Characteristics of the onset of the growing season in Poland based on the application of remotely sensed data in the context of weather conditions and land cover types

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Abstract
We present the results of research concerning the temporal and spatial variability of the dates of the onset of the growing season (OGS) in Poland using satellite data. The data from the years 2001-2010 were obtained from the MODIS Global Land Cover Dynamics Product (MCD12Q2). The study examined the relationship between the OGS dates and types of land cover, meteorological elements (air temperature and snow depth), and atmospheric circulation conditions. In the study period, the average OGS dates for the entire country showed the strongest correlation with minimum air temperature from January to March (R²=0.95). The photosynthetic activity of vegetation in early spring was also considerably influenced by the strength of zonal flow and the type of land cover. The latest OGS dates in Poland were observed in areas with a higher share of wetlands and inland waters, and the earliest ones in urban areas and agricultural land.

Keywords: MODIS, growing season, Enhanced Vegetation Index (EVI), atmospheric circulation, land cover, Poland.

Introduction
The analysis of the long-term variability of the onset and end of the growing season can be one of the methods used in research on climate change [Menzel and Fabian, 1999; Ahas et al., 2002; De Beurs and Henebry, 2005; Jeong et al., 2011]. On the one hand, an extended period with positive air temperature values at temperate latitudes provides the possibility of cultivation of new species of crops. On the other hand, it causes the abandonment of growing of other plants, less adaptable to the new climatic conditions [Schwartz and Reiter, 2000; Richardson et al., 2009, 2010; Żmudzka, 2013]. A longer growing season, combined with a higher content of CO₂ in the atmosphere and increased CO₂ absorption by plants in the process of photosynthesis, can also contribute to the growth of net primary production [Craine et al., 2003; Kimball et al., 2006]. The problem is important not only from the point
of view of environmental sciences. Therefore, it requires a multidisciplinary approach [White et al., 1999; Churkina et al., 2005; Böttcher et al., 2014; Cornelissen and Makoto, 2014].

Remote sensing is a useful method of observation of vegetation at different spatial scales. In the 1980’s, due to the high cost of data acquisition and low density of measuring stations, scientists started using satellite data to observe the growth and development of plants [Myneni et al., 1997]. One of the first indicators widely used for this purpose was the Normalized Difference Vegetation Index [Rouse et al., 1973]. The NDVI is based on the contrast between the maximum absorption in the red band due to chlorophyll pigments and the maximum reflection in the infrared caused by leaf cellular structure. The launch of new satellites, with improved temporal, spatial and spectral resolutions, resulted in an increase in the number of new vegetation indices. An example is the Enhanced Vegetation Index (EVI), based on similar assumptions as NDVI, but providing a greater dynamic range. Therefore, it is more suitable for capturing dynamic crop phenology without reaching saturation [Huete et al., 2002; Galford et al., 2008; Ganguly et al., 2010; Fraga et al., 2014; Li et al., 2014].

Remote sensing of vegetation at various spatial and temporal scales is commonly based on Earth monitoring data obtained from a number of orbital instruments (e.g. MODIS, AIRS, HIRS, AVHRR). Vegetation indices have been used in many studies dealing with changes in phenology at various sites [e.g. Gitelson and Kaufman, 1998; Tucker et al., 2005; Beck et al., 2006; Bunn and Goetz, 2006; Fensholt et al., 2009; Kim et al., 2012].

Polish literature on the subject provides several methods of determining the dates of the onset of the growing season (OGS). They are only based on days when monthly or daily mean air temperature crosses the threshold of 5°C [Gumiński, 1948; Huculak and Makowiec, 1977; Nieróbca et al., 2013]. The main disadvantage of using the threshold method is that small differences in air temperature between neighbouring meteorological stations could lead to large differences in the dates [Jaagus and Ahas, 2000]. No detailed studies exist so far concerning the determination of the onset of the growing season in Poland based on the application of satellite data. We are the first to present the results of research concerning the temporal and spatial variability of the OGS dates in all the territory of Poland using remotely sensed data. The analysis is very important because could be used in research on climate change. This paper focuses on the following aspects:

a) presentation of the temporal and spatial variability of the OGS dates in Poland based on remotely sensed data;

b) identification of the correlation between the OGS dates and thermal and nival conditions, land cover types, and the main characteristics of atmospheric circulation.

