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DETERMINATION OF WHEAT CROP STATUS AFTER WINTER USING SIMULATED PROBA-V AND GROUND-BASED DATA

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Abstract: *The VEGETATION Programme is one of the major instruments for satellite monitoring of agricultural crops in Europe. A successor satellite of the instruments VEGETATION-1 and VEGETATION-2, currently operating on-board of the French satellites SPOT 4 and SPOT 5, is envisaged, called PROBA-V. Its launch is scheduled for 2012. It will feature some improved characteristics of the acquired images, such as enhanced spatial resolution and data acquisition technology. Prior to launching into orbit a new satellite mission, its characteristics and operation are thoroughly tested. From users' point of view, it is of particular importance to assess the applicability of the data it is expected to provide. The article presents the results from a conducted research on assess the potentialities of PROBA-V simulated data (PROBA-V SD) for determining winter crop status after winter. For this assessment are used NDVI (Normalized Difference Vegetation Index), NDWI (Normalized Difference Water) and LAI (Leaf Area Index) index images generated therefrom and ground-based measurements and satellite image from SPOT 5. The PROBA-V SD were obtained based on a multispectral satellite image from Landsat 5 TM acquired on 26.03.2011. The simulation was performed by the VITO simulation team (SPS). The field measurements and phenological observations of the three fields were made during the last decade of March 2011. The fields were sown with winter wheat of the Enola variety. The methodology of the study is based on: geo-information technologies, geodatabase, and statistical methods.*

As a result of the carried out study it was established that PROBA-V SD NDVI, NDWI, LAI may be used to monitor winter wheat status (unsatisfactory, good, or very good) after winter, with 75% compliance accuracy for the classes determined from them and the classes separated from ground-based data. For the purpose, during future validation of satellite data, a minimum set of ground-determined winter wheat status parameters have been determined, such as LAI, TPC, AGB, chlorophyll a+b, and Available Water Content (AWC/0-5 cm).

ОПРЕДЕЛЯНЕ НА СЪСТОЯНИЕТО НА ПШЕНИЧЕН ПОСЕВ СЛЕД ПРЕЗИМУВАНЕ ЧРЕЗ СИМУЛИРАНИ PROBA-V И НАЗЕМНИ ДАННИ

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Ключови думи: *геоинформационни технологии, зимни култури, PROBA-V SD, LAI, вегетационни индекси*

Резюме: *Програмата VEGETATION е един от основните инструменти за сателитен мониторинг на земеделските култури в Европа. Предвижда се наследник на функциониращите в момента прибори VEGETATION-1 и VEGETATION-2, които работят на борда на френските спътници SPOT 4 и SPOT 5 да бъде сателитът PROBA-V. Извеждането му в орбита е планирано през 2012 г. Той ще се характеризира с някои подобрени характеристики на получаваните изображения като повишаване на пространствената разделителна способност и технологията, използвана за събирането на данни. Преди извеждането в орбита на нова спътникова мисия нейните характеристики и функциониране се тестват подробно. От гледна точка на потребителите от особено значение е да се оцени приложимостта на данните които се очаква тя да предоставя. В настоящата статията се представят резултатите, получени от проведено изследване за оценка на възможностите на симулирани PROBA-V данни за определяне на състоянието на пшеничен посев след презимуване. За тази цел са използвани генерирани от тях NDVI, NDWI и LAI индексни изображения,* *наземни данни, сателитни изображения от SPOT 5 HRG . Симулираните PROBA-V данни са получени на базата на многоканално спътниково изображение от Landsat 5 TM заснето на 26.03.2011 г. Симулацията е извършена от екипа по симулации (SPS) на VITO. Полевите измервания и фенолоичните наблюдения на три полета с площ над 1,5 km^2 засети със зимна пшеница, сорт «Енола» са извършени в последното десетдневие на месец март 2011 г. При обработката и анализа на данните е използвана гео-базата данни изградена по проекта PROAGROBURO. В резултат от проведеното изследване се установи, че за оценка на състоянието на зимна пшеница (незадоволително, добро и много добро) след презимуване могат да се използват PROBA-V SD NDVI, NDWI, LAI с точност 75% на съответствие на групите определени по тях и групите отделени по наземни данни. За тази цел при бъдеща валидация на спътниковите данни са определени минимален набор от наземно определени параметри на състоянието на зимната пшеница, като индекс на листната повърхност, TPC, AGB, хлорофил a+b, AWC/0-5 cm.*

Introduction

Winter crops, such as wheat grown in Bulgaria, are sown in autumn and pass through the initial development vegetation stage before the beginning of winter. They pass winter on the field reaching a certain development stage while being subject to the influence of various, including unfavourable, meteorological factors (frost, draught, soil over moisturizing, and strong wind) which create preconditions for crop damages. Therefore, one of the first things to be made upon resuming winter crop vegetation in spring is to assess vitality rate and damage scale after winter. The current practice is to monitor certain representative crop sections and generalize the results to cover the entire field, farm, or land. The use of satellite Earth observation systems to monitor agricultural environments provides to supplement this information with satellite images and vegetation products generated therefrom, obtaining data both at local, as well as at regional and global level. This is related most often with the successful operation of such systems as NOAA-AVHRR, Envisat-MERIS, SPOT-VEGETATION, Terra/Aqua-MODIS, Landsat TM (Table 1), which provide to receive operative data about the Earth's surface in various ranges of the electromagnetic spectrum with medium or low spatial resolution. The greater part of the biometric and biophysical parameters of agricultural crops, as well as the soil type, structure and moisture affect the reflectance characteristics of the sown fields in different spectral ranges. This provides to measure these parameters using satellite images acquired in different spectral ranges.

