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COMPARISON OF SEVERAL VEGETATION INDICES CALCULATED ON THE BASIS OF A SEASONAL SPOT XS TIME SERIES, AND THEIR SUITABILITY FOR LAND COVER AND AGRICULTURAL CROP IDENTIFICATION

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K e y w o r d s: vegetation indices, crop identification, SPOT XS.

A b s t r a c t

The fact that many vegetation indices have been proposed over last decades made specialists search for the most suitable vegetation index for a given remote sensing application. In this paper several vegetation indices have been compared and analyzed based on multispectral SPOT images taken for the same season (2003) and agricultural test area (Żuławy Wiślane). The suitability of vegetation indices was examined in terms of their further use for land cover/crop identification. The results show that there are no significant differences between simple and advanced indices, either for different land cover types or crops.

PORÓWNANIE KILKU WKAŹNIKÓW ROŚLINNOŚCI WYLICZONYCH NA PODSTAWIE JEDNOSEZONOWEJ SERII OBRAZÓW SPOT XS I ZBADANIE ICH UŻYTECZNOŚCI DO OKREŚLANIA TYPU POKRYCIA TERENU ORAZ IDENTYFIKACJI WYBRANYCH UPRAW ROLNICZYCH

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S ł o w a k l u c z o w e: wskaźniki roślinności, identyfikacja upraw, SPOT XS.

S t r e s z c z e n i e

Znaczna liczba zaproponowanych dotychczas w literaturze wskaźników roślinności skłania do poszukiwania najlepszego, najbardziej odpowiedniego wskaźnika do danego zastosowania teledetekcji. Porównano i zanalizowano wybrane wskaźniki obliczone na podstawie obrazów satelitarnych SPOT XS z jednego sezonu wegetacyjnego (2003) dla obszaru Żuław Wiślanych. Użyteczność wskaźników zbadano z punktu widzenia ich przydatności w identyfikacji upraw rolniczych i form pokrycia terenu. Wyniki wskazują, że nie ma znaczących różnic między prostymi i zaawansowanymi wskaźnikami roślinności, ani dla różnych typów pokrycia terenu, ani odmiennych upraw rolniczych.

Introduction

Natural vegetation cover and agricultural crops are frequently the subjects of remote sensing studies. The information obtained in this way is a source of knowledge used for monitoring and evaluating the Earth's vegetative cover. It is also used for environmental resources management. One of the ways enabling to get such information is determination of vegetation indices (VIs). Over years many vegetation indices have been proposed for determining the vigor and health of vegetation. Theirs formulas resulted from attempts to create better indices, which means that they take into account many factors, like soil reflectance, atmosphere, vegetation density etc. The aim of all these improvements and modifications is to get more reliable information about vegetation based on remotely sensed values (reflectances).

The usual form of a vegetation index is a ratio of reflectance measured in two bands, or their algebraic combination. Spectral ranges (bands) to be used in VIs calculation are selected depending on the spectral properties of plants. First researchers interested in the spectral properties of plants were WILLSTATTER and STOLL (1913). They studied the phenomena of light entering plant cells. Later studies, concerning interactions between light of a different wavelength with vegetation, allowed to determine bands used in VIs. Nearly all commonly used VIs are based on near-infrared (NIR) and red (R) bands. In general, reflectance in Red band depends on chlorophyll content, and reflectance in Near Infrared – on internal structure of the plant cell. Reflectances in these spectra are uncorrelated with each other and they show high spectral contrast for vegetation.

It should be mentioned that despite many studies it is sometimes difficult to determine precisely what is expressed by VIs. Although clearly correlated with chlorophyll absorption by foliage, it has been related to many plant properties, including the percentage of green cover and biomass, productivity, absorbed photosynthetically active radiation – APAR, leaf area index – LAI and biophysical properties such as photosynthetic capacity. The correlations between the biophysical parameters of plants and VIs, especially between LAI and the most popular index NDVI, are frequentlt the subjects of investigations. According to many authors when LAI > 3, NDVI becomes saturated. It means that information about vegetation is much poorer in a such situation. Hence some other VIs were proposed and elaborated.

As demonstrated in many papers, the reflectance in R and NIR bands, and in consequence Vis, are also related to:

- vegetation type (trees, bushes, grass, etc.), precisely type of leaves, their shape, inclination angle,
- crop ”architecture”,
- plant growth stage,
- leaf pigment content: chlorophyll and other pigments like carotene, xantophyll etc. (their composition and distribution in leaves),
- water content of plants, and many other.

Also the soil, atmosphere and geometry of Sun – target – sensor affect the radiation recorded by the sensor, and then influence the values of VIs. These factors introduce ”noise” to the information which can be acquired from vegetation indices. Soil color can change the value of VI. Some studies have shown that dark soil resulted in higher values of VIs for parcels partially covered by vegetation, compared with bright soil when the NDVI index was calculated, and smaller values in the case of the PVI index. Changes in VIs accounted for approx. 50%.

Moreover, the atmosphere and all suspended particles significantly influence the radiation reaching the sensor, and – indirectly – vegetation indices. In order to separate the influence of atmosphere from the vegetation signal, bands other than NIR and R are introduced to VIs formulas. This is usually a blue band. It is assumed that this band contains almost all effect of atmosphere on radiation (influence of scattering, absorbing etc.). In this study the blue band was unavailable among all SPOT specific spectral bands.

Despite many factors disturbing the vegetation signal, VIs are sensitive to plant physiology, internal structure of the crop/vegetation community or their spatial ”pattern”, and can be used for land cover and agricultural crop mapping. In the natural and intuitive approach, VIs are perceived as ”neochannels” in colour compositions, substituting original bands as colour plans RGB (Red-Green-Blue). The use of VIs is recommended by e.g. the JRC/IPSC Institute in remote sensing methodology of agricultural crop identification within the framework of Common Agricultural Policy. The advantage of VIs is that they can exhibit, in a single ”index image”, the properties of the objects originally registered in two bands. Thus we can reduce the number of bands and include in the composition additional channels obtained with one or several sensors, at the same or different times.

Objective

Many different vegetation indices (VIs) have been developed in last decades. Tasking into account their number, it seems that the following questions should be answered: which VIs are the most suitable for mapping purposes, and at which stage of crop development? Are we allowed to use VIs arbitrarily, or should we determine which of them improves the accuracy of land cover and crop identification to the highest degree? These questions are stemming from fact that the sensitivity of VIs to many factors (e.g. plant growth stage, chlorophyll content, etc.) is different. The aim of the present study was to find VIs best suited for crop identification with a given multitemporal but uniseasonal SPOT XS data set. We had at our disposal five programmed multispectral SPOT images taken for the same season (2003) and agricultural test area. The satellite registrations were separated in time by some weeks or even a month, so the crop development phase, density, percentage of foliage cover and "architecture" have changed over this period. We have distinguished a priori 4 types of vegetation: cereals, rapeseed, sugar beet and maize that can be considered examples of different crop "architecture". Thus it seemed interesting to compare several most populalr VIs for this data set, and choose the most suitable one in terms of its further use for land cover/crop identification. We examined the differences between VIs for the same and various crops on all registration dates, to find the most distinctive Vis. Then several VIs were used as input channels for making colour compositions. The measure of their suitability was the colour contrast of output images.

Types of vegetation indices

Vegetation indices can be classified into the following groups:

1) Slope-based VIs – the position of each point in 2-dimensional NIR-Red space is geometrically equivalent to the slope (tangent) of the line connecting the origin of reference and this particular point on a scattergram.

2) Distance-based VIs – they require to establish the "soil line" and measure the perpendicular distance of each point from this line. On scattergrams presenting soils and various plants, points of the soil form a line at approximately 45, passing through the origin. Some plants overlap this line (mostly arid-region plants and litter), whereas the majority of them are spread out in a fan towards the NIR axis. The determination of the slope and intercept of the soil line requires to draw a line through this cloud of points representing soil in NIR-Red space.

Another difference between distance-based and slope-based VIs is the orientation of lines of equal vegetation intensity/vividness ("isovegetation lines"), regardless of moisture conditions. In slope-based VIs isolines converge at the origin, whereas in distance-based VIs all isolines remain parallel to the soil line. SAVI family VIs are also classified into this group, although isolines for these VIs are neither parallel nor convergent at the origin.

3) Orthogonal transformation VIs – based on decorrelation of a set of spectral bands through orthogonalization. These VIs produce new uncorrelated bands. Each band represents a different "dimension" of the information contained in the original band set.