Materials and methods

Study area

Poland is a country located in Central Europe, between the Baltic Sea in the north and the Carpathian and Sudety Mountains in the south (Fig. 1). It occupies an area of approximately 312.7 thousand km², with a meridional extent of 649 km and a latitudinal extent of 689 km. The country is distinguished by a latitudinal course of geographical regions. Approximately 90% of the area is below 300 m a.s.l., which indicates the dominance of lowland areas. The highest peaks of the Carpathians in the south reach above 2000 m a.s.l. The mountains are adjacent to the highlands in the north. The central and north part of Poland is occupied by
vast plains. The north part of the country is rich in post-glacial lakes and landforms. Arable land reaches the highest contribution in the country’s area (approximately 60%), followed by forests (30%) (Fig. 2). Anthropogenic areas (5%) and inland waters (2%) represent a smaller share of the total area. In recent years, in the structure of sown areas of arable land, cereals have accounted for 73%, forage crops for 11%, and industrial crops for 9%. The species composition of cereals is determined by climatic and soil conditions. Among cereals, winter wheat production is predominant (approximately 33%), followed by triticale (16%), barley (13%) and rye (11%).

Figure 1 - Topography of Poland with a grid net resolution 0.25° x 0.25°.

Figure 2 - Map of land use in Poland by CORINE Land Cover 2006.
Poland is located in the temperate transitional climate zone, and is distinguished by a high variability of types of weather, particularly in the cold season. This also results in a considerable inter-annual variation of mean air temperature values and number of days with snow cover from December to February [Wibig and Głowicki, 2002; Falarz, 2004]. The atmospheric circulation over Poland has a significant impact on the spatial and temporal variability of thermal and nival conditions in winter [Bednorz, 2002; Ustrnul, 2006; Falarz, 2007]. Strong air flow from the east, i.e. from the interior of the Eurasian continent, contributes to negative anomalies in air temperature, and longer persistence of snow cover. In contrast, a strong air flow from the North Atlantic in winter determines the occurrence of types of weather typical of late autumn or early spring.

It has been determined based on the thermal method that the growing season in Poland lasts for approximately 220 days on the average, i.e. from the end of March to the first days of November [Żmudzka, 2012; Nieróbca et al., 2013]. It is the shortest in the north-eastern part of the country (<200 days), and the longest in south-western Poland (>225 days in a year).

**Remotely sensed data**

Satellite data from the years 2001-2010 were extracted from the MODIS Global Land Cover Dynamics product (MCD12Q2, version 5), providing information related to global vegetation phenology. The data product was obtained through the online Data Pool at the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota [https://lpdaac.usgs.gov/data_access]. Product is generated at a spatial resolution of 500 m in MODIS sinusoidal projection, and data files are stored in Hierarchical Data Format. The algorithm used in the MCD12Q2 product characterizes vegetation growth cycles using four transition dates estimated from time series of MODIS Enhanced Vegetation Index (EVI) values [Zhang et al., 2003, 2006]. The data set is generated using EVI computed from MODIS Nadir Bidirectional Reflectance Distribution Function (BRDF)-Adjusted Reflectance (NBAR) data [Schaaf et al., 2002]. In general, transition dates (where the units are days of year) correspond to: (1) greenup, (2) maturity, (3) senescence, and (4) dormancy, i.e. the date of onset of EVI (1) increase, (2) maximum, (3) decrease, and (4) minimum [Ganguly et al., 2010]. In the study, the onset of the growing season (OGS) related to the greenup onset dates, which are given as day numbers from January 1 (e.g. the number 80 indicates the 80th day of year, i.e. March 21). To assess the spatial variability of the dates, the area of the country was covered with a regular grid with a resolution of 0.25º x 0.25º (Fig. 1). Hence, the study area was divided into 653 pixels. The OGS dates obtained from the MCD12Q2 product were adjusted to the grid cell resolution by means of the weighted average method.