The VEGETATION Programme is one of the major instruments for satellite monitoring of agricultural crops in Europe. A successor satellite called PROBA-V („V"stands for Vegetation) of the instruments VEGETATION-1 and VEGETATION-2, currently operating on-board of the French satellites SPOT 4 and SPOT 5, is envisaged. Its launch is scheduled for 2012. It will feature some improved characteristics of the acquired images, such as enhanced spatial resolution and data acquisition technology.

Prior to launching into orbit a new satellite mission, its characteristics and operation are thoroughly tested. From users' point of view, it is of particular importance to assess the applicability of the data it is expected to provide. In relation with this, in 2010, the implementation of the PROBA-V Preparatory Programme (http://eo.belspo.be) started, which has two main objectives:

- to familiarize the potential users with this new dataset, its characteristics and quality;
- to prepare the PROBA-V dataset for its actual operation with respect to the envisaged technical improvements.

In 2010, a call for research proposals was announced in the context of the PROBA-V Preparatory Programme. Twelve projects were selected which started their work in 2010. One of these projects was PROAGROBURO, which examined the usefulness of the PROBA-V mission for agricultural applications in Bulgaria and Romania based on simulated data. This study was carried out under the PROAGROBURO Project and its objective was to assess the potentialities of PROBA-V simulated data (PROBA-V SD) for determining winter crop status after winter.

When using multispectral images, the users performing agromonitoring address increasingly not primary data, but their derivative products. These constitute essentially various indices with different degree of spatial generalization and time averaging. They are produced by a network of dedicated thematic centres for receiving, processing and distribution of space information that satisfies best the users' requirements. Thus, the user may choose the product he/she is most interested in.

To study Earth vegetation cover using satellite data, spectral vegetation indices of the type of NDVI (Normalized Difference Vegetation Index), as well as calculation algorithms for biophysical parameters, such as LAI (Leaf Area Index) and radiation absorbed during photosynthesis FPAR (Fraction of Photosynthetically Active Radiation) (Table 1) are used. In the current study, the potentials of PROBA-V SD for determining winter wheat status after winter on fields with area above 1.5 km^2 were assessed using NDVI, NDWI, and LAI index images generated therefrom.

Table 1. Characteristics of some contemporary and future European low SR remote sensing satellite instruments used for crop monitoring*

Satellite	Instruments/Channels (µm)	Orbit details	Spatial resolution	Temporal resolution	Description	Start of the mission	End of the mission
PROBA-V	PROBA-VEGETATION: VNIR B0 Blue: (0.44-0.48); VNIR B1 Red: (0.62-0.698); VNIR B2 NIR: (0.79-0.90); SWIR: (1.56-1.65)	Sun-synchronous, Polar orbit; Inclination: ; Altitude: 830 km; Swath: 2250 km;	300 m (VNIR) / 600 m (SWIR)	at least one acquisition per day beyond 35° latitude	PAR, FPAR, NDVI, LAI, Earth surface albedo, Land surface imagery, Ocean imagery, and water leaving radiance, Vegetation type, Land cover	2012	2015/2017
SPOT Vegetation 1&2	VEGETATION: (0) Blue: (0.43-0.47); (2) Red: (0.61-0.68); (3) NIR: (0.78-0.89); SWIR: (1.58-1.75)	Sun-synchronous, Polar orbit; Inclination: ; Altitude: 830 km; Swath: 2200 km;	1.15 km	26 days	PAR, FPAR, NDVI, LAI, Earth surface albedo, Land surface imagery, Ocean imagery and water leaving radiance, Vegetation type, Land cover	1998 (VGT 1); 2002 (VGT 2)	2013 (VGT 1); 2002 - 2014 (VGT 2)
Envisat	MERIS VIS-NIR: 15 bands selectable across range: 0.390 to 1.040 (programmable bandwidth 2.5 - 30 nm); AATSR VIS - NIR: (0.555, 0.659, 0.865), SWIR: (1.6), MWIR: 3.7, TIR: (10.85, 12)	Sun-synchronous, Altitude: 782 km; Swath: MERIS (1150 km) / AATSR (500 km); Inclination: 98.52°	MERIS (Ocean: 1040m × 1200m, Land & Coast: 260m × 300m) AATSR (1km)	MERIS / AATSR (3 days)	Land (Vegetation), Ocean and Coast (Sea Surface Temperature, Ocean Colour/Biology), Atmosphere (Clouds/Precipitation)	2002	2013
Sentinel-1 a,b,c	C-band: 5.405 GHz; HH, VV, HH+HV, VV+VH;	Sun-synchronous, Polar orbit; Inclination: 98.19°; Altitude: 693 km; Swath: 80 km - 250 km interferometer wide swath mode	5 m	12 days	Providing continuity of C-band SAR data for operational applications notably in the following areas: monitoring of sea ice zones and the arctic environment, surveillance of marine environment, monitoring of land surface motion risks and mapping in support of humanitarian aid in crisis situations	2013-2020	2020-2026
Sentinel-2 a,b,c	MSI (Multi Spectral Instrument) 13 bands in the VNIR/SWIR (0.40 - 3.0)	Sun-synchronous, Polar orbit; Inclination: 98.62°; Altitude: 786 km; Swath: 290 km	10 m, 20 m, 60 m	10 days	Supporting land monitoring related services, including: generation of generic land cover maps, risk mapping and fast images for disaster relief, generation of leaf coverage, eaf chlorophyll content and leaf water content	2013-2020	2020-2027
Sentinel-3 a,b,c	OLCI (Ocean and Land Colour Instrument) 21 bands in VNIR/SWIR (0.4 - 1.3)	Sun-synchronous, Polar orbit; Inclination: 98.65°; Altitude: 814.5 km; Swath: 1270 m (OLCI); 1675 km/750 km (SLST)	(OLCI) 300 m; (SLST) 500 m (VIS, SWIR) and 1 km (MWIR, TIR)	27 days	Supporting global land and ocean monitoring services, in particular: sea/land colour data and surface temperature; sea surface and land ice topography; coastal zones, inland water and sea ice topography; vegetation products	2013-2020	2021-2027