4) Red Edge Inflection Point (REIP) – VIs based on waveform analysis techniques (REIP_Gaus (MILLER et al. 1990), REIP_Poly (BROGE, LEBLANC, 2001), REIP_Lagr (DAWSON, CURRAN 1998). They make use of the Gaussian, polynomial and Lagrangian models, respectively. The red edge is a characteristic feature of the spectral response of vegetation. It is a rapid change in reflectance observed in the spectrum of green plants at the transition between the visible and near-infrared wavelengths. The red edge is a fairly wide feature of approximately 30 nm. The measure making it easier to compare particular plant species is the point of maximum slope on the red-infrared curve. The typical location of the inflection point is between 690 nm and 740 nm in fresh leaves, and is determined by the interaction between chlorophyll absorption of red light and the internal scattering process in the leaf. Increased or decreased chlorophyll content (plants having good conditions for development and plants growing under stress conditions) results in the shift of the inflection point towards longer or shorter wavelengths, respectively. Unfortunately, red-edge changes cannot be applied to quantify environmental stress, because they are also related to leaf age, development stage, and canopy architecture. Moreover, the presence or absence of other pigments, such as the non-photosynthetic leaf pigment anthocyanin, also affects the location of the red edge (USTIN et al. 1996).

It is usually assumed that information provided by VIs regards green vegetation. In fact the colour of vegetation changes during its growth. It influences the reflectance of vegetation in green bands, which can be misleading. In such a case only reflectance in NIR indicates that there exists live, non-dry, vegetation. GAMON and SIMS (2002) associated change of colour with the contents of various pigments, and developed indices based on pigment absorption features, indicating the condition of a given plant.

In this study we focused on the first two groups only, because these VIs are commonly used in remote sensing, the best known of them being widely applied in the software available on the market. The third group is closer to hyperspectral imagery and will be analyzed separately.

Slope-based Vegetation Indices

Ratio Vegetation Index

The Ratio Vegetation Index (RATIO) was proposed by ROUSE et al. (1974). This technique is characterized by limited applicability as for vegetation assessment. Firstly, it does not allow to eliminate the effects of topography and variations in the sun illumination angle, so that the output images reflect only the presence of green vegetation. Secondly, RATIO images do not have normal distribution and, in consequence, desirable statistical properties.

$$\text{RATIO} = \frac{\text{NIR}}{\text{R}} \quad (1)$$

Normalized Difference Vegetation Index

The Normalized Difference Vegetation Index (NDVI) was introduced by ROUSE et al. (1974). This is the most commonly used VI, as it enables to eliminate topographic effects and variations in the sun illumination angle, as well as other atmospheric elements such as haze. NDVI images, in contrast to RATIO, have normal distribution.

$$\text{NDVI} = \frac{\text{NIR} - \text{R}}{\text{NIR} + \text{R}} \quad (2)$$

Transformed Vegetation Index

The Transformed Vegetation Index (TVI) proposed by Deering et al. (1975) is aimed at eliminating negative values and transforming NDVI histograms into a normal distribution.

$$\text{TVI} = \sqrt{\text{NDVI} + 0.5} \quad (3)$$

However, it cannot be calculated when NDVI < –0.5.

Thiam's Transformed Vegetation Index

In order to avoid problems which occur in *TVI*, PERRY and LAUTENSCHLAGER (1984) proposed the Corrected Transformed Vegetation Index (CTVI).

$$\text{CTVI} = \frac{(\text{NDVI} + 0.5)}{\left|(\text{NDVI} + 0.5)\right|} \cdot \sqrt{\left|(\text{NDVI} + 0.5)\right|}$$

Then Thiam simplified CTVI and introduced the Thiam's Transformed Vegetation Index (TTVI), making use of the absolute value of NDVI:

$$\text{TTVI} = \sqrt{\left|(\text{NDVI} + 0.5)\right|} \quad (4)$$

Distance-based vegetation indices

The procedure is based on the soil line concept. Pixels near the soil line are assumed to represent the soil, and those far away are assumed to represent vegetation. Distance-based VIs using the soil line require the slope (a) and intercept (b) of the line as inputs in calculations.

Perpendicular Vegetation Index 1

The Perpendicular Vegetation Index 1 (PVI_1) was developed by PERRY and LAUTENSCHLAGER (1984) as:

$$PVI_1 = \frac{a\mathrm{NIR} - \mathrm{R} + b}{\sqrt{a^2 + 1}} \quad (5)$$

Perpendicular Vegetation Index 2

The Perpendicular Vegetation Index 2 (PVI_2) was proposed by WALTHER and SHABAANI (1991) and, BANNARI et al. (1996).

$$PVI2 = \frac{\mathrm{NIR} - a\mathrm{R} + b}{\sqrt{1 + a^2}} \quad (6)$$

Difference Vegetation Index

The Difference Vegetation Index (DVI) was suggested by RICHARDSON and WIEGAND (1977) as an easier vegetation index calculation algorithm. Similarly as in PVI_1, also in DVI zero indicates bare soil, values less than zero indicate water, and those greater than zero indicate vegetation.

$$DVI = a\mathrm{NIR} - \mathrm{R} \quad (7)$$

Soil Adjusted Vegetation Index

The Soil Adjusted Vegetation Index (SAVI) was proposed by HUETE (1988). It is aimed at minimizing the soil influence on vegetation quantification by introducing the soil adjustment factor L. For high vegetation cover the value of L is 0.0 (or 0.25), and for low vegetation cover – 1.0. For intermediate vegetation cover L = 0.5, and this value is used most widely.

$$SAVI = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R} + \mathrm{L}}(1 + \mathrm{L}) \quad (8)$$

Transformed Soil Adjusted Vegetation Indices 1 and 2

The Transformed Soil Adjusted Vegetation Indices 1 and 2 ($TSAVI_1$, $TSAVI_2$), proposed by BARET et al. (1989) and BARET and GUYOT (1991) respectively, require to know the values a and b (slope and intercept) of the soil line *a priori*. $TSAVI_2$ has a factor of 0.08 to minimize the effect of background soil brightness.

$$TSAVI_1 = \frac{a(\mathrm{NIR} - a\mathrm{R} - b)}{\mathrm{R} + a\mathrm{NIR} - ab} \quad (9)$$

and

$$TSAVI_2 = \frac{a(\mathrm{NIR} - a\mathrm{R} - b)}{\mathrm{R} + a\mathrm{NIR} - ab + \mathrm{X}(1 + a^2)} \quad (10)$$

X = 0.08.

Modified Second Adjusted Vegetation Indices 1 and 2

The Modified Second Adjusted Vegetation Indices 1 and 2 ($MSAVI_1$, $MSAVI_2$) were developed. These indices are variants of SAVI, where the factor L is dynamically adjusted. In $MSAVI_1$ the factor L is described by the following expression:

$$L = 1 - 2 \cdot a \cdot NDVI \cdot WDVI$$

(WDVI is Weighted Difference Vegetation Index (CLEVERS 1988),

$$WDVI = NIR - aR).$$

$MSAVI_2$ is an iterated version of $MSAVI_1$, developed by substituting $1 - MSAVI_{(n-1)}$ as the L factor in $MSAVI_{(n)}$, and then inductively solving $MSAVI_{(n)} = MSAVI_{(n-1)}$;

$$MSAVI_1 = \frac{NIR - R}{NIR + R + L}(1 + L) \tag{11}$$

and

$$MSAVI_2 = \frac{2NIR + 1 - \sqrt{(2NIR + 1)^2 - 8(NIR - R)}}{2} \tag{12}$$

Study area

The study area is located in northern Poland, around the Vistula River and its arm, Nogat. It is a part of Żuławy Wiślane. The geographic coordinates of the study area are: NW latitude 5407', longitude 1845', SE: latitude 5350', longitude 1910'. The test area consists of two different parts. The western part is a flat plain (Vistula delta), whereas the eastern part is a slightly hilly postglacial area. Soils of the area are: *Eutric Fluvisol* (western part), *Eutric Cambisol* (eastern part). Main crops cultivated here are: winter wheat, spring wheat, sugar beet, winter and spring rapeseed, maize. Potatoes and other cereals (barley, rye) are very rare. From spring through summer, when this study was conducted, average temperature was about 17°C. From April through June the amount of rainfalls was insufficient, which had a negative influence on plants. At the end of July heavy rainfalls occurred.

Materials and Methods

Satellite data

Satellite data were collected by SPOT during one vegetative season on 15th April, 6th May, 5th June, 26th June and 1st August 2003. The characteristics of each scene and results of radiometric calibration are presented in Table 1.

