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Feasibility study of vegetation indices derived from Sentinel-2 and PlanetScope satellite images for validating the LAI biophysical parameter to monitoring development stages of winter wheat

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Abstract: The main objective of the presented work is to assess applicability of vegetation indices derived from non-commercial and commercial satellites for monitoring development stages of winter wheat. Two types of data were used in the study: Sentinel-2 and PlanetScope images. Various vegetation indices were derived from these data and correlated with ground measured LAI values. The results of the study revealed that there is a good relationship between satellite based indices – Normalized Difference Vegetation Index – NDVI, Enhanced Vegetation Index – EVI, Soil Adjusted Vegetation Index – SAVI and ground based LAI, but strength of this relation depends on the phase of crop development. Sentinel-2 and PlanetScope data are suitable for estimating LAI with high accuracy and their precision for LAI determination is very similar. Depending on availability, they can be used interchangeably. The highest correlation between ground measured LAI and vegetation indices for Sentinel-2 appeared SAVI – $r = 0.862$ (phase: early tillering) and for PlanetScope NDVI – $r = 0.667$ (phase: ripening). Compatibility of average LAI values derived from PlanetScope and Sentinel-2 images are 33.21% and 10.63%.

Keywords: PlanetScope, Sentinel-2, monitoring, Leaf Area Index, vegetation indices, winter wheat

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1. Introduction

Remote sensing for agricultural and crop-management applications aims at providing spatially and spectrally derived surface parameters for crop classification and mapping (Waldner et al., 2015), crop forecasting and yield predictions (Chlingaryan et al., 2018), crop status and condition (Zhang et al., 2014), disease detection and nutrient deficiency (Me et al., 2017). Critical issues such as the optimum spatial, spectral and temporal resolutions can be main factors limiting the usefulness of remote sensing products for precision crop management. However, current satellite-based products have been improved to apply in crop management due to the high spatial and spectral resolutions provided and the short revisit periods.

Planet, an aerospace company, builds and operates the largest constellation of small imaging satellites called PlanetScope (PS). Planet operates with more than 175 PlanetScopes and collects multispectral (MS) imagery in 4 bands with a spatial resolution of 3.7 m and a collection capacity of 300 million square km per day. PS imagery is used in particular for vegetation dynamics monitoring (Gašparović et al., 2018).

Several empirical indices have been proposed and used through the years, which allow an easy identification and monitoring of the vegetation conditions from satellite measurements (Zhang et al., 2014; Milas and Vincent, 2016). In most cases, the crop condition is assessed by using various satellite-derived indices.

The Leaf Area Index (LAI) is an important vegetation biophysical parameter which represents a ratio of leaf area to per unit ground surface area (Chen and Black, 1992). LAI drives both the within and the below canopy microclimate, determines and controls canopy water interception, radiation extinction, water and carbon gas exchange (Watson, 1947). LAI can characterize an impact of meteorological conditions on the development of vegetation (Zheng and Moskal, 2009). Therefore, numerous efforts were undertaken in the research centers in the past decades to prepare effective methods for deriving this variable from satellite data (Price J.C., 1993; Friedl et al, 1994; Carlson and Ripley, 1997; Turner et al., 1999; Zheng and Moskal, 2009; Aboelghar et al., 2010; Frampton et al, 2013; Jiang et al., 2016; Bochenek et al., 2017).

The main objective of the presented work is to examine usefulness of the new-generation of high-resolution satellite images for monitoring vegetation condition. It is particularly important to obtain the crop condition information at an early stage of the crop-growing season. Two types of satellite data were considered: Sentinel 2 images (Drusch et al., 2012) and PlanetScope. The availability of cloudless satellite images depending on the revisit periods were studied in a temporal profile and conclusions were drawn on precision of remotely sensed LAI estimate as a biophysical parameter allowing for monitoring development stages of winter wheat.