*** Sources: CEOS EO Handbook database 2011 (http://database.eohandbook.com), ESA Earthnet – ESA Operational EO Missions, ENVISAT (https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat), SPOT-Vegetation (http://free.vgt.vito.be), PROBA-V (http://probav-iuc.org, http://probav-iuc.org/assets/PROBA-V-PP_call_for_ proposals.pdf), Landsat TM (http://glcf.umiacs.umd.edu), Terra/Aqua-MODIS (http://lpdaac.usgs.gov) (Date accessed 24 April 2012).**

NDVI is a potential indicator of winter wheat status, whereas its information value varies depending on the spatial resolution of source satellite data. Its values are affected by most agricultural crop biometric characteristics, such as crop density, plant height, fresh and dry biomass, total area cover and more, as well as surface layer soil moisture.

Leaf Area Index (LAI) is an important biophysical parameter describing the structure of vegetation cover and the velocity of the energy exchange taking place in it. It is used in agriculture to assess plants' ability to intercept light, as an input parameter in various crop growth models, or in yield forecasting (Dadhwal, 2004; Doraiswamy *et al.* 2004), as well as in precision farming (Dammer *et al*. 2008).

Normalized Difference Water Index (NDWI), Gao, (1996), has not been offered as a satellite product so far, but it is used in agromonitoring as an indicator of green biomass water content and soil moisture.

Each of these indices is intended to assess different parameters of the soil-vegetation system, whereas their joint use may provide better results.

Study subject

The study subject is three fields located in North-East Bulgaria, on the land of the Village of Lozenets, Municipality of Kroushari, District of Dobrich. This land is part of the *Zhiten* test area chosen under the PROAGROBURO Project to test PROBA-V SD. These fields are designated further in the text by I, II, and III and occupy area of 1.9 km^2, 1.5 km^2, and 2.2 km^2, accordingly. The studied area falls within the European-continental province of the temperate climatic belt. Climate is moderately warm, without clearly expressed dry season (Topliiski, 2006). The average annual air temperature is 10.2° C. The precipitation maximum is in June and the minimum – in February. The annual precipitation is 540 mm. The average field altitude is 200 m.a.s.l. The zonal soils are represented mostly by *Haplic* and *Calcic Chernozems*, and the azonal ones – by *Gleyic Colluvisols*. The agroclimatic conditions are suitable for growing winter crops.

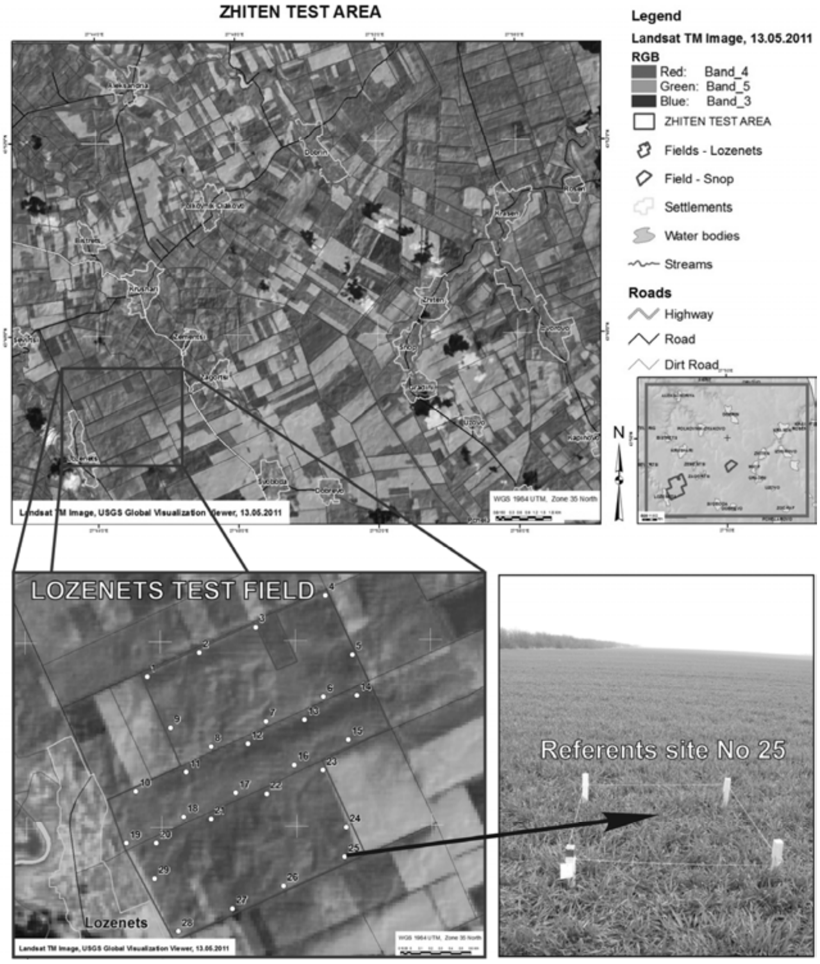


Fig. 1. Location of the three test fields in the *Zhiten* test area (Bulgaria) and spatial distribution of the reference sites

Data and methods

1. Data

The work employs two types of data: 1) PROBA-V SD, and 2) Ground-based data.