**Meteorological data**

The relationship between weather conditions and the OGS dates was studied based on average values of monthly minimum, maximum, and mean air temperature, and the mean depth of snow cover in Poland from January to March. The values at a resolution of 0.25 degrees were obtained from the Food Security Meteodata database (http://mars.jrc.ec.europa.eu). These data were derived from the European Centre for Medium-Range Weather Forecasts Interim Reanalysis [Dee et al., 2011]. In addition, the onset of growing
season was analysed depending on atmospheric circulation conditions over Poland. To determine the direction of air flow at \( \phi=52^\circ 30'N, \lambda=20^\circ 00'E \) grid point (Central Poland), the zonal and meridional component of the geostrophic wind was derived from the National Centers for Environmental Prediction and the National Center for Atmospheric Research Reanalysis [Kalnay et al., 1996]. The direction was determined for each day in the period from December to March, when the daily mean geostrophic wind speed was above 2 ms\(^{-1}\). To characterize changes in the strength of zonal flow over Poland, the study also applied the winter-mean North Atlantic Oscillation Index (from December to March), defined as the difference between normalised sea level pressure over the Gibraltar and South-West Iceland [Jones et al., 1997]. When the North Atlantic Oscillation index is positive (deep Iceland Low and a strong Azores High), the westerly flow across western and Central Europe is enhanced.

### Land cover data
In order to evaluate the effects of land use on the variability of the OGS dates in Poland, the relevant data with pixel resolutions of 100 m x 100 m were taken from Corine Land Cover 2006 database [CLC, 2012]. The CLC maps were elaborated based on the visual interpretation of satellite images, and show artificial and agriculture areas, forests, wetlands, and water bodies with the overall thematic accuracy of more than \( >85\% \). We determined the percentage share of each CORINE land cover class in all of grid cells (0.25º x 0.25º) over Poland. The percentage values were used to determine the relationship between the OGS dates and the distribution of land cover types within grid cells.

### Statistical methods
Linear correlation and simple linear regression were applied to explain the relationship between the OGS dates and the analysed environmental variables. The statistical significance of correlation coefficients was tested by the Student t-test at \( \alpha=0.05 \) and \( \alpha=0.01 \). The Jackknife method was used to validate the regression models. Based on the method, the accuracy of the models was determined by means of the determination coefficient \((R^2)\), root mean square error \((\text{RMSE})\), and the standard error of the estimate \((\text{SEE})\). The spatial variability of thermal and nival conditions was evaluated based on Kendall’s tau rank correlation coefficient [Kendall, 1975]. It is a measure free from the parent distribution describing the association between two variables of interests.

### Results and Discussion
#### Thermal, nival, and atmospheric circulation conditions in Poland
In the period 2001-2010, the lowest mean values of air temperature in January, February, and March occurred in north-eastern Poland and in the montane areas in the southern part of the country, while the highest values were recorded in western Poland (Fig. 3a-c). Furthermore, the highest mean depths of snow cover in the period from January to March were recorded in the montane regions and eastern Poland (Fig. 3d). Mean air temperature and depth of snow cover showed relatively high temporal variability (Fig. 4a-d). Very clear longitude gradients of both air temperature (directed from west to east) and depth of snow cover (from east to west) were also confirmed (Tab. 1). This is associated with the location of the country in Central Europe, where at this time of year, temperature and nival conditions can
be influenced by the Atlantic Ocean from the west and the Eurasian continent from the east [Clark et al., 1999; Sepp and Jaagus, 2002].

Figure 3 - Mean monthly air temperature in (a) January, (b) February, and (c) March, and (d) mean depth of snow cover from January to March (2001-2010).

Figure 4 - Features of the empirical distribution of (a) minimum, (b) maximum and (c) mean air temperature values, and (d) average depth of snow cover in the period from January to March in Poland. The yearly values are derived from each of the analysed pixels.
Table 1 - Kendall tau rank correlation coefficients (n=653) between thermal and nival conditions, and coordinates of analysed pixels (2001-2010).