2. Study area

The test site for the research work has been situated in the western part of Poland – Wielkopolska region. The agricultural area is a part of Joint Experiment

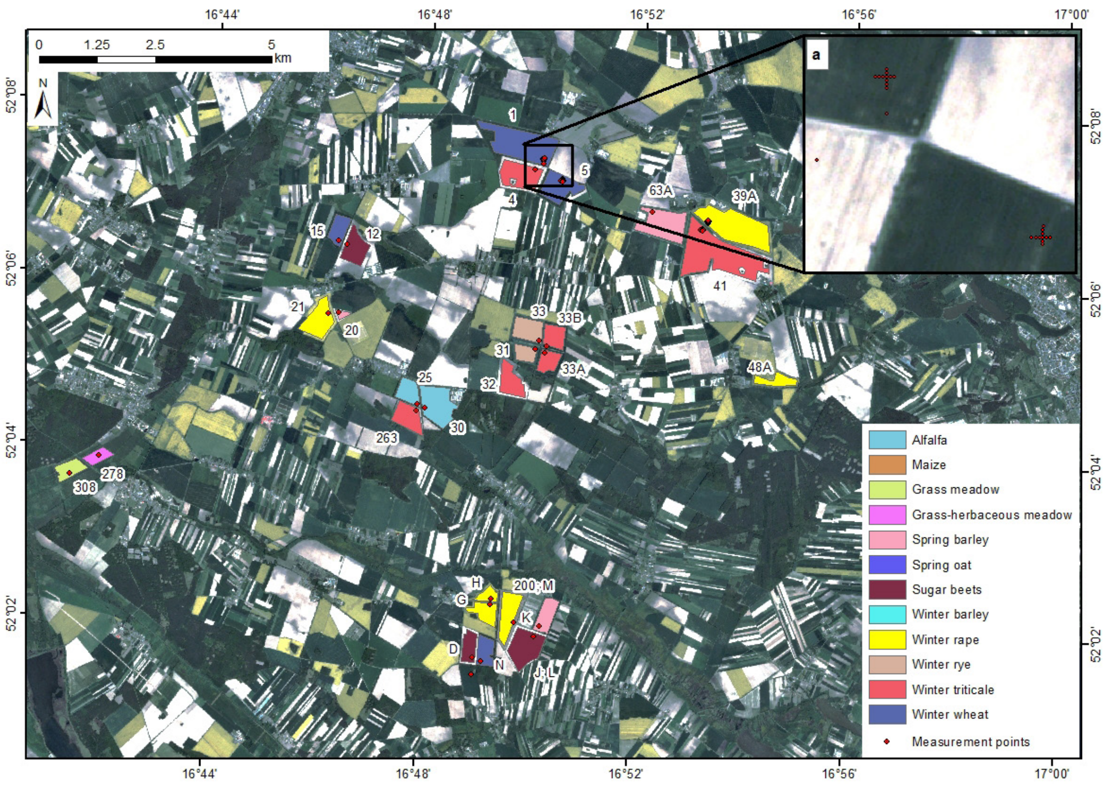

Fig. 1. Agricultural test site – JECAM Wielkopolska region. a) cross-shaped measuring transects

of Crop Assessment and Monitoring (JECAM). It is characterized by a mixture of agricultural crops, with winter wheat, rape and maize as dominant species. The field pattern is characterized by a diversified surface area. In order to properly match the satellite information with the ground data, only large fields exceeding 100 m in width were taken into account. The analyses presented in this article were performed using winter wheat fields, which dominate within the study area. Ground measurements of Leaf Area Index were conducted on previously mapped fields from the beginning of April to harvest. Four measurement fields were selected. On two of them cross-shaped measuring transects consisting of 11 measurements were determined (Figure 1a). The size of the Elementary Sampling Unit (ESU) has been 10 m for a single measurement point. The LAI value consisted of an average from the three independent measurements (one measurement = two above and eight below top of canopy). The measurements were carried out at the dates of Sentinel-2 acquisitions, using LAI 2000 / 2200 Plant Canopy Analyzers (every ten days). The test site and pattern of fields used for ground measurements with the point numbers are presented in Figure 1.