Table 1

Satellite data description

K – J identification	069 – 240	069 – 240	069 – 240	069 – 240	069 – 240
Date	2003.04.15 10:00:02	2003.05.06 09:55:49	2003.06.05 09:52:56	2003.06.26 09:46:19	2003.08.01 09:57:14
Instrument	HRV 2	HRV 1	HRVIR 2	HRVIR 2	HRVIR 2
Preprocessing level	1B	1B	1B	1B	1B
Spectral mode	XS	XS	XI	XI	XI
Number of spectral bands	3	3	4	4	4
Spectral band indicator (gain number, absolute calibration gains ($W/m^2/sr/\mu m$))	XS1 (8) 1.43774) XS2 (8) 1.26620) XS3 (6) 1.50824)	XS1 (8) 1.30509 XS2 (8) 1.27265 XS3 (6) 1.53995	XS1 (6) 3.03890 XS2 (5) 2.63588 XS3 (4) 1.90685 XS4 (3) 8.191106	XS1 (6) 3.03890 XS2 (5) 2.63588 XS3 (3) 1.27350 XS4 (3) 8.19106	XS1 (6) 3.03890 XS2 (5) 2.63588 XS3 (3) 1.27350 XS4 (3) 8.19106
Orientation angle	14.6°	13.8°	13.0°	12.3°	13.8°
Incidence angle	R2.0°	R6.4°	R11.4°	R15.5°	R6.7°
Sun angles (°)	Azimut: 164.6 Elevation: 44.5	Azimut: 162.7 Elevation: 51.4	Azimut: 158.8 Elevation: 57.1	Azimut: 155.3 Elevation: 57.6	Azimut: 158.9 Elevation: 53.0
Scene center location					
Latitude	N054°01'02"	N053°57'54"	N054°00'59"	N054°00'59"	N054°01'01"
Longitude	E018°58'14"	E019°01'25"	E019°01'58"	E019°06'50"	E019°02'15"
Radiometric calibration					
C($W/m^2/sr/\mu m$)					
C_1	1.43774	1.30509	3.03890	3.03890	3.0389
C_2	1.26620	1.27265	2.63588	2.63588	2.63588
C_3	1.50824	1.53995	1.90685	1.27350	1.2735
C_4			8.19106	8.19106	8.19106

cont. Table 1

$E(W/m^2/\mu m)$					
E_1	1865	1865	1851	1851	1851
E_2	1615	1620	1586	1586	1586
E_3	1090	1085	1054	1054	1054
E_4	–	–	240	240	240
d	1.00316	1.00876	1.0145851	1.01651126	1.0149861
d_2	1.00633	1.01760	1.0293829	1.033295	1.030196783
Sun elevation	44.5°	51.4°	57.1°	57.6°	53°
Θ = 90-sun elevation	45.5°	38.6°	32.9°	32.4°	37°
cos(q)	0.70090926	0.7815204	0.83961986	0.8443279	0.79863551
cal_coefficients					
1	0.00168216	0.00168061	0.000684733	0.000683502	0.0007204413
2	0.00220573	0.00198408	0.00092133	0.0009196748	0.0009693768
3	0.00274366	0.00244821	0.0019164	0.0028643333	0.0030191305
4	–	–	0.00195926	0.0019557429	0.0020614371

Each image was radiometrically calibrated, which means that the reflectance on the top of atmosphere (TOA) was calculated. This step permits to normalize the pixel values for each registration and eliminate changes in solar illumination (solar zenithal angle differences). Radiometric calibration coefficients "C_i" enabling luminance calculation were retrieved from SPOT scene metadata. TOA reflectance was calculated following the simple formulas:

$$L = \frac{DN}{C_i} \tag{13}$$

$$r = \frac{\pi \cdot L \cdot d^2}{E_s \cdot \cos\theta} \tag{14}$$

$$r = \frac{\pi \cdot d^2}{E_{si} \cdot \cos\theta} \cdot \frac{DN}{C_i} = \frac{\pi \cdot d^2}{E_{si} \cdot \cos\theta \cdot C_i} \cdot DN = cal\_coeff \cdot DN \tag{15}$$

where:
- r – TOA reflectance,
- L – at the sensor luminance,
- DN – original digital numbers of the pixels in SPOT bands.

A constant value, equal to reflectance of the darkest object in the image (reflectance of deep clear water) was subtracted from the XS3 band (NIR) to remove the influence of atmosphere in this channel.

Ground-truth data

Almost at the same time when SPOT images were taken, field surveys were conducted, i.e. on 12th April, 1st May, 11th May, 6th June, 23/24th June, 4th July, 30th July. They consisted in collecting plant samples (destructive methods) to obtain the characteristics of parcels and vegetation, observations and description of plant conditions and growth stages, taking digital photographs of the parcels and plants. The characteristics of parcels and vegetation in our study are canopy cover percentage, soil moisture (soil samples were collected in order to estimate this parameter), biomass and leaf area index (LAI). These measurements were performed for a few parcels as a reference for further image interpretation, and not in view of any statistical estimations of relationships between vegetation parameters and vegetation indices.

For many parcels (about 120) the type of crop/land cover and main development stages were recorded. Of this set we selected a subset of large parcels of different types for index calculation: 16 parcels for winter wheat, 5 – spring wheat, 13 – winter rape, 4 – spring rape, 17 – sugar beet, 5 – maize, 3 – hemp, 2 – fallow, 1 – deciduous forest, 1 – coniferous forest, 1 – lake (water). The areas of each parcel/crop are presented in Table 2.

Table 2

Area (ha) of each parcel

Parcel ID	Area (ha)	Parcel ID	Area (ha)	Parcel ID	Area (ha)	Parcel ID	Area (ha)
9 (ww)	73.34	40 (sw)	18.34	13 (sr)	2.77	89 (sb)	18.25
11 (ww)	53.46	47 (sw)	18.19	14 (sr)	3.11	90 (sb)	35.91
16 (ww)	54.55	91 (sw)	12.14	25 (sr)	13.83	105 (sb)	12.62
22 (ww)	36.97	97 (sw)	15.19	96 (sr)	54.44	117 (sb)	15.88
24 (ww)	58.54	19 (wr)	21.34	4 (sb)	13.06	59 (m)	7.11
32 (ww)	21.43	20 (wr)	46.67	8 (sb)	16.25	63 (m)	44.19
45 (ww)	15.15	21 (wr)	28.07	23 (sb)	38.66	64 (m)	9.56
51 (ww)	13.85	29 (wr)	20.23	37 (sb)	36.19	65 (m)	7.34
57 (ww)	54.44	60(wr)	16.81	38 (sb)	26.08	76 (m)	54.38
58 (ww)	22.33	66 (wr)	16.14	42 (sb)	9.44	108 (h)	11.54
62 (ww)	55.43	67 (wr)	17.73	43 (sb)	5.83	109 (h)	34.50
69 (ww)	48.88	68 (wr)	15.36	48 (sb)	60.39	113 (h)	46.92

cont. Table 2

82 (ww)	20.39	77 (wr)	26.67	53 (sb)	19.07	107 (f)	24.42
86 (ww)	35.82	80 (wr)	20.03	55 (sb)	7.69	111 (f)	33.29
92 (ww)	66.44	81 (wr)	25.22	61 (sb)	51.37	118 (fd)	180.09
94 (ww)	17.42	95 (wr)	19.65	84 (sb)	65.85	119 (fc)	224.61
33 (sw)	37.16	112 (wr)	41.70	88 (sb)	10.35	120 (w)	100.44

Crop	area (ha)	crop	area (ha)
Winter wheat (ww)	648.44	hemp (h)	92.96
Spring wheat (sw)	101.02	fallow (f)	57.71
Winter rape (wr)	315.61	deciduous forest (fd)	180.09
Spring rape (sr)	74.15	coniferous forest (fc)	224.61
Sugar beet (sb)	442.90	water (w)	100.44
Maize (m)	122.58		

Each crop has its own growth rate, which was visible in plots; the average values of VIs were determined for each plot and different dates. Based on these values and direct observations, having specified plant growth stages (for wheat, rape and sugar beet only), we determined three main stages: I – stage of vegetation emergence (and/or bare soil), II – mid-stage, which included the following phases: tillering, earing for wheat; blooming for rape, development of leaves and roots, closing of inter-rows for sugar beet (canopy closure), III – mature stage.

Table 3

The stages of crop development versus dates of satellite imaging

Species	Emergence and/or bare soil	Mid-stage	Pre-tasseled/mature stage
Winter wheat	VIs of 15th April	VIs of 6th May and 5th June	VIs of 26th June and 1st August
Spring wheat	VIs of 15th April and 6th May	VIs of 5th June	VIs of 26th June and 1st August
Winter rape	VIs of 15th April	VIs of 6th May	VIs of 5th June and 26th June
Spring rape	VIs of 15th April and 6th May	VIs of 5th June	VIs of 26th June
Sugar beet	VIs of 15th April and 6th May	VIs of 5th June	VIs of 26th June and 1st August
Maize	VIs of 15th April and 6th May	VIs of 5th June	VIs of 26th June and 1st August
Hemp	VIs of 26th June	VIs of 1th August	Not imaged

Table 4

Growth stages of winter wheat, spring wheat, winter rape, spring rape, sugar beet and maize

Specification	Winter wheat	Spring wheat	Winter rape	Spring rape	Sugar beet	Maize
15th April	tillering	emergence	stem elongation	emergence	–	–
1st May	stem formation	tillering	flower bud development	emergence	emergence	Emergence
11th May	stem formation	stem formation	flowering	stem elongation	development of leaves	Emergence
5th June	earing	thickening of leaf sheath	seed ripening	flowering	development of leaves and roots	stem elongation
26th June	wax maturity	earing	maturity	flowering	row closeness	stem elongation
1st August	maturity/ /harvest	maturity/ /harvest	harvest/ /harvested	harvested	row closeness	Cob development

Results

The first results obtained are the coefficients *a* – *slope* and *b* – *intercept* of the soil line equation calculated for each date. The coefficients were estimated on the basis of actual data i.e. the values of reflectance in RED and NIR channels for the pixels representing dark (wet, rough) and bright (dry) bare soils. They were determined adopting RED as an independent and NIR as a dependent variable in regression calculations, using the Idrisi_32 package.