<table>
<thead>
<tr>
<th>Meteorological element</th>
<th>Months</th>
<th>Coordinates</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jan</td>
<td>0.14**</td>
<td>–0.72**</td>
<td>–0.37**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Feb</td>
<td>0.06*</td>
<td>–0.75**</td>
<td>–0.31**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mar</td>
<td>–0.20**</td>
<td>–0.45**</td>
<td>–0.15**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Apr</td>
<td>–0.40**</td>
<td>–0.14**</td>
<td>–0.07**</td>
<td></td>
</tr>
<tr>
<td>Snow cover</td>
<td>Jan</td>
<td>–0.26**</td>
<td>0.42**</td>
<td>0.45**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Feb</td>
<td>–0.15**</td>
<td>0.31**</td>
<td>0.31**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mar</td>
<td>–0.21**</td>
<td>0.41**</td>
<td>0.45**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Apr</td>
<td>–0.27**</td>
<td>0.49**</td>
<td>0.42**</td>
<td></td>
</tr>
</tbody>
</table>

*, ** – significant at \( p \leq 0.05, p \leq 0.01 \), respectively

The results confirmed that the direction of air advection in the cold season has a significant impact on the thermal conditions and snow cover in Poland (Tab. 2). In years with intensified air flow from the west, temperatures considerably higher than normal, and lower depth of snow cover are recorded. Reverse dependencies are observed in years with an increased frequency of air flow from the east. This suggests that the variability of the OGS dates in Poland could be accounted for by the characteristics of the atmospheric circulation.

Table 2 - Correlation coefficients (n=30) between the air flow directions over Poland from December to March and the area averages of air temperature and depth of snow cover from January to March (1981-2010).

<table>
<thead>
<tr>
<th>Meteorological element</th>
<th>N</th>
<th>NE</th>
<th>E</th>
<th>SE</th>
<th>S</th>
<th>SW</th>
<th>W</th>
<th>NW</th>
</tr>
</thead>
<tbody>
<tr>
<td>T min</td>
<td>–0.17</td>
<td>–0.42*</td>
<td>–0.74**</td>
<td>–0.36</td>
<td>–0.26</td>
<td>0.30</td>
<td>0.72**</td>
<td>0.58**</td>
</tr>
<tr>
<td>T max</td>
<td>–0.22</td>
<td>–0.33</td>
<td>–0.66**</td>
<td>–0.47**</td>
<td>–0.33</td>
<td>0.20</td>
<td>0.79**</td>
<td>0.62**</td>
</tr>
<tr>
<td>T mean</td>
<td>–0.14</td>
<td>–0.38*</td>
<td>–0.76**</td>
<td>–0.46*</td>
<td>–0.28</td>
<td>0.25</td>
<td>0.77**</td>
<td>0.66**</td>
</tr>
<tr>
<td>Snow cover</td>
<td>–0.10</td>
<td>0.29</td>
<td>0.65**</td>
<td>0.36</td>
<td>0.31</td>
<td>–0.18</td>
<td>–0.55**</td>
<td>–0.29</td>
</tr>
</tbody>
</table>

*, ** – significant at \( p \leq 0.05, p \leq 0.01 \), respectively

**Characteristics of the dates of the onset of the growing season in Poland**

Satellite data showed the presence of the earliest average dates of the onset of the growing season in the western lowlands and central part of Poland, varying between 80 and 86 DOY (21-27 March) (Fig. 5a). In the analysed period, the average OGS dates appeared the latest in northern Poland and in the high mountain areas – between 92 and 100 DOY (2-10 April). These are similar to the dates in Poland obtained by using air temperature thresholds [Żmudzka, 2012; Nieróbca et al., 2013]. The period with a permanent increase in daily mean air temperature above 5°C suggests not only the onset of the thermal growing season [Jones and Briffa, 1995], but also the timing of an increase in the photosynthetic activity of vegetation after winter. Values of the coefficient of variation indicate areas with relatively high fluctuations of the OGS dates during the period considered (Fig. 5b). North-western Poland stood out in terms of the values (CV> 11%). In this region, the earliest onset of the growing season was approximately 72 DOY (March 13) in 2002, and the latest 120 DOY (April 30) in 2010.
The OGS dates occurred between 86 and 88 DOY (27-29 March) in almost one-third of the territory of Poland (Fig. 6). Both the earliest (DOY 80-82, 21-23 March) and the latest dates (DOY 98-100, 8-10 April) concerned very small areas of the country. This suggests quite low spatial variability of timing of onset of the growing season in Poland. Greater variation was found in the case of temporal variability of the OGS dates. In two years, 2003 and 2006, the median of OGS dates in Poland was higher than the average from the period from 2001 to 2010 by two standard deviations. It amounted to 95 and 97 DOY, respectively (4 and 6 April) (Fig. 7). In 2002, 2007, and 2008, the median of dates was lower than the average value by two standard deviations, and amounted to approximately 81 DOY (22 March).
Influence of thermal and nival conditions

