (2) values only F3 differed significantly from F1 and F2. *NDVI* (1), *STVI* (2), *GRVI* (5) and *MNDVI* (4) presented a smaller variation than *MSI* (3) as these indices also involve red and green bands, which were the poorer discriminator of fallow fields than NIR and SWIR bands (Fig. 3).

3.2. Spectral differences between fallow fields and arable crops

At the time when the measurements were made, significant differences in the spectral response between the fallow fields and six arable crops occurred. Table 2 contains information about the crop growth stage, ground cover and aboveground biomass of the five arable crops and the meadow. In May, soil was partially covered by plants in corn, potatoes and spring oat crop and the spectral responses of these crops were determined, to a large extent, by soil background (Tueller 1987). Spectral properties of winter rye, winter oilseed rape and meadow were determined by "green" plants which entirely cover the soil.

Due to the presence of NPV in the vegetation on fallow fields their red reflectances on 22 May were relatively high and significantly higher than reflectances from winter rye and the meadow consisted of "green" plants only. However, absorption of red radiation by "green" plants of the fallow fields caused that their red reflectances were significantly lower than the reflectances from corn and potato crops. The red (650 nm) reflectance factors of fallows F1 and F2 did not differ significantly from the factors of winter oilseed rape and spring oat. Relatively high red reflectance from the winter oilseed rape was caused by the presence of yellow flowers and from the spring oat by the presence of bare soil for which the average percentage field-of-view of the luminancemeter was 20% (Fig. 3).

In the NIR waveband on 22 May the fallow fields, as well as the potato and corn crops, showed much lower spectral response than "green" crops. In the NIR wavelengths the reflectance from dead plant material is often greater than from "green" vegetation (Nagler *et al*. 2003), however according to van Leeuwen (1996) plant litter reflectance may be lower if the NPV is dark. A high proportion of dark NPV and low amount of "green" biomass on F3 resulted in the lowest NIR reflectance compared to the reflectance from all crops and fallows. Insignificant differences in R_{850} values occurred between F1, F2, potato and corn fields (Fig. 3).

The lowest reflectance in the SWIR waveband was recorded from winter oilseed rape and winter rye where plant biomass was highest. The values of the 1650 nm reflectance factors of both these crops were about twice lower than average values from all fallow fields, as well as the potato and corn fields. With the increasing amount of NPV on the fallow fields and the proportion of bare soil in the crops, the reflectance in the SWIR wavelengths increased and differences between F2 and spring oat, as well as between F1 and F3 and potato and corn fields were insignificant.

The spectral differences between fallow fields and arable crops were greater using vegetation indices than reflectance factors of individual wavelengths. Among the five indices only *GRVI* (5) and *NDVI* (1) of fallow fields were significantly different from these indices of all arable crops and the meadow. The *GRVI* (5) and *NDVI* (1) of the fallow fields showed significantly lower values than that of crops with high "green" vegetation cover and significantly higher values than that of crops where a soil background dominated. However, the greatest differences between the fallow fields and the arable crops showed *STVI* (2), using red, NIR and SWIR wavelengths. The average value of this index for the three fallow fields was about fivefold higher than for the winter rye and the meadow, while *NDVI* (1) and *GRVI* (5) values were only 1.3 and 1.6 times lower respectively (Fig. 3).

The spectral variation among fallow fields and differences between fallow and crop fields can be observed by changes in reflectances around the 'red edge'. The 'red edge' is the sharp change in leaf reflectance, approximately between 650 nm, where the strong absorption of radiation by chlorophyll is observed and 850 nm, where the increased multiple scattering of radiation occurs (Curran *et al*. 1991). The crops with the high amount of "green" biomass have the greatest slopes of the red edge among the three fallow and six crop fields (Fig. 4). The slopes