Table 5 shows that all *slope* coefficients are of the same order and quite close to one another, whereas *intercept* is general less than 1% except for April, 15th. It means that the correction factors in some index formulas is not very important.

Ten vegetation indices were calculated for each date. We ignored TTVI and SAVI for the following reasons: TTVI – because the absolute value in the formula generated "artifacts", giving the same value of the index for rich vegetation and water bodies. SAVI – because it requires an arbitrarily

Table 5

Parameters of soil line

Specification	15th April	6th May	5th June	26th June	1st August
Reflectance in Red used as an independent variable	a = 1.1034 b = –0.0234	a = 1.0710 b = –0.0092	a = 1.0703 b = –0.0015	a = 1.0960 b = –0.0014	a = 1.0443 b = –0.0014

Table 6

Original ranges of VIs

Specification	RATIO		NDVI		TVI		PVI_1		PVI_2		DVI		$TSAVI_1$		$TSAVI_2$		$MSAVI_1$		$MSAVI_2$	
	Min	max	min	max	min	Max	min	max	min	max	Min	max	min	max	min	max	min	max	min	max
15th April	0.11	3.60	–0.81	0.56	0.44	1.25	–0.08	0.16	–0.08	0.14	–0.13	0.18	–0.5	0.58	–0.23	0.42	0.15	0.35	–0.14	0.37
6th May	0.00	5.64	–1.00	0.70	0.00	1.30	–0.05	0.24	–0.07	0.23	–0.09	0.30	–0.92	0.30	–0.32	0.53	-0.16	0.51	–0.14	0.53
5th June	0.00	5.91	–1.00	0.71	0.00	1.31	–0.09	0.22	–0.09	0.22	–0.12	0.30	–1.12	0.71	–0.48	0.53	-0.24	0.50	–0.20	0.51
26th June	0.00	9.48	–1.00	0.81	0.00	1.35	–0.06	0.35	–0.07	0.35	–0.09	0.46	–1.16	0.81	–0.38	0.64	-0.17	0.74	–0.15	0.71
1st August	0.00	9.07	–1.00	0.80	0.00	1.34	–0.06	0.30	–0.06	0.32	–0.09	0.40	–1.05	0.80	–0.35	0.62	-0.16	0.67	–0.14	0.67

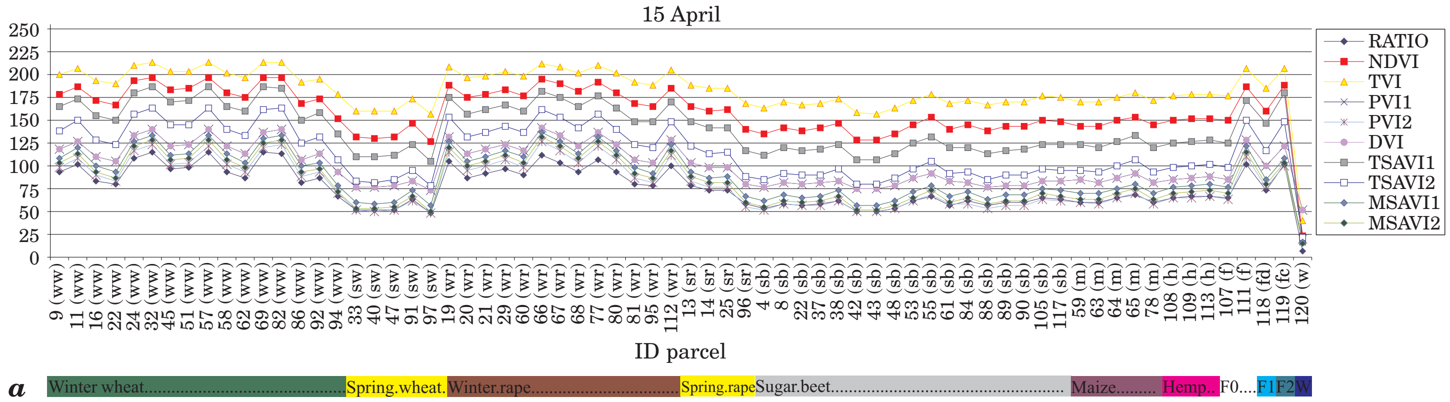
chosen factor "*L*". Instead of choosing "*L*" from among the values 0, 0.5 and 1.0, as recommended in literature, we decided to calculate more realistic values of "*L*" as suggested in the MSAVI definition. Due to the fact that the *NDVI* values on some images were less than 0.5, the TVI formula was also modified, adding the value 1.0 instead of 0.5 to *NDVI* under the square root term in the *TVI* formula, to make it meet the specific conditions. In order to compare Vis, their original ranges were standardized by scaling them linearly according to the byte scale (0–255). This procedure enabled to compare all VIs applying the same reference. All values of indices are shown in Figures 1a-1e (graphs), and the original ranges of VIs are presented in Table 6.

Samples of images representing the indices are shows using the same colour palette for each picture. These are 8-bit images with the 256 indexed palette ranging from dark brown through pale yellow to dark green. It permits easy interpretation of the results. The interpretation of the colours can be easily carried out with the help of the pictures taken during field visits, showing a general view of the crops. For each date a few samples are shown:

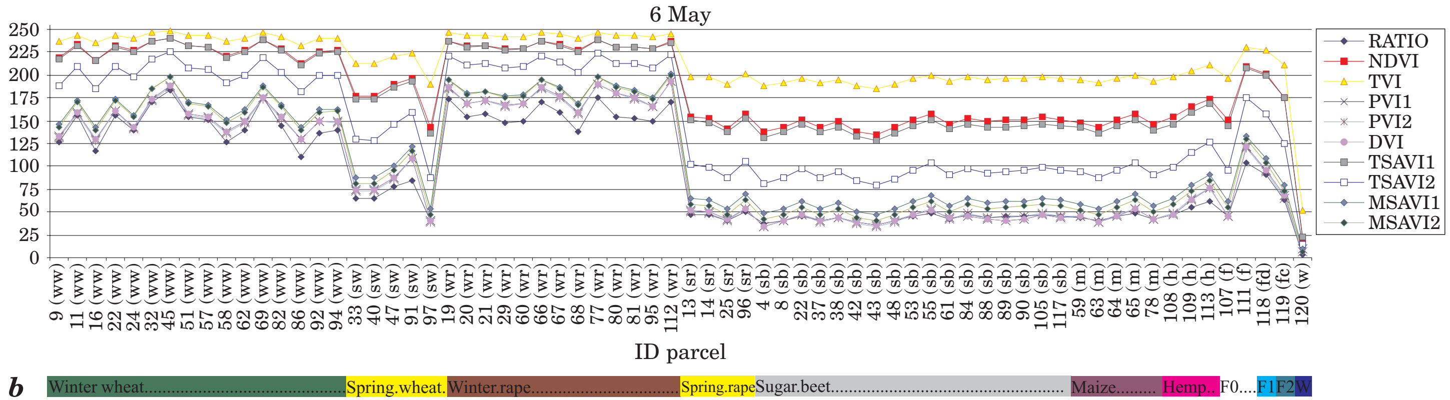
- The most interesting index – chosen from among all suitable ones,
- RATIO – the simplest, not normalized index,
- NDVI – the most widely used and recognized index,
- TVI – the index showing the maximal values for each date.