The PROBA-V SD were obtained based on a multispectral satellite image from Landsat 5 TM acquired on 26.03.2011. The simulation was performed by the VITO System Performance Simulator team (SPS) under the PROAGROBURO Project. During the simulation, 4 Landsat 5 TM (Table 2) channels were used. This study uses input simulation data in the form of TOA (Top of Atmosphere) reflectance. The PROBA-V SD were georeferenced and resampled after the nearest neighbour method to pixel size of 300 m (for the blue, red, and near infrared channels) and 600 m (for the shortwave infrared channel). Then, the four channels were united in a common file with pixel size of 300 m.

Table 2. PROBA-V spectral bands and the corresponding bands of the high resolution images used for their simulation

PROBA-V bands (μm)	VNIR B0: Blue (0.45-0.49)	VNIR B1: Red (0.61-0.69)	VNIR B2: NIR (0.78-0.89)	SWIR: SWIR (1.57-1.65)
Corresponding Landsat TM bands (μm)	Band 1: Blue (0.45-0.52)	Band 3: Red (0.63-0.69)	Band 4: NIR (0.76-0.90)	Band 5: SWIR (1.55-1.75)

The field measurements and phenological observations of the three fields were made during the last decade of March 2011. The fields were sown with winter wheat of the *Enola* variety with sowing norm of 24 kg/dka during the period 28.09.–04.10.2010, whereas for technical reasons, the sowing of field **III** continued until 28.10.2010. The previous crop sown on field **I** was sunflower, on **II** – rapeseed, and on **III** – sunflower and rapeseed. Spring fertilization was performed on all three fields in the end of February and the first decade of March. The phenological status of the wheat crop in the studied fields during the third decade of March 2011 was as follows: for field **I** – 75% of the crop was in the *tillering* phenophase, and 25% – in the *leaf formation* phenophase; for field **II**, this ratio was 70/30%, and for field III, it was 60/40%. The crop passed the winter in the *leaf-formation* phenophase, which was not favorable for its development. To determine the phenological status of the wheat crop, data from the carried out field observations and measurements was used, as well as data provided by the farmer Zahari Zhandov, owner of the three studied fields.

The ground-based measurements were performed on 29 reference sites located on the three fields, each one sized 1 m^2, which were chosen in advance (Fig. 1). They were spaced at a distance of 600 m from each other. During the experiment, biometric measurements were performed on these sites, including: TPC (Total Projective Cover) crop density, average plant height, LAI, AGBf, and AGBd (fresh and dry weight of Above-Ground Biomass), chlorophyll-*a* and chlorophyll-*b* and carotene amount in the leaves, weed class. Samples were collected from 4 sites of each field to determine soil moisture. The coordinates of the reference sites were determined my GPS measurements.

2. Methods

The methodological framework of the study is presented in Fig. 2 below. The methodology of the study is based on:

- Geo-information technologies providing to perform complex processing and thematic interpretation of the information from various sources in a uniform coordinate system. The geodatabase composed under the PROAGROBURO Project was used;
- Statistical methods. For assessment of the winter wheat status at reference sites level, data from 9 reference sites were used for which there was a complete set of biometric data and surface soil moisture data. The tested hypothesis was, that the variability of the satellite products from PROBA-V SD, i.e. vegetation indices (VIs) and LAI, depends on the variability of field-measured biometric and biophysical data. Principal Component Analysis (PCA) was used to reduce the data dimensionality of field measured variables and VIs and biophysical parameters. The χ^2 (chi-squared) test was used to assess the level of independence of the factor scores obtained after the PCA from field data and PROBA-V SD. The 9 reference sites were classified in three classes of winter wheat status, i.e. (1) unsatisfactory, (2) good, (2) very good, using the PROBA-V SD NDVI, NDWI, and LAI. This was carried out using the dynamical programming algorithm (Fisher 1958). The three classes were clearly statistically discernible both for PROBA-V SD NDVI and NDWI. To verify the classes thus obtained with the relevant classes of ground-based data, a discriminant analysis was used. For the purpose, multiple correlation and regression analysis was made, which determined the optimal

combination of independent status variables, namely: AWC/0-5cm, TPC, chlorophyll *a+b*, and AGBf. Apart from this, Wilks' Lambda test for the classes' separability from ground-based data was also made.