3. Materials and methods

3.1. Satellite data

Two types of satellite data have been used for the research works:

– Sentinel-2 satellite images, collected at 10 m, 20 m and 60 m resolution in 12 spectral bands;
– PlanetScope satellite images, collected at 3 m resolution in 4 spectral bands.

Spectral characteristics of both sensors are given in Table 1.

Sentinel-2 images were collected over the agricultural test site five times during the growing season related to cereals: on 1 April, 1 May, 21 May, 20 June and 30 July, 2017. PlanetScope available and cloudless images were acquired on: 2 April, 19 May, 28 May, 22 June, 9 July and 22 July. Table 2 presents the dates of acquiring imagery

Table 1. Spectral characteristics of Sentinel-2 and PlanetScope sensors

Sensor	Revisit time	Spatial resolution [m]	Band number	Central wavelength [nm]	Bandwidth [nm]
Sentinel-2A	every 10 days	10	2	499.6	98
			3	560.0	45
			4	664.5	38
			8	835.1	145
		20	5	703.9	19
			6	740.2	18
			7	782.5	28
			8a	864.8	33
			11	1613.7	143
			12	2202.4	242
			1	443.9	27
		60	9	945.0	26
			10	1373.5	75
PlanetScope	daily at nadir	3	1	485.0	60
			2	545.0	90
			3	630.0	80
			4	820.0	80

Table 2. Dates of acquiring imagery

Phase	Sentinel-2	PlanetScope
Early tillering	01-04-2017	02-04-2017
Tillering	01-05-2017	-
Jointing	21-05-2017	19-05-2017
Heading	-	28-05-2017
Ripening	20-06-2017	22-06-2017
Ripening	-	09-07-2017
Senescence	30-07-2017	22-07-2017

At the preliminary stage of work three vegetation indices, which characterize different aspects of crop condition and development, were derived from Sentinel-2 and PlanetScope data. The vegetation indices which have been selected are calculated on the basis of the same spectral ranges in order to ensure comparability of the results. The indices characterizing general plant condition are as follows:

- Normalized Difference Vegetation Index – NDVI Rousse et al. (1973)
  NDVI = (Band 8 – Band 4) / (Band 8 + Band 4)
  Band 8: 784.5 – 899.5 nm (NIR); Band 4: 650 – 680 nm (Red)
- Enhanced Vegetation Index – EVI
  Huete et al. (1997)
  EVI = 2.5 *[(Band 8 – Band 4) / (Band 8 +6*Band 4 – 7.5*Band 2 + 1)]
  Band 8: 784.5 – 899.5 nm (NIR); Band 4: 650 – 680 nm (Red)
  Band 2: 457.5 – 522.5 nm (Blue)
- Soil Adjusted Vegetation Index – SAVI
  Huete (1988)
  SAVI = 1.5*[(Band 8 – Band 4) / (Band 8 + Band 4 + 0.5)]
  Band 8: 784.5 – 899.5 nm (NIR); Band 4: 650 – 680 nm (Red)

3.2. Ground-based data

In order to obtain appropriate reference data for assessing impact of temporal resolution for monitoring development stages, ground campaigns have been conducted during 2017 growing season, with ground measurements of Leaf Area Index. This biophysical parameter has been chosen as the key parameter to estimate biomass of winter wheat (Zheng and Moskal, 2009) and plant condition (Watson, 1947). The distribution of measurement points was used in such a way as to take into account the variability of LAI within Sentinel-2 pixel at 10 m resolution, selecting only homogenous surfaces. Three LAI measurements were taken and the average was calculated afterwards. Photographic documentation was taken and the phase of winter wheat development was noted. Dates of ground measurements were synchronized with acquisitions of satellite data (every ten days).

3.3. Analytical approach

In the next stage of work, it was decided to perform a correlation analysis between particular vegetation indices derived from satellite images and ground measured LAI values, in order to find if any significant relationship exists between these two parameters. The analysis was done separately at each date of the growing season in which satellite images were available in order to assess at which phase of crop development the relationship is the strongest, enabling a reliable estimation of LAI on the basis of satellite data. The second goal of the analysis was to determine which vegetation indices are the best for LAI assessment. Linear regression was assumed in the correlation analysis. The whole set of ground measurement points and related satellite-based indices was divided into two parts: a training set for determining the relationship and a test set for verifying the established relations. The regression equations obtained as a result of the correlation analysis were next applied for generating LAI values at the test points. Finally, those values were compared with the ground LAI measurements and differences between these two datasets were computed and statistically assessed.