Results for 15th April

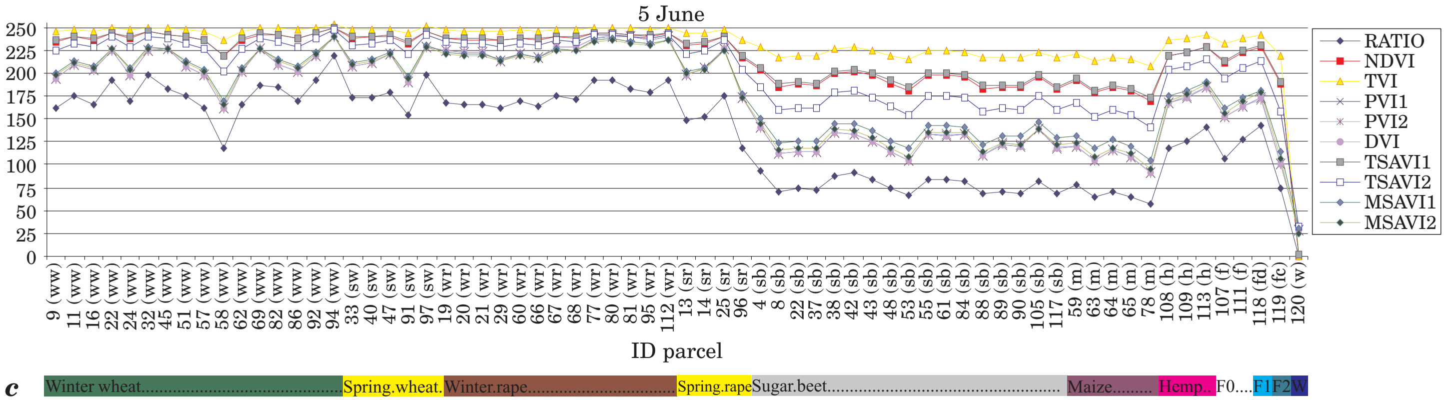
On 15th April there was not much vegetation on arable land. Only winter crops (winter wheat and winter rape) could be found in the field. The other parcels were bare soil. In each parcel TVI had the highest value for each type of cover and crop. A similar situation was observed for all the dates. The highest values of this index result from fact that the constant value of 1.0 instead of 0.5 was included in the formula. The next index is NDVI. It also overestimates the "greenness", as clearly visible in Figures 2b and 2c. $TSAVI_1$ is about 5–8% smaller in relation to NDVI. $TSAVI_2$ is about 10 – 12% smaller compared with $TSAVI_1$. PVI_1 is about 10% lower than $TSAVI_2$. The remaining VIs are "located" between RATIO and PVI_1. RATIO achieved the smallest values. There are: $MSAVI_1$, $MSAVI_2$ and PVI_2. PVI_1 and PVI_2 are closer to $TSAVI_2$ for them, whereas in parcels with emerging winter vegetation PVI_1 and PVI_2 are closer to $MSAVI_1$. It is also visible In Graph 1a that all polylines have the same shape and represent almost constant shifts between them for each parcel regardless of the type of crop/ /cover. Thus for this date each index has the same significance for crop/ /cover identification and none of them can be considered preferable.



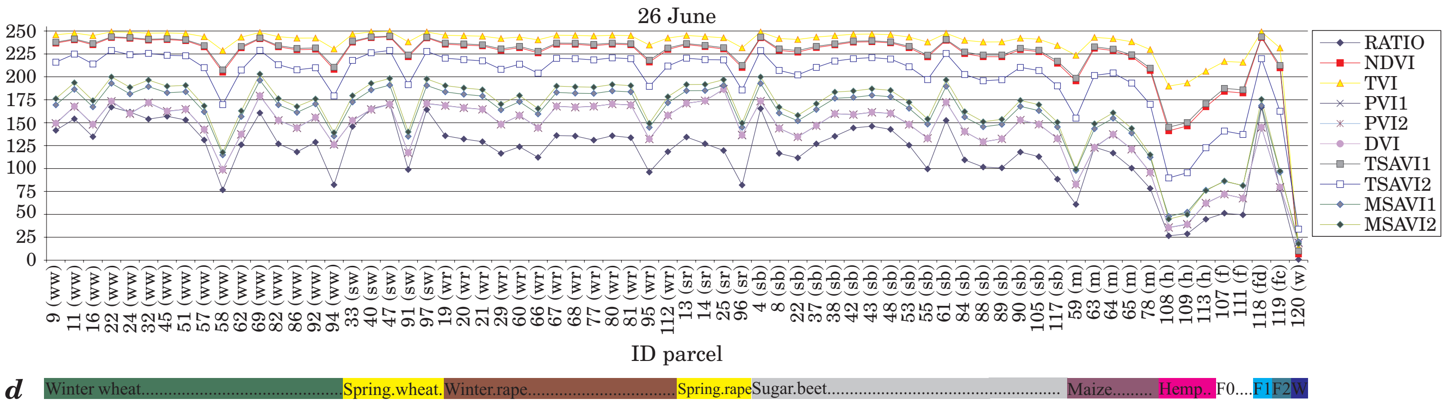
15 April
RATIO
NDVI
TVI
PVI1
PVI2
DVI
TSAVI1
TSAVI2
MSAVI1
MSAVI2
ID parcel
a
Winter wheat
Spring.wheat.
Winter.rape
Spring.rape
Sugar.beet
Maize
Hemp..
F0....
F1F2
W



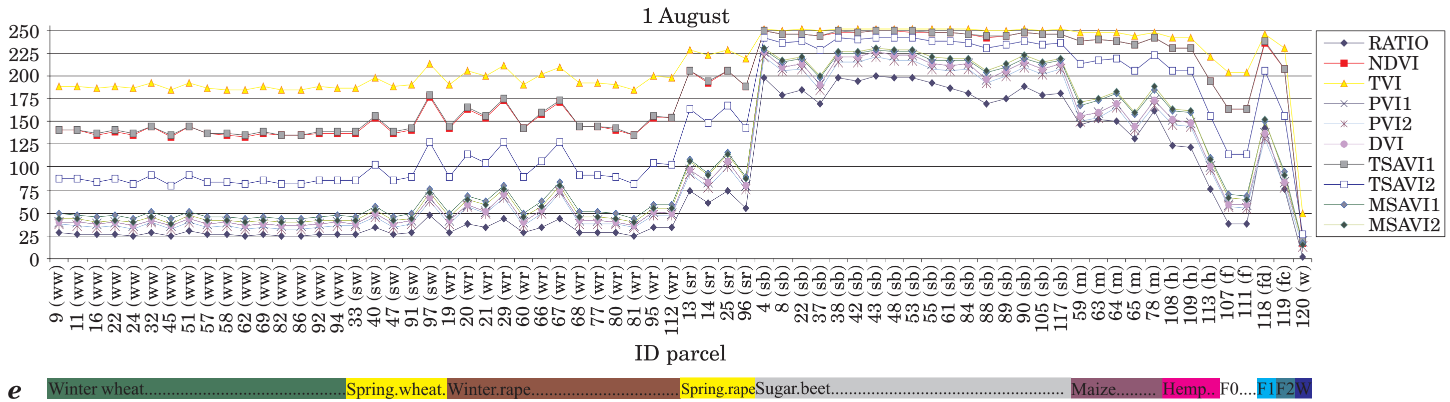
6 May
RATIO
NDVI
TVI
PVI1
PVI2
DVI
TSAVI1
TSAVI2
MSAVI1
MSAVI2
ID parcel
b
Winter wheat
Spring.wheat.
Winter.rape
Spring.rape
Sugar.beet
Maize
Hemp..
F0....
F1F2
W


5 June
RATIO
NDVI
TVI
PVI1
PVI2
DVI
TSAVI1
TSAVI2
MSAVI1
MSAVI2
ID parcel
Winter wheat
Spring.wheat.
Winter.rape
Spring.rape
Sugar.beet
Maize
Hemp..
F0....
F1F2W

c


26 June
RATIO
NDVI
TVI
PVI1
PVI2
DVI
TSAVI1
TSAVI2
MSAVI1
MSAVI2
ID parcel
Winter wheat
Spring.wheat.
Winter.rape
Spring.rape
Sugar.beet
Maize
Hemp..
F0....
F1F2W

d



e

Fig. 1a - 1e . The byte scaled values of vegetation indices for each test parcel and date of satellite registration (F0 - fallow, F1 - deciduous forest, F2 - coniferous forest, W - water)