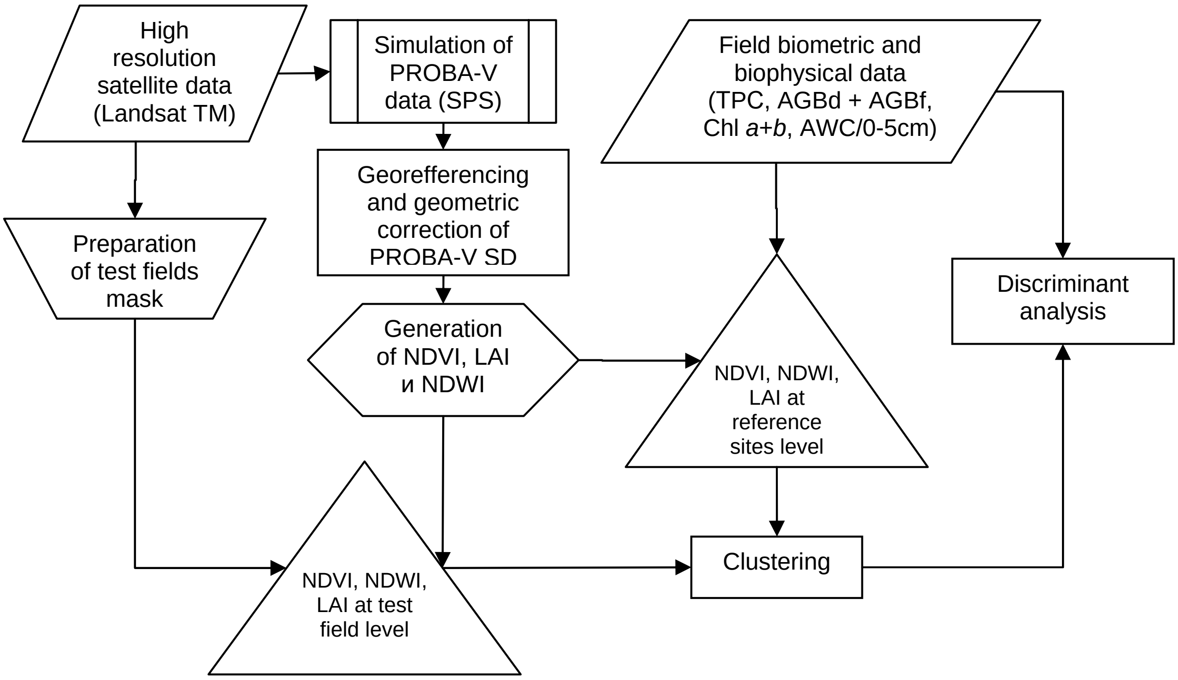


Fig. 2. Flowchart of the methodological framework

2.1. Geometric correction of PROBA-V SD scenes using as a reference SPOT 5 image.

The PROBA-V SD image obtained by the VITO SPS team was orthorectified using ASTER GDEM and georefferenced using ground-measured GPS reference points. This was made as PROBA-V SD comes with no projection after the simulation procedure and needs to be geocorrected and rectified.

2.2. Generation of NDVI, NDWI and LAI index images from PROBA-V SD

Two vegetation indices (VI) were used as indicators of crop status: NDVI and NDWI, Fig. 3. The NDVI index is usually considered as a direct indicator of plants' photosynthetic activity (Rouse *et al*. 1973; Tucker 1979). The NDVI was calculated by (1):

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}, \tag{1}$$

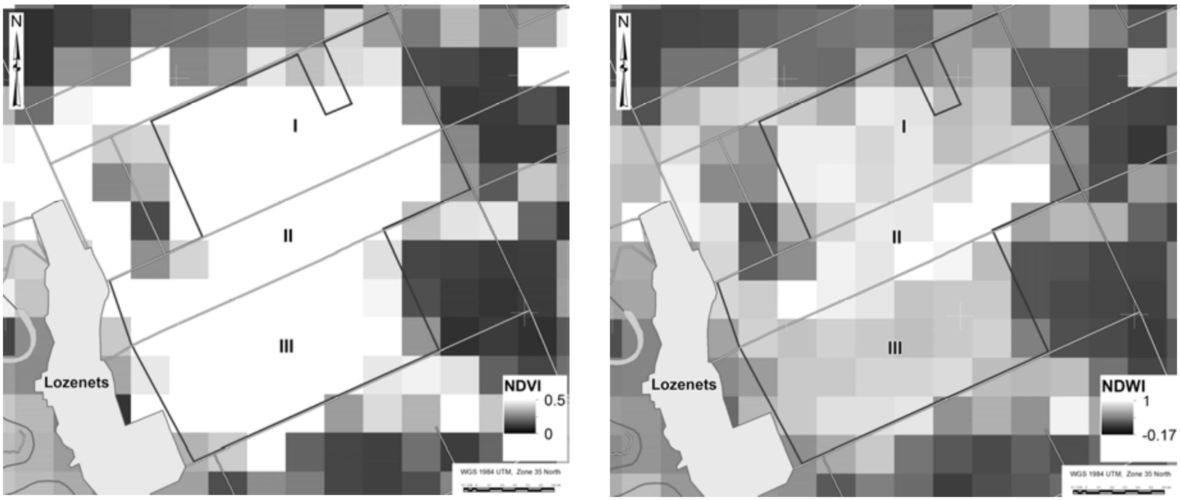
where NIR and RED are accordingly the near infrared and the red waveband. NDWI was used as an indicator of plants' water content, since it uses the negatively-correlated-with-water shortwave infrared (SWIR) spectral waveband (Gao 1996). The NDWI index was calculated by (2):

$$NDWI = \frac{(NIR - SWIR)}{(NIR + SWIR)}, \tag{2}$$

where NIR and SWIR are accordingly the near infrared and the shortwave infrared waveband.

Remote sensing methods provide data for LAI quickly and over great regions (Zheng and Moskal 2009). Different definitions of LAI are available, which is due to the differences in plant morphology, methods and purpose of LAI measurement (Gonsamo, 2009; Zheng and Moskal, 2009). In remote sensing, LAI is most often defined as *half the total green leaf intercepting area per unit ground surface area* (Chen and Black, 1992).