In addition, the impact of the temporal and spatial resolution of Sentinel-2 and PlanetScope satellite images for monitoring development stages of winter wheat was evaluated. The number of cloudless images in each development phase of 2017 were compared.

4. Results and discussion

4.1. Analysis of Sentinel-2 data

Correlation analysis between ground measured LAI and LAI derived from the selected S-2 based vegetation indices has been done separately for each phase of the growing season and for particular vegetation indices. The aim of the analysis was to study temporal variation of precision of LAI estimation and to determine which indices are best suited to remote sensing based LAI estimation. In 2017, the study has been performed for four phases of development stage of winter wheat: tillering (the beginning of April and May), jointing (the middle of May), ripening (the middle of June) and senescence (the end of July), using 22 measurement points for regression analysis. The results of the analysis are presented in Table 3.

Table 3. Results of the correlation analysis (*r* coefficient) for 2017 Sentinel-2 data

Date	Phase	NDVI	EVI	SAVI
01 April 2017	Early tillering	0.727	0.857	0.862
01 May 2017	Tillering	0.534	0.445	0.518
21 May 2017	Jointing	0.241	0.211	0.346
20 June 2017	Ripening	0.741	0.571	0.652
30 July 2017	Senescence	0.421	0.397	0.402

The following conclusions can be drawn from the presented analysis:

1. the highest correlation between ground measured LAI and vegetation indices appears for SAVI (early tillering), $r = 0.862$;
2. high correlation between ground measured LAI and all vegetation indices exists at the beginning of April (early tillering) and in the middle of June (ripening);
3. correlation around $r = 0.5$ was achieved using all vegetation indices for tillering and senescence;
4. lower correlation with ground measured LAI appears for all vegetation indices at the end of May (jointing).

The conclusions are supported by phenological behaviour of winter wheat, which is related to canopy cover by plants. In the stage of early tillering the value of LAI is lower (~0.4) than in the following stage of development (~1.5); this implies the dominance of bare soil with subsequent reduction of vegetation indices. In case of homogeneous pixels, the correlation with vegetation indices is higher. The occurrence of soil clearance and lowering of chlorophyll and water content reduce the correlation (jointing and senescence). This is especially true for all vegetation indices which are sensitive to chlorophyll content in plants, being based on the usage of the NIR band (Bochenek et al., 2017).

The stage of early tillering proved to be the most useful. These findings are in line with the previous studies by the authors, which resulted in conclusions that both stages of wheat development – tillering and heading – are important for estimating crop yield in Poland with the use of satellite data (Dabrowska-Zielinska et al., 2002).

The regression equations derived from the correlation analysis served for determining LAI values on the basis of particular vegetation indices. Next, satellite based LAI values for control points were compared with the ground measured ones, in order to estimate precision of LAI determination of differences between satellite based and ground measured LAI (in percent).

4.2. Analysis of PlanetScope

In parallel to the analysis of Sentinel-2 images, an analogous analysis of PlanetScope images at 3 m resolution has been performed. The same three vegetation indices as before have been derived from PlanetScope: NDVI, SAVI and EVI. They were used for the analysis on six available dates in 2017: 2 April (early tillering), 19 May (jointing), 28 May (heading), 22 June (ripening), 9 July (ripening) and 30 July (senescence). The results of the correlation analysis between the ground measured LAI and the vegetation indices are presented in Table 4.