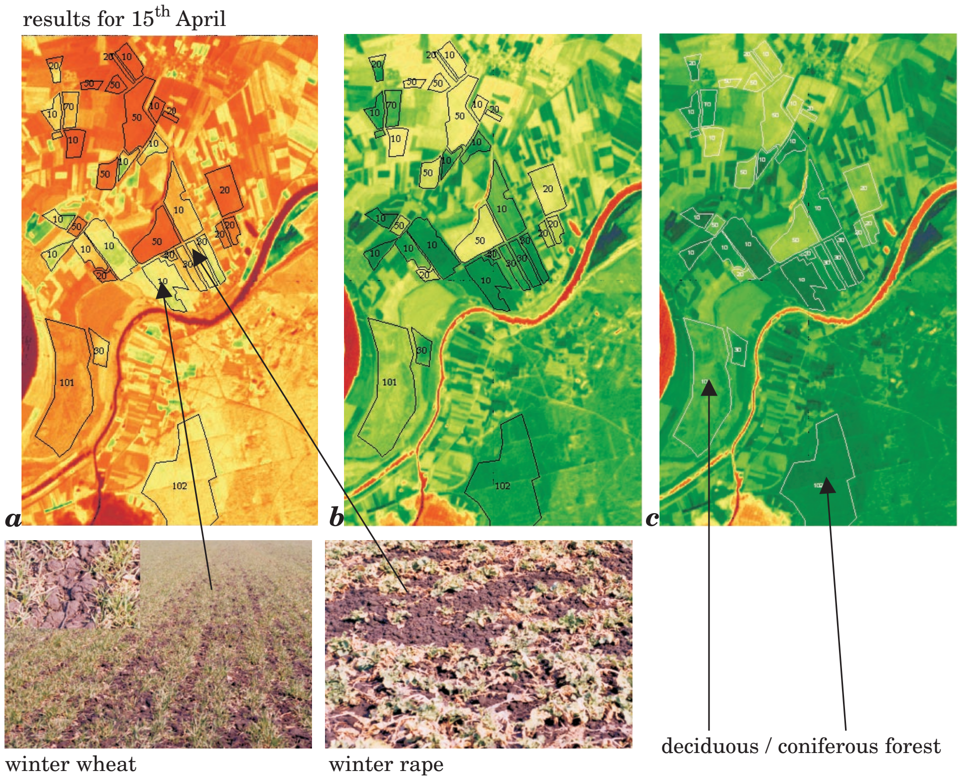


Fig. 2. RATIO (a), NDVI (b) and TVI (c) for 15.04.2003

Results for 6th May

The change in vegetation development between 15th April and 6th May was quite significant. The radiometric contrast between parcels became higher and VIs also changed. TVI had the highest values, but showed the lowest contrast between crops. NDVI and $TSAVI_1$ had almost the same values. **The best separation of winter crops from spring crops and other land cover types (forest, water) was possible with the $TSAVI_2$ image**, providing the highest contrast between them. The values of the other indices ($MSAVI_1$, $MSAVI_2$, DVI, PVI_1, PVI_2) were very close to each other, so the contrast obtained was a bit smaller than for $TSAVI_2$.

Results for 5th June

The values of NDVI, TVI, $TSAVI_1$ and $TSAVI_2$ were very high for winter and spring wheat, similarly as for winter rape. They presented a contrast to the group of spring broad-leaf crops (maize, sugar beets). In the above group of indices the most striking contrast was noted in the case of $TSAVI_2$. These indices showed little variation for parcels of the same crop, even a winter wheat parcel representing crop growing under poor condi-

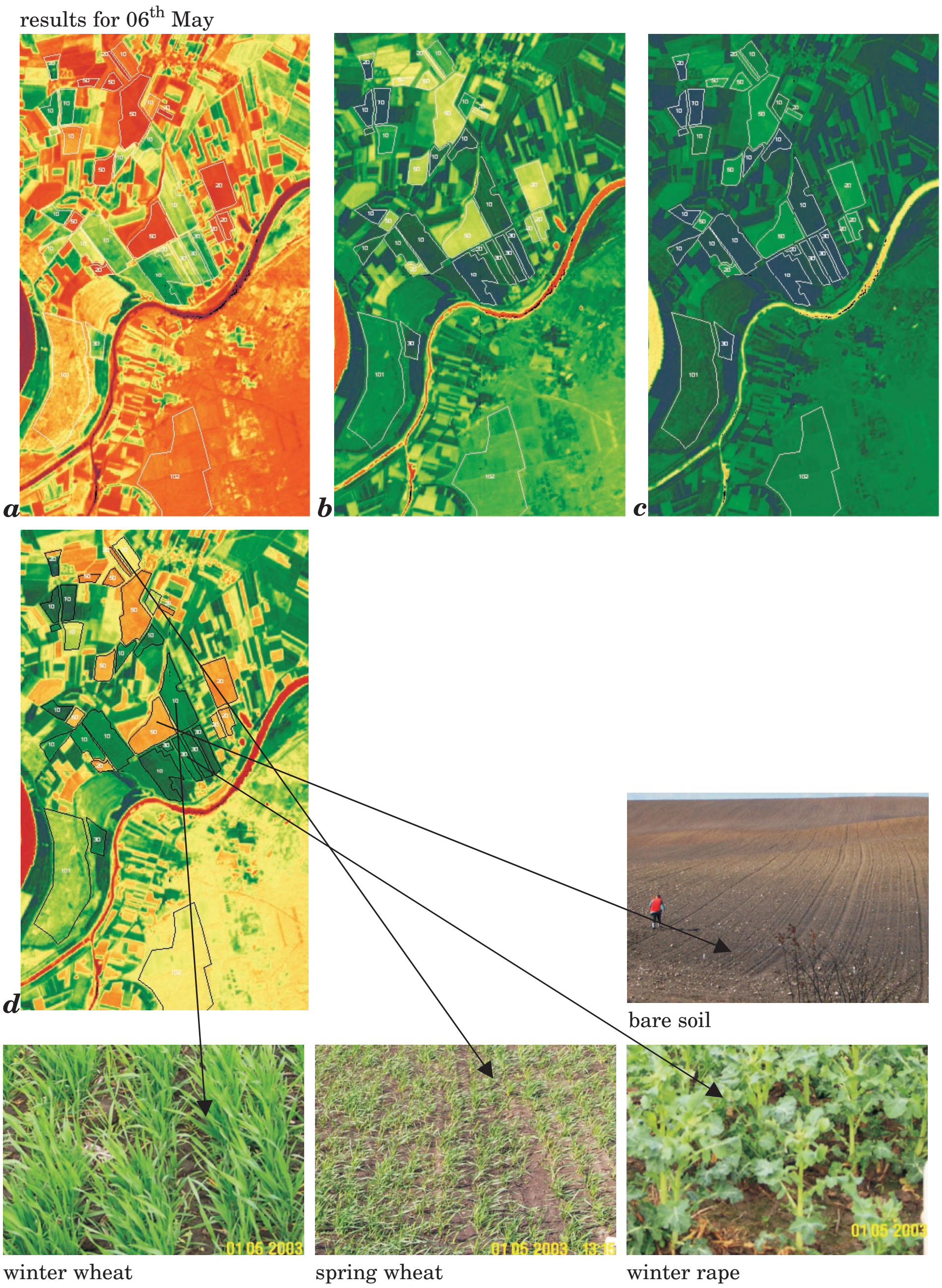


Fig. 3. RATIO (*a*), NDVI (*b*), TVI (*c*) and TSAVI2 (*d*) for 06.05.2003

tions (infrequent and insufficient fertilization). Higher intra-class variations, unfavourable from the perspective of classification, were recorded for RATIO, but this index was characterized by the sharpest contrast between groups. Other indices did not show any significant advantageous features.

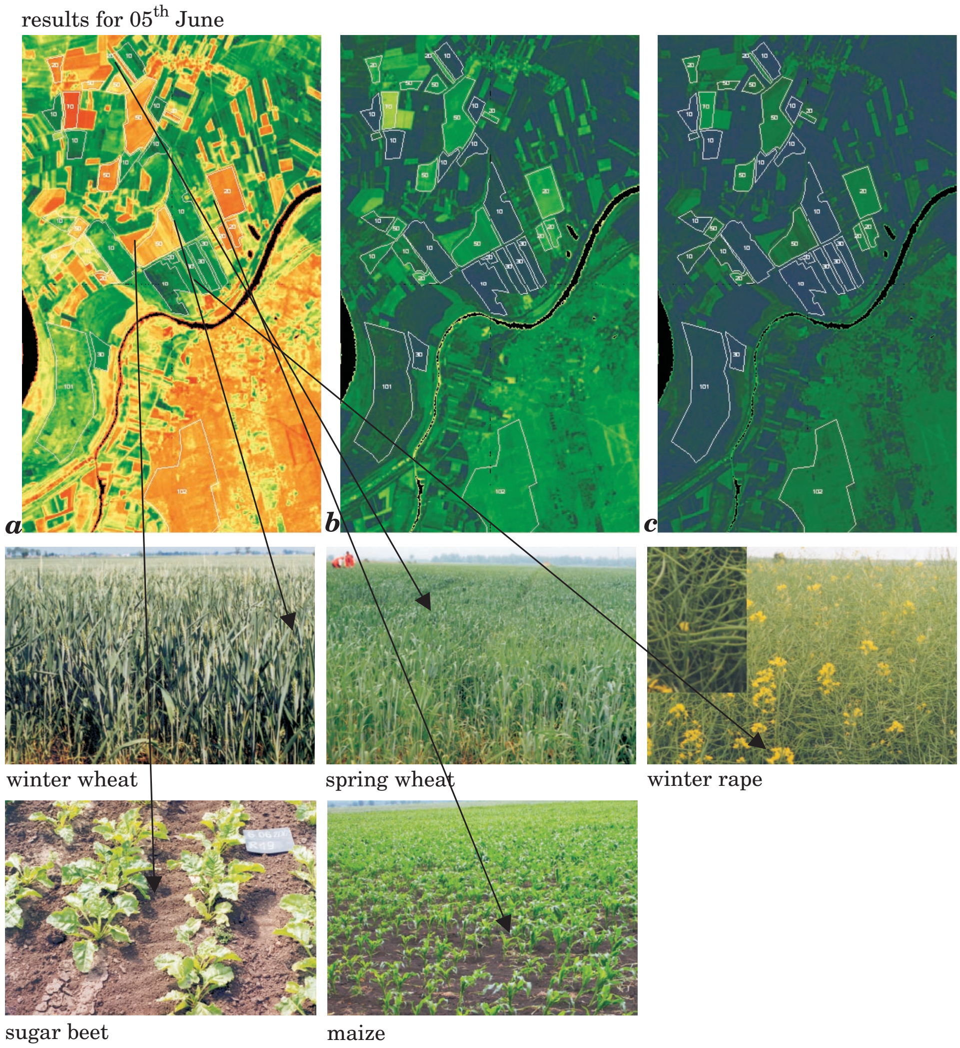


Fig. 4. RATIO (*a*), NDVI (*b*) and TVI (*c*) for 05.06.2003

Results for 26th June

This date is least advantageous for crop differentiation for two reasons:

– all crops are fully developed, cover soil totally and show a more or less green colour,

– rainfall deficits are common in June.