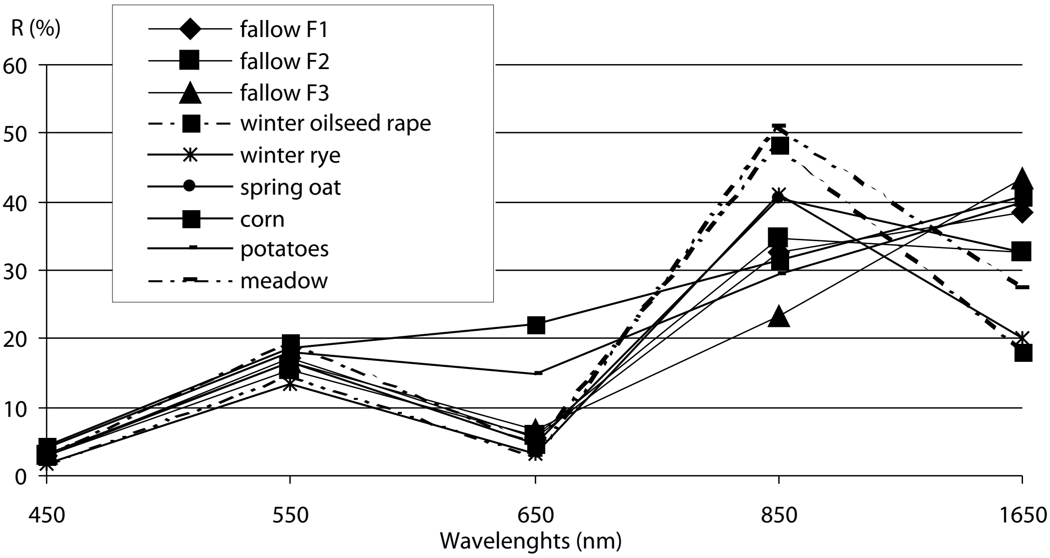

Fig. 4. The spectral reflectance (R – %) curves of the three fallow fields (Table 2), the five arable crops and the natural meadow (Table 1) recorded on 22 May.

for fallow fields, where NPV was mixed with "green" vegetation, are intermediate to those for crops with a high amount of "green" biomass and crops with a large proportion of bare soil. With increasing proportion of NPV in fallow fields the red edge decreased, and became similar to the slope for corn crop, which spectral properties were determined by the soil. This is consistent with Asner (1998) who found that as NPV content increases in "green" grass canopies the red edge becomes flatten and spectral reflectance curves of NPV and soils have similar shapes in the red and NIR wavelength ranges. However, according to Nagler (2000) the red edge is generally greater for NPV than for soils.

The slope of spectra from 850 nm to 1650 nm also changed in relation to the biomass of "green" vegetation and the proportion of NPV and soil in the field-of-view of the luminancemeter. The slope of the reflectance in this spectral region for crops with a high biomass of "green" vegetation decreased, while it increased for crops with plants partially covering the soil and fallow fields with an NPV proportion greater than about 40% (F1 and F3).

4. CONCLUSIONS

The research shows that there is a possibility of separating fallow fields of different age and situated on different soil types using using reflectance spectra. The soil conditions and the time for which the fields remain uncultivated determine the amount of the aboveground biomass, as well as its "green" to dead parts ratio. As the proportion of nonphotosynthetic vegetation NPV (nonphotosynthetic vegetation), increased in the total biomass on the fallow fields, the reflectance in the red and the SWIR (shortwave infrared) wavelengths increased, whereas the reflectance in the NIR (near-infrared) wavelengths decreased. The most considerable spectral variance among the three analysed fallow fields was observed in the reflectance of the SWIR wavelengths. Since the variance in the reflections of red wavelengths was statistically insignificant among fallow fields, the easiest method of differentiating individual fields was by means of the *MSI* index (3), calculated only from the NIR and the SWIR reflectance factors.

In the second part of May, when seasonal biomass peak of winter crops and meadows occurs and spring crops partly covers the soil, significant differences were observed in the spectral properties of fallow and cultivated fields. Using remotely sensed crop reflectance data, fallow fields can be successfully discriminated from the arable crops. Reflectance in the individual wavebands did not discriminate between the three fallow fields and five arable crops and the natural meadow and the vegetation indices gave better discrimination. Among the evaluated vegetation indices *NDVI* (1) and *GRVI* (5) were the best for discriminating between the fallow fields and crops. The fallow fields and crops with small vegetation cover (e.g. corn) which could practically be treated as base soil surface were better separated using *NDVI* (1). When differentiating fallow fields from crops in which the soil was totally covered by plants (e.g. winter rape, winter rye and meadow), the *STVI* index (2) was more useful as it combines reflectance factors from the red bandwidths as well as the NIR and SWIR wavelengths.