Table 4. Results of the correlation analysis (*r* coefficient) for 2017 PlanetScope

Date	Phase	NDVI	EVI	SAVI
02 April 2017	Early tillering	0.463	0.342	0.472
19 May 2017	Jointing	0.451	0.267	0.439
28 May 2017	Heading	0.503	0.549	0.492
22 June 2017	Ripening	0.385	0.417	0.371
09 July 2017	Ripening	0.667	0.588	0.648
30 July 2017	Senescence	0.122	0.084	0.103

Results of the analysis reveal:

1. the highest correlation between the ground measured LAI and the vegetation indices appears for NDVI (ripening), $r = 0.667$;

2. high correlation between ground measured LAI and all vegetation indices exists at 28 May (heading) and 9 July (ripening), $r = 0.5$ or higher was achieved using all vegetation indices;
3. correlation around $r = 0.5$ was achieved using all vegetation indices for early tillering and jointing (except EVI);
4. low correlation with ground measured LAI appears for all vegetation indices at the end of July (senescence).

The correlation coefficients are lower than in the case of applying S-2 based vegetation indices. However, while applying the regression equations based on the NDVI index for LAI estimation, comparable accuracy of estimation for test points to that achieved using S-2 data (10%) was obtained. During all development stages one can observe a similar level of correlation coefficients between the ground measured LAI and the vegetation indices. In order to better characterize the pixels in the whole field, the cross-transects have been designed. The LAI sampling was organized in the form of transects with 11 points situated at the appropriate distances to represent 60 × 60 m of field. Using this approach provides more detailed information about 3 and 10 m pixels. Summarizing, a general conclusion can be drawn that vegetation indices based on 3 m PlanetScope images can be used for LAI estimation with good accuracy.

4.3. Comparative analysis of Sentinel-2 and PlanetScope

In order to assess impact of ground resolution on values of vegetation indices and hence on the precision of LAI estimates a study has been conducted, applying PlanetScope data and Sentinel-2 images for this purpose. On the basis of calculated vegetation indices, linear regression patterns were derived for LAI. In the next step, LAI derived from vegetation indices was calculated on the basis of both types of satellite images. LAI was calculated separately for each development stage. Next, the results of the modeled LAI were compared with LAI values measured in the field. Table 5 presents the average percentage difference between these two values.

Table 5. The average percentage difference between LAI derived from satellite images and ground measured LAI values

Phase	Sentinel-2	PlanetScope	
Early tillering	18.49%	54.97%	
Tillering	12.43%	-	
Jointing	7.33%	8.71%	
Heading	-	8.57%	
Ripening	9.18%	7.86%	
Senescence	5.73%	85.93%	
	10.63%	33.21%	Average

The following conclusions can be drawn from the presented analysis:

1. Compatibility of LAI values derived from PlanetScope and Sentinel-2 images depends on the phase of plant development, being high at tillering, jointing, heading and ripening stages (mean difference between both values is 7.84–12.43% on average) and lower at the early tillering (Sentinel-2: 18.49%, PlanetScope: 54.97%).
2. During the senescence stage, better results were obtained for LAI of Sentinel-2 (5.73%) than LAI of PlanetScope (85.93%).
3. LAI values derived from PlanetScope images at 3 m resolution can be effectively used for LAI estimation when Sentinel-2 data are not available.
4. The individual analysing points are characterized by varying accuracy. Results of the comparative analysis of LAI estimation based on Sentinel-2 and PlanetScope data are presented in Figure 2.

The conclusions drawn from the analysis are important from the practical point of view; they confirm that Sentinel-2 and PlanetScope images can be used for assessing LAI with high accuracy. The information of LAI should be taken from both satellites as then, the frequency of crop monitoring is much higher. In turn, it allows to make yield prognosis on the basis of satellite data, described in the previous study (Kowalik et al., 2014), using Sentinel-2 and PlanetScope data for this purpose.