As a consequence the spectral characteristics of crops/cover reflect rather the influence of local soil moisture and fertility conditions (in the deep soil profile) than vegetation type. As shown in Graph 1d, all indices had a similar shape and exhibited rather ”greenness” of particular parcels than differences between crops. No particular benefit can be derived from these indices, compared with earlier periods.

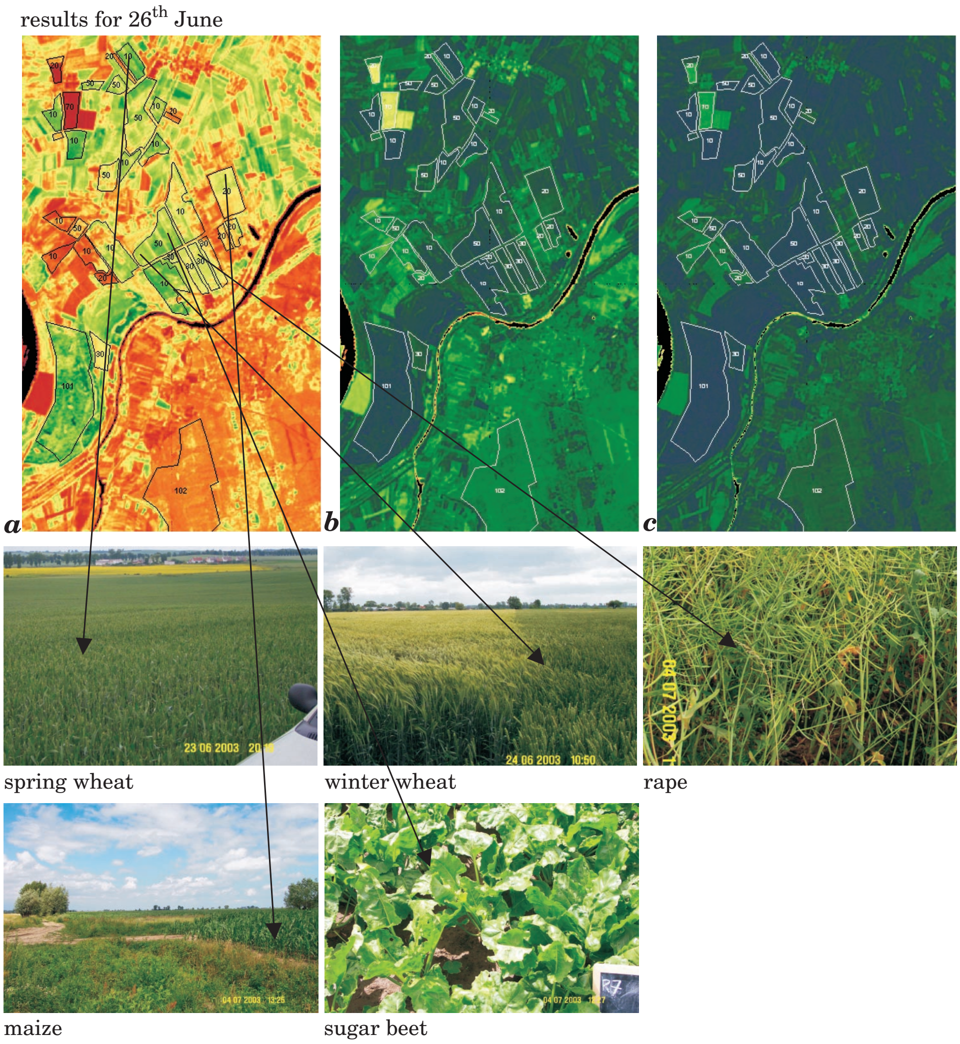


Fig. 5. RATIO (*a*), NDVI (*b*) and TVI (*c*) for 26.06.2003

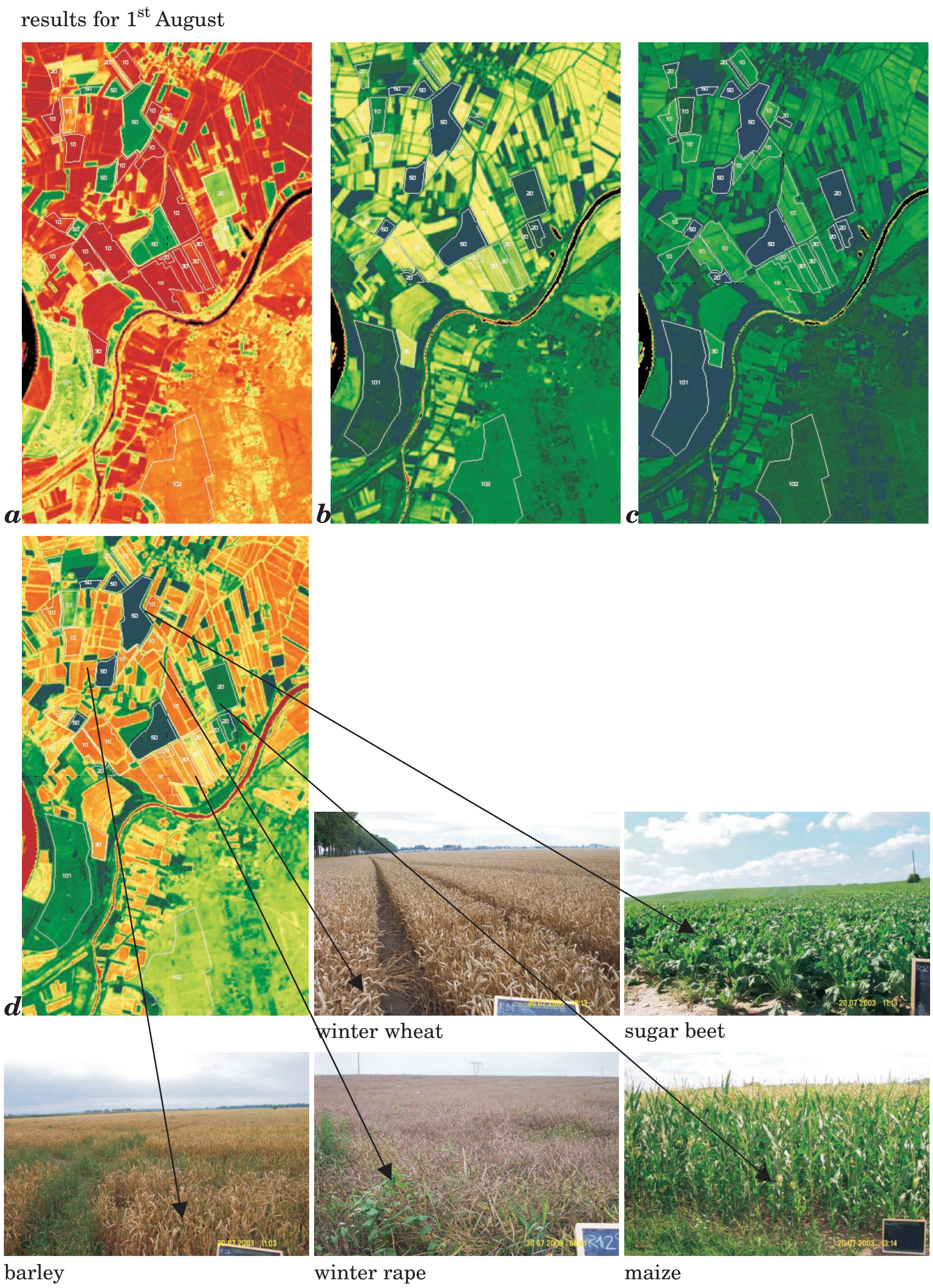


Fig. 6. RATIO (*a*), NDVI (*b*), TVI (*c*) and TSAVI2 (*d*) for 01.08.2003

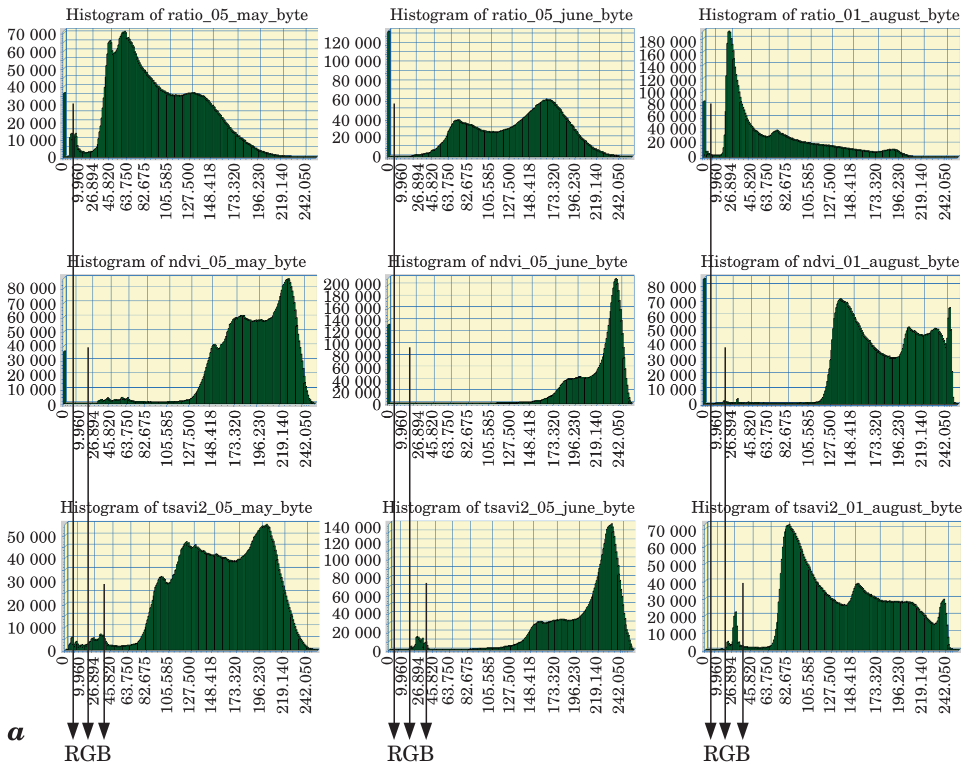
Results for 1st August

Some characteristics of the indices are comparable to those of 5th June. The biggest values, as usual, were noted for TVI. NDVI and $TSAVI_1$ were equal. RATIO showed the lowest values for all parcels except a deciduous forest. The most interesting index was this time $TSAVI_2$, enabling to distinguish clearly between the parcels of sugar beet and maize, which was impossible on 5th June. The usefulness of RATIO and $TSAVI_2$ was similar. On the NDVI image maize and sugar beet are completely confused. The values of the remaining indices are close to each other, and can be placed between RATIO and $TSAVI_2$, closer to RATIO.

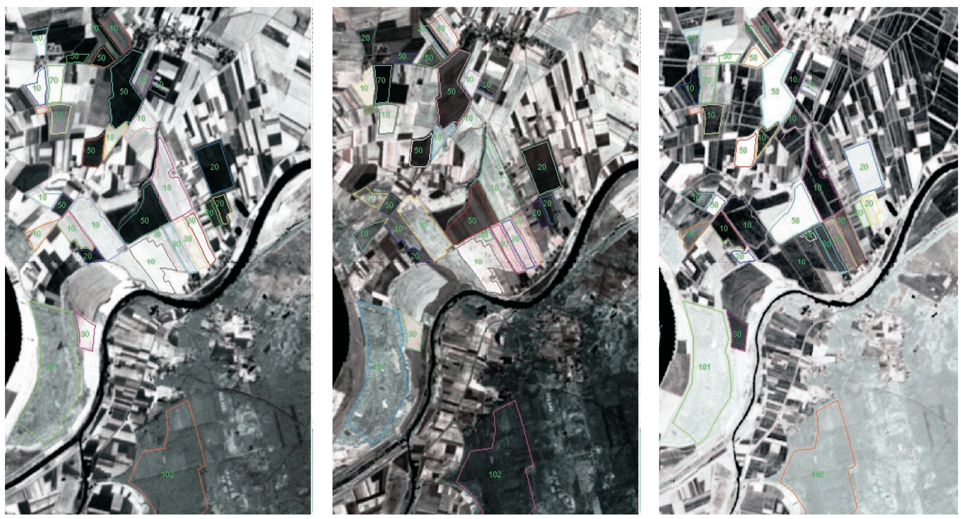
Monotemporal and multitemporal colour compositions made with different indices

Histograms in rows below represent:
- First row: RATIOs for 6th May, 5th June & 1st August,
- Second row: NDVIs for 6th May, 5th June & 1st August,
- Third row: TSAVI2 for 6th May, 5th June & 1st August.

For illustration of the differences in interpretation of images composed of different indices the colour compositions were made using the indices calculated for 6th May, 5th June and 1st August. Three compositions were made using RATIO (Fig. 8a), NDVI (Fig. 8b) and $TSAVI_2$ (Fig. 9a) series, all with **linear histogram stretching** during the phase of colour generation. The highest colour saturation and a vivid contrast were obtained for the composition of RATIO channels; the composition of NDVI channels is very bright and the composition of $TSAVI_2$ channels is of intermediary visual quality. It seems that for this data set the RATIO or $TSAVI_2$ colour compositions should be used for land cover and crop identification. The excessive brightness of the linear NDVI composition results from high index values **for all the dates**. Another histogram stretch function – EQUALIZATION – was also applied, which allowed to achieve clear-cut results. No visible differences were found while processing three different indices versus time. An example of this procedure is shown in Figure 9b as NDVIs composition. Exactly