The most similar spectral characteristics were between fallow fields and crops in which the soil was only partially covered by plants (potatoes and oat). This results from similar NPV spectral characteristics that are present in fallow fields and soils not fully covered by cultivated plants. Further research is required since, depending on the humidity and the decay of dead parts of plants, NPV can be lighter or darker than the soil, and consequently resemble its spectrum to a greater or a lesser degree

5. REFERENCES

Adamczewski K., Matysiak K. 2002 – [Compendium of growth stage identification keys for mono- and dicotyledonous plants] – Instytut Ochrony Roślin, Poznań, 85 pp. (in Polish)

Asner G. P. 1998 – Biophysical and biochemical sources of variability in canopy reflectance – Remote Sens. Environ. 64: 234–253.

Balcerkiewicz S. 1997 – Wokół krajobrazu porolnego słów kilka [About post-agricultural landscape some words] – Przegląd Przyrodniczy, VIII, 1/2: 3–12. (in Polish)

Baret F., Fourty T. 1997 – Estimation of leaf water content and specific leaf weight from reflectance and transmittance measurements – Agronomie, 17: 455–464.

Bochenek Z. 1999 – Operacyjne wykorzystanie zdjęć satelitarnych NOAA AVHRR do oceny warunków rozwoju upraw w Polsce [Operation use of NOAA AVHRR satellite images for crop condition assessment in Poland] – Fotointerpretacja w geografii – Problemy Telegeoinformacji, 29:3–13. (in Polish)

Carter M. R. 1993 – Soil sampling and methods of analysis – Lewis Publishers, CRC Boca Raton, Fl.

Curran P. J., Dungan J. L., Macler B. A., Plummer S. E. 1991 – The effect of a red leaf pigment on the relationship between red edge and chlorophyll concentration – Remote Sens. Environ. 35: 69–76.

Daughtry C. S. T., Walthall C. L., Kim M. S., Brown de Colstoun E., McMurtrey J. E. 2000 – Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance – Remote Sens. Environ. 74: 229–239.

Jensen J. R. 1996 – Introductory Digital Image Processing – Upper Saddle River, New Jersey: Prentice Hall. 316 pp.

Jensen J. R. 2000 – Remote sensing of the environment – New York: Prentice-Hall.

Jorge L. A. B., Garcia G. J. 1997 – A study of habitat fragmentation in Southeastern Brazil using remote sensing and geographic information systems (GIS) – Forest Ecology and Management, 98: 35–47.

Kuusk A. 1991 – The angular distribution of reflectance and vegetation indices in barley and clover canopies – Remote Sens. Environ. 37: 143–151.

Lelong C. C. D., Pinet P. C., Poilve H. 1998 – Hyperspectral imaging and stress mapping in agriculture: a case study on wheat in Beauce (France) – Remote Sens. of Environ. 66: 179–191.

Lillesand T. M., Kiefer R. W. 2000 – Remote sensing and image interpretation. John Wiley & Sons, pp. 230–236.

Nagler P. L., Daughtry C. S. T., Goward S. N. 2000 – Plant litter and soil reflectance – Remote Sens. Environ. 71: 207–215.

Nagler P. L., Inoue Y., Glenn E. P., Russ A. L., Daughtry C. S. T. 2003 – Cellulose absorption index (CAI) to quantify mixed soil-plant litter scenes – Remote Sens. Environ. 87: 295–309.

Niedźwiecki E., Meller E., Malinowski R. 1998 – Wartość i przydatność rolnicza odłogowanych gleb Pomorza Zachodniego [The value and usefulness for agriculture soils of fallow fields in Pomorze Zachodnie region] – Bibl. Fragm. Agron. 5: 35–43. (in Polish)

Numata I., Soares J. V., Roberts D. A., Leonidas F. C., Chadwick O. A., Batista G.T. 2003 – Relationships among soil fertility dynamics and remotely sensed measures across pasture chronosequences in Rondônia, Brazil – Remote Sens. Environ. 88: 446–455.