5. Conclusions

The main objective of the presented work was to examine usefulness of non-commercial and commercial, high-resolution satellite images for gene-

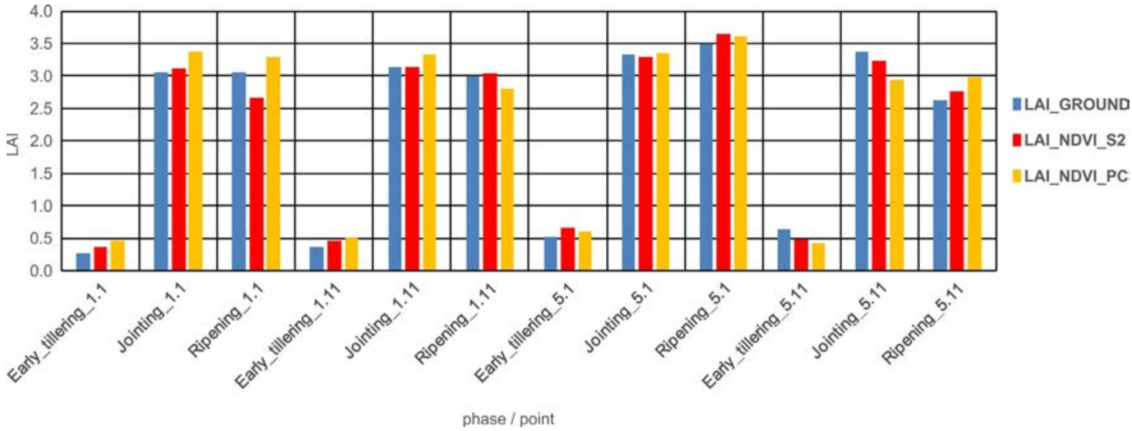

Fig. 2. Comparison of LAI estimation based on Sentinel-2 and PlanetScope images

rating LAI information. The results of the work point out that application of both types of satellite data – Sentinel 2 and PlanetScope – is justified, while keeping proper time of data acquisition and applying appropriate vegetation indices derived from original satellite data and the proper sampling strategy for LAI ground-based measurements. It was found that the accuracy of LAI estimation on the basis of vegetation indices is high between tillering and ripening stages of winter wheat. The highest accuracy of LAI estimation was obtained in the crucial heading stage of winter wheat growth which confirms previous research (Bochenek et al., 2017). Three vegetation indices derived from satellite data – Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI) and Soil Adjusted Vegetation Index (SAVI) are suitable for estimating LAI with high accuracy; their precision for LAI determination is very similar. Vegetation indices can be used successfully for monitoring winter wheat condition.

Vegetation indices derived from PlanetScope data proved to be efficient for LAI estimation. The precision of LAI determination is similar to that obtained with the use of Sentinel-2 based vegetation indices. In the case of a cloudless sky, the temporal resolution of Sentinel-2, which is nowadays 5 days, appears to be sufficient for observing crop condition. However, frequent cloudiness may result in a lack of data for analysis. Our study revealed that it is advisable to purchase PlanetScope data, which enables a daily revisit to monitor the development stages of winter wheat.

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Studium wykonalności wykorzystania wskaźników roślinnych generowanych na podstawie obrazów satelitarnych Sentinel-2 i PlanetScope do monitorowania faz rozwoju pszenicy ozimej

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Streszczenie: Głównym celem prezentowanej pracy jest ocena przydatności wskaźników roślinnych pochodzących z komercyjnego i niekomercyjnego satelity do monitorowania faz rozwoju pszenicy ozimej. W badaniach wykorzystano dwa typy danych: zobrazowania satelitarne PlanetScope i Sentinel-2. Na ich podstawie wygenerowano różne wskaźniki wegetacji i skorelowano je z wartościami LAI pomierzonymi w terenie. Wyniki analiz wykazały, że istnieje wysoki związek pomiędzy wskaźnikami NDVI, EVI i SAVI a naziemnymi wartościami LAI. Okazało się, że siła tej zależności zależy od fazy rozwoju upraw. Stwierdzono, że zobrazowania satelitarne Sentinel-2 i PlanetScope pozwalają na szacowania LAI z dużą dokładnością, a dokładność obu danych jest podobna. W zależności od dostępności bezchmurnych zdjęć, obrazy można stosować zamiennie.

Słowa kluczowe: PlanetScope, Sentinel-2, monitoring, wskaźnik projekcyjny liści, wskaźniki roślinne, pszenica ozima