the same (identical) compositions, not presented here, were obtained using RATIO and $TSAVI_2$ series. Examples of compositions derived from three different indices (RATIO, NDVI, $TSAVI_2$) for each date are also shown in Figure 7. The results of applying equalization stretching are clearly visible. Almost all nuances in differences between the indices were eliminated, except slightly accentuated rapeseed parcels for 5th of June.



a

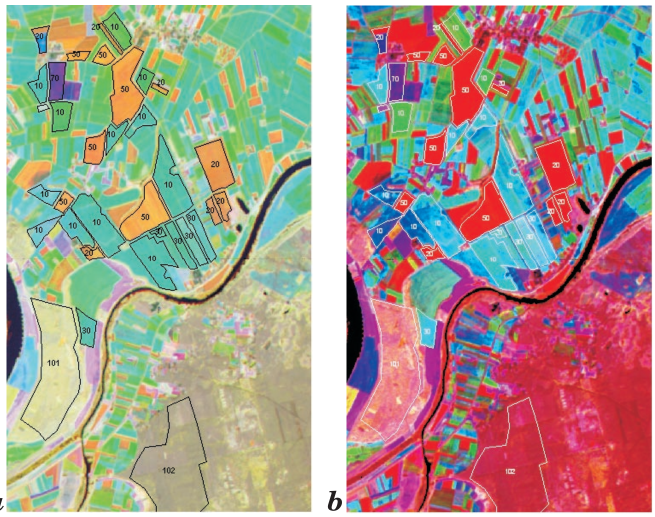


b 6 May 5 June 01 August

Fig. 7. One day compositions (RATIO, NDVI, $TSAVI_2$ as RGB components with HISTOGRAM EQUALIZATION stretching)

a ***b***

Fig. 8. Color composition from RATIO (a) and NDVI (b) indices of 06^{th} May, 05^{th} June and 1^{st} August (all histograms are LINEARLY stretched)



a ***b***

Fig. 9. Color composition from TSAVI2 (*a*) NDVI (b) indices of 06^{th} May, 05^{th} June and 1^{st} August ($TSAVI_2$ LINEARLY stretched, NDVI – stretched with HISTOGRAM EQUALIZATION function)

Conclusions

The conclusions expressed below are drawn from a sensor and site-specific data set and should not be simply extended to other situations and geographical localizations. Nevertheless, as shown in the results, the differences in values of vegetation indices are minor for defined crops and land cover types. In some cases, particularly for 15^{th} of April (early spring conditions) and 26^{th} June (full vegetation cover), there is an almost constant shift for each of the parcels examined. It means that each VI has the same signification and usefulness. In other cases, when the stages of development of crops and plants differ more, the values of particular VI*s* cause not only various changes in the colours of palette (which could be more or less useful for interpretation) but also lead to slightly increased separability of certain crops. No significant differences were found as regards the suitability of particular VI*s* for the data set tested. It means that the user can calculate any simple VI or NDVI without a concern about its strong implication for the results of crop identification. Moreover, some stronger contrast stretching, like histogram equalization, can eliminate the subtle differences between VI*s* (Fig. 7). If the user is particularly interested in the identification of crops or land cover types at any specific date or with a few registrations only (2–3), he/she should verify how different VI*s* work for this specific data set. However, if a larger multitemporal data set is available and land cover types or crops can be identified based on their multitemporal characteristics, all subtle VI*s* studies can be neglected particularly in perspective of their loss through strong histogram stretching.

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