The empirical approach for deriving LAI is used with low resolution data (Chen *et al*. 2002). Most often, the reflectance in different spectral zones or spectral vegetation indices is correlated with ground-measured values of LAI (Turner *et al*. 1999). For winter wheat and for other types of crops, this relationship is usually curvilinear (Yang *et al*. 2007).



a) b)

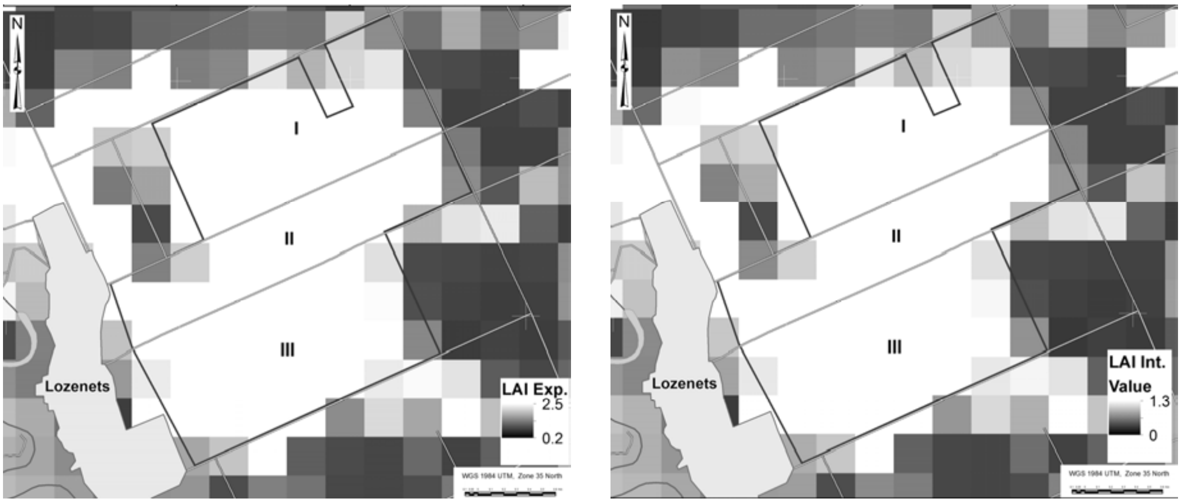
Fig. 3. a) NDVI and b) NDWI images from PROBA-V SD (26.03.2011)

PROBA-V SD LAI images were generated using two empirical relationships between LAI and NDVI, Fig. 4. The used methods referred to in the text as: 1) exponential, and 2) interpolation are:

Exponential relationship between LAI and NDVI, suggested by White *et al*. (1997), (3).

$$LAI = 0.2273 \cdot e^{4.972 \cdot NDVI} \tag{3}$$

Interpolation based on the backup look-up table (LUT) of the MODIS LAI algorithm (Knyazikhin *et al*. 1999) for ‘biome class 1’ – ‘pastures/cereals’. This relationship is based on regression curves and is used in the spare algorithm for MODIS LAI.



a) b)

Fig. 4. a) LAI Exp. and b) LAI Int. images from PROBA-V SD (26.03.2011)

2.3. Preparation of test fields’ mask and deriving the values of NDVI, NDWI, and LAI

To be able to localize and discern the test fields on PROBA-V SD scenes, a mask was prepared. Essential to its preparation were the spatial coordinates, and not the values of the reflectance coefficient. For the purpose, images with higher SR (spatial resolution) were used. This study used a satellite image from SPOT 5 HRG acquired on 24.04.2011, as well as data from the performed GPS measurements. Thus, using differential corrections, the localization accuracy of the identified fields within the range 2–5 m was improved. The test fields’ mask was used to derive the values of NDVI, LAI, and NDWI from the index images for each individual pixel, as well as to obtain the averaged values for each of the three studied fields. The pixels located on the boundary of the test fields are “mixed” with other types of earth surface. Since they do not reflect actually the status in the respective fields, these cases were excluded from the analysis.

Results and discussions

The assessment of the potentials of PROBA-V SD NDVI, NDWI, and LAI indices to determine the status of wheat crops after winter was done by comparison of factor loadings and factor scores of ground-measured data and PROBA-V SD. The results are presented on Fig. 5.