Piekarczyk J. 2001 – Temporal variation of the winter rape crop spectral characteristics – Int. Agrophysics, 15: 101–107.

Piekarczyk J. 2004 – Zmienność charakterystyk spektralnych zbóż ozimych i nieużytków porolnych w sezonie wegetacyjnym [Temporal variation of winter grain crops and fallows spectral characteristics] – Problemy Ekologii Krajobrazu, 13: 221–226. (in Polish)

Phinn S. R., Stow D. A., Franklin J., Mertes L. A. K., Michaelsen J. 2003 – Remotely Sensed Data for Ecosystem Analyses: Combining Hierarchy Theory and Scene Models – Environmental Management, 31:0429–0441.

Pinter P. J., Jackson R. D., Idso S. B., Reginato R. J. 1983 – Diurnal patterns of wheat spectral reflectances – IEEE Trans. Geosci. Remote Sens. 21: 156–163.

Price K. P., Guo X., Stiles J. M. 2002 – Optimal Landsat TM band combinations and vegetation indices for discrimination of six grassland types in eastern Kansas – Int. J. of Remote Sens. 23: 5031–5042.

Purevdorj T., Tateishi R., Ishiyma T., Honda Y. 1998 – Relationships between percent vegetation cover and vegetation indices – Int. J. of Remote Sens. 19: 3519–3535.

Ridao E., Oliveira C. F., Conde J. R., Minguez M. I. 1996 – Radiation interception and use, and spectral reflectance of contrasting canopies of autumn sown faba beans and semi-leafless peas – Agric. Forest Meteor. 79: 183–203.

Ridao E., Conde J. R., Minguz M. I. 1998 – Estimating fAPAR from nine vegetation indices for irrigated and nonirrigated faba bean and semileafless pea canopies – Remote Sens. Environ. 66: 87–100.

Rock B. N., Williams D. L., Vogelman J. E. 1985 – Field and airborne spectral characterization of suspected acid deposition damage in red spruce (*Picea rubens*) from Vermont – Proc. Symp. on Machine Processing of Remotely Sensed Data. Purdue University, West Lafayette, IN, pp. 71–81.

Rouse J. W. Jr., Haas R. H., Schell J. A., Deering D. W. 1973 – Monitoring vegetation systems in the Great Plains with ERTS (In: Proceedings of the Earth Research Technical Satellite–1 Symposium) – Goddard Space Flight Center, Washington, DC, 309–317.

Rychnowska M. 1976 – Alluvial grassland hydrosphere: primary production and plant processes – Polish Ecological Studies, 2: 103–112.

Seelan S. K., Soizik L., Casady G. M., Seielstad G. A. 2003 – Remote sensing applications for precision agriculture: A learning community approach – Remote Sens. of Environ. 88: 157–169.

Steven M. D., Malthus T. J., Baret F., Xu H., Chopping M. J. 2003 – Intercalibration of vegetation indices from different sensor systems – Remote Sens. Environ. 88: 412–422.

Strączyńska S., Rola H. 1998 – Wpływ różnych sposobów zagospodarowania odłogu na fizykochemiczne właściwości gleby [ ] – Bibl. Fragm. Agron. 5: 181–187.

Tueller P. T. 1987 – Remote sensing science application in arid environments – Remote Sens. Environ. 23: 143–154.

van Leeuwen W. J. D., Huete A. R. 1996 – Effects of standing litter on the biophysical interpretation of plant canopies with spectral indices – Remote Sens. Environ. 55: 123–138.

Vaesen K., Gilliams S., Nackaerts K., Coppin P. 2001 – Ground-measured spectral signatures as indicators of ground cover and leaf area index: the case of paddy rice – Field Crops Res. 69: 13–25.

Wiegand C. L., Richardson A. J., Escobar D. E., Gerbermann A. H. 1991 – Vegetation Indices in crop assessments – Remote Sens. Environ. 35: 105–119.

Woolley J. T. 1971 – Reflectance and transmittance of light by leaves – Plant Physiol. 47: 656–662.