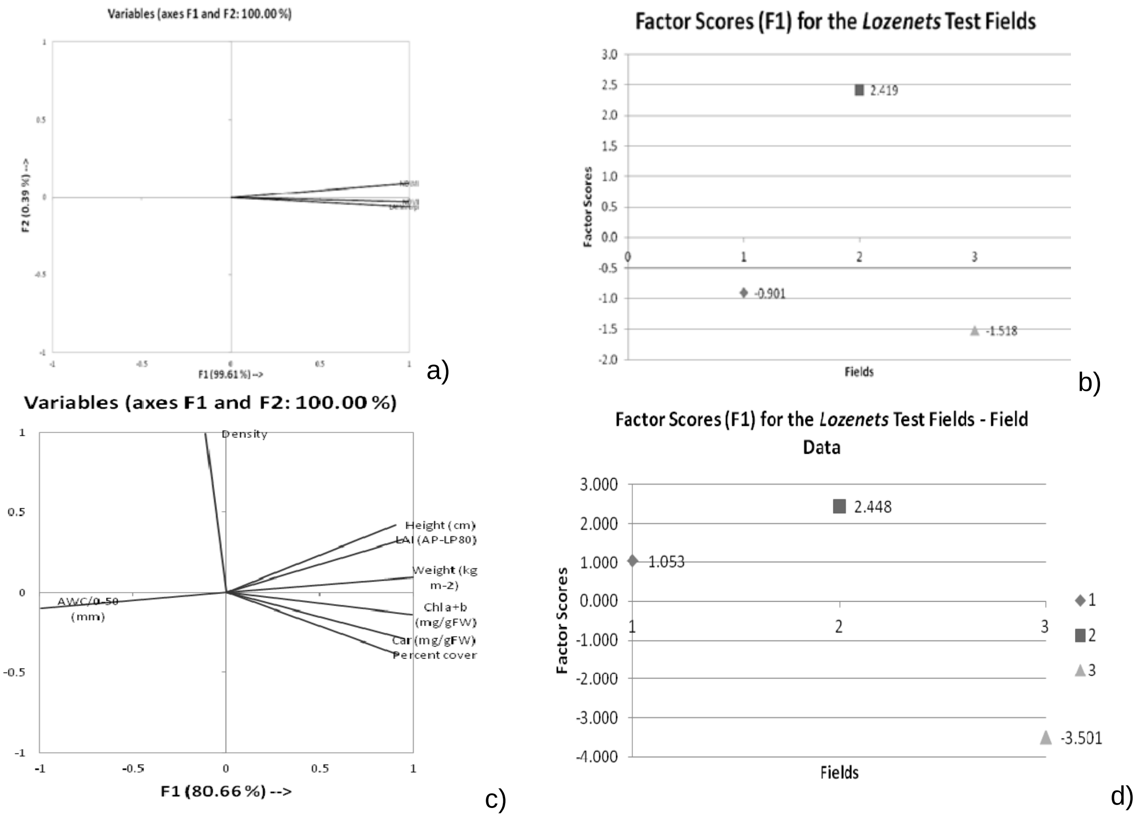
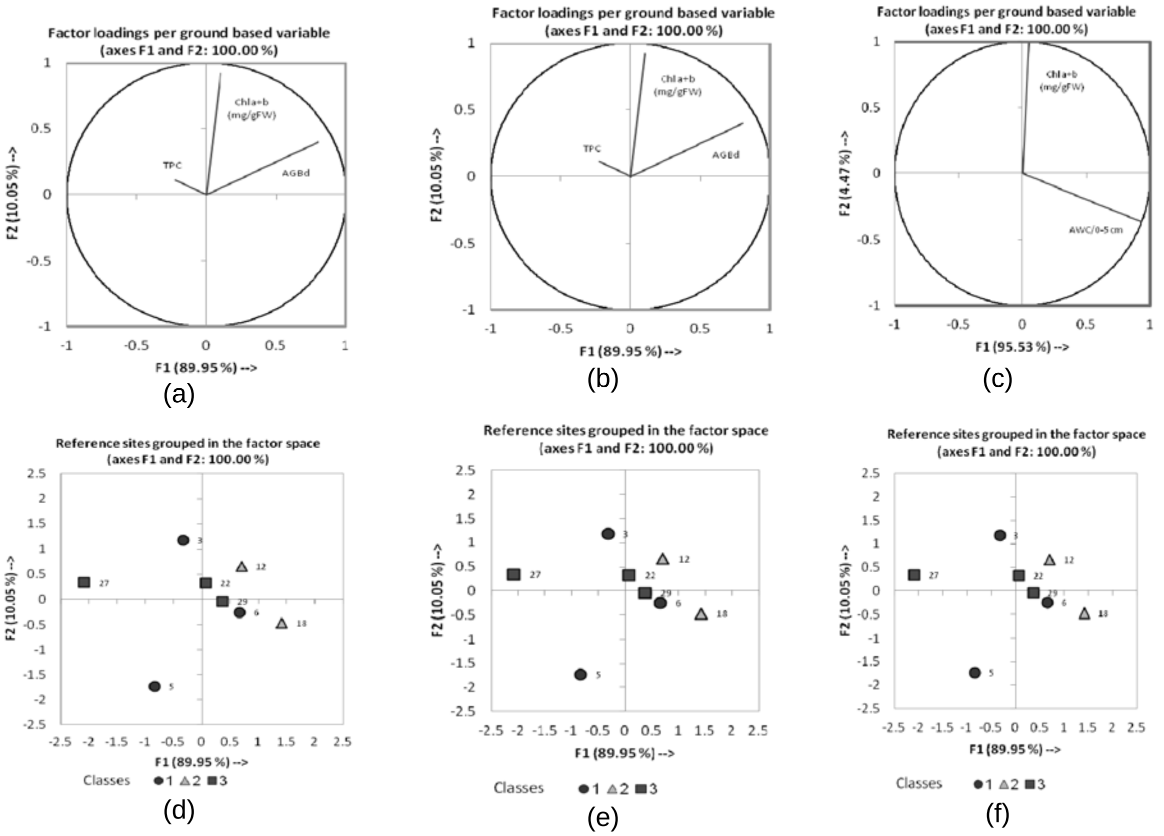


Fig. 5. Factor loadings of the PROBA-V SD variables a) and bi-plot of its factor scores (F1) b); factor loadings of the ground-measured variables c) and bi-plot of its factor scores (F1) d) for the *Lozenets* test fields (*Tillering*)

It can be seen from the figure that the PROBA-V SD VIs and LAI estmated after the Interpolation method, form the first factor (F1), whereas the second factor (F2) is formed mainly by NDWI. The factor scores for the F1, which account for 99.1% of the overall variability in the input VIs and LAI data, shows clearly that field II tops in score ranking, followed by field I and field III. The contribution of the ground-measured variables in forming factors1 and 3 (F1 and F2) is represented in Fig. 5 c and 5 d. The environmental meaning of the factors so formed shows that the F1 accounts mostly for plant structure and pigment content, whereas the F2 accounts for some structural parameters of winter wheat. According to the factor scores of F1 (80.66% of overall variability), it can be concluded that field II is in more favourable condition than field I, followed by field III. This leads to the conclusion that both ground-measured data and PROBA-V SD detect the differences in field status at field level. The χ^2 (chi-squared) test statistics (2.147, df = 2, α = 0.05) is significant and shows that the factor scores F1 and F2 estimated from field and satellite data are strongly dependent from one another. Therefore, the changes in the field measured parameters follow the changes of the PROBA-V SD VIs and LAI. The initially classified PROBA-V SD NDVI, NDWI, and LAI into three classes: 1) unsatisfactory, 2) good, and 3) very good status have been tested for their separability. The Wilks' Lambda test showed that F (observed value) 0.835 << F (critical value) 4.323, thus confirming the null hypthesis for difference in the groups of ground-based data.

During the verification for compliance of the observation classes from PROBA-V SD NDVI with the ground-measured data, the following ranking of the reference sites in the bi-factor space was obtained, Fig. 6.



(a) (b) (c)

(d) (e) (f)

Fig. 6. Factor loadings (F1 and F2) of the ground-measured variables (a-c) and bi-plots of factor scores (F1 and F2) for PROBA-V SD NDVI classes d), LAI classes e), and NDWI classes f) for *Lozenets* reference sites

On Fig. 6 a the contribution of LAI in the formation of F1 is greatest, while with F2, the contribution of LAI and TPC is greatest. Nevertheless, the percent participation of F2 is negligibly small and therefore, it may be assumed that F1 is formed entirely of LAI, AGBf, and TPC. The clustering of the reference sites in the bi-factor space correspond to the clusters separated from PROBA-V SD NDVI. Although, there is a relatively poor separation of class 1 (unsatisfactory status) by F1, while class 2 (good) and class 3 (very good) are well separated from each other. This is also confirmed by the results from the cross-validation of PROBA-V SD by ground-based data, as shown on Table 3.

Table 3. Confusion matrix of F1 and F2 classes (PROBA-V SD NDVI, NDWI, and LAI) and F1 and F2 classes (TPC, AGBd, AGBf, AWC/0-5 cm, and chlorophill *a*+*b*)

	F1 and F2 classes (TPC, AGBd, and clorophill *a*+*b*)			
PROBA-V SD NDVI classes	**to 1**	**to 2**	**to 3**	**Sum**
from 1	2 (25.0%)	0 (0.0%)	1 (12.5%)	3 (37.5%)
from 2	0 (0.0%)	2 (25.0%)	0 (0.0%)	2 (25.0%)
from 3	1 (12.5%)	0 (0.0%)	2 (25.0%)	3 (37.5%)
Sum	3 (37.5%)	2 (25.0%)	3 (37.5%)	8 (100.0%)
PROBA-V SD LAI classes	F1 and F2 classes (TPC, AGBd, and chlorophill *a*+*b*)			
from 1	2 (25.0%)	0 (0.0%)	1 (12.5%)	3 (37.5%)
from 2	0 (0.0%)	2 (25.0%)	0 (0.0%)	2 (25.0%)
from 3	1 (12.5%)	0 (0.0%)	2 (25.0%)	3 (37.5%)
Sum	3 (37.5%)	2 (25.0%)	3 (37.5%)	8 (100.0%)
PROBA-V SD NDWI classes	F1 and F2 classes (AGBf, AWC/0-5 cm, and clorophill *a*+*b*)			
from 1	3 (37.5%)	0 (0.0%)	0 (0.0%)	3 (37.5%)
from 2	1 (12.5%)	2 (25.0%)	0 (0.0%)	3 (37.5%)
from 3	1 (12.5%)	0 (0.0%)	1 (12.5%)	2 (25.0%)
Sum	5 (62.5%)	2 (25.0%)	1 (12.5%)	8 (100.0%)

During the discriminant analysis the results for the percent error of PROBA-V SD NDVI, NDWI and LAI classes are identical (25%) when using three ground-measured variables for F1 and F2 (TPC, AGBd, and Chl *a*+*b*) for NDVI and LAI, and F1 and F2 (AGBf, AWC/0-5 cm, and clorophill *a*+*b*) for NDWI. The confusion is greatest with class 1 (unsatisfactory status) which shares its members with class 3, as well as of class 3 with class 1. The major error in the validation of data for PROBA-V SD NDWI and F1 and F2 classes is between the PROBA-V SD NDWI classes 2 and 3 (good and very good status) and F1 and F2 class 1 (unfavourable status).

Conclusions

The results from the field measurements and PROBA-V SD of the *Lozenets* test fields, sized 1.5 km^2, prove the differences in fields' vegetation status. This conclusion is supported by the factor scores for the three test fields estimated using field data and PROBA-V SD. This provides for extending the monitoring of winter wheat at field level on a regular basis by using the satellite data and products from PROBA-V.

The significance of the χ^2 (chi-squared) test statistics of (2.147; 2 DF) shows that both datasets, i.e. field-measurement data and PROBA-V SD VIs and biophysical products, are strongly dependent.

It was established that PROBA-V SD NDVI, NDWI, and LAI may be used to monitor winter wheat status after winter dormancy with 75% accuracy. This is based on the good correspondence of the three classes of winter wheat crop status: (1) unsatisfactory, (2) good, and (3) very good determined by PROBA-V SD and ground-based data.

It is suggested that during future validation of PROBA-V satellite data, a minimum set of ground-measured winter wheat status parameters, such as LAI, TPC, AGBf and AGBd, Chl *a*+*b*, and AWC/0-5 cm have to be determined.

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