The comparison of the previous results suggests a relationship between the temporal variability of the OGS dates and thermal and nival conditions (Figs. 4 and 7). In order to demonstrate this correlation, the area averages of the OGS dates, as well as the minimum, maximum, and mean air temperature and depth of snow cover for January, February, and March were calculated. The area averages of these variables were used for the development of simple regression equations and the calculation of certain measures fitting the models (Tab. 3). In the case of air temperature, the lowest RMSE error values were obtained for the mean values from January to March, and the highest for January. The area averages of the OGS dates were best defined by the model where the minimum temperature from January to March was the explanatory variable ($R^2=0.95$). This confirms results by other authors [e.g. Black et al., 2000; Chen and Pan, 2002; Tanja et al., 2003] stating that air temperature is the key factor controlling spring onset of photosynthesis and onset of the growing season.

Similar conclusions are suggested by the analysis of measures fitting the models for each pixel (n=653). In this case, the smallest RMSE error values also concerned minimum air temperature, where values were calculated for the period from January to March. At the scale of the entire country, the coefficient of determination ($R^2$) reached a value above $>0.7$ in almost 70% of all the regression models. In comparison to the other independent variables, this proportion was smaller, reaching 52.7% and 32.0% for the mean and maximum air temperature, respectively, and only 3.1% for depth of snow cover (almost 80% of $R^2<0.5$).
Table 3 - Relationships between the area averages of the OGS dates retrieved from the MODIS product, and the area averages of air temperature and depth of snow cover in Poland (n=10). Determination coefficients ($R^2$), root mean square error (RMSE), and standard error of the estimate (SEE) are also presented.

<table>
<thead>
<tr>
<th>Meteorological element</th>
<th>Months</th>
<th>Model equation</th>
<th>$R^2$</th>
<th>RMSE</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$OGS = -1.15 \times t_{\text{min}} - 82.26$</td>
<td>0.54</td>
<td>3.77</td>
<td>4.22</td>
</tr>
<tr>
<td>T min</td>
<td>Jan</td>
<td>$OGS = -1.71 \times t_{\text{min}} - 80.65$</td>
<td>0.75</td>
<td>2.81</td>
<td>3.14</td>
</tr>
<tr>
<td></td>
<td>Feb</td>
<td>$OGS = -2.29 \times t_{\text{min}} - 84.08$</td>
<td>0.69</td>
<td>3.13</td>
<td>3.47</td>
</tr>
<tr>
<td></td>
<td>Mar</td>
<td>$OGS = -2.36 \times t_{\text{min}} - 79.25$</td>
<td>0.95</td>
<td>1.31</td>
<td>1.46</td>
</tr>
<tr>
<td></td>
<td>Jan-Mar</td>
<td>$OGS = -1.01 \times t_{\text{max}} - 88.95$</td>
<td>0.40</td>
<td>4.36</td>
<td>4.83</td>
</tr>
<tr>
<td>T max</td>
<td>Feb</td>
<td>$OGS = -1.94 \times t_{\text{max}} - 93.47$</td>
<td>0.67</td>
<td>3.20</td>
<td>3.57</td>
</tr>
<tr>
<td></td>
<td>Mar</td>
<td>$OGS = -2.01 \times t_{\text{max}} - 102.09$</td>
<td>0.50</td>
<td>3.92</td>
<td>4.41</td>
</tr>
<tr>
<td></td>
<td>Jan-Mar</td>
<td>$OGS = -2.21 \times t_{\text{max}} - 95.86$</td>
<td>0.73</td>
<td>2.93</td>
<td>3.24</td>
</tr>
<tr>
<td>T mean</td>
<td>Jan</td>
<td>$OGS = -1.12 \times t_{\text{mean}} - 85.58$</td>
<td>0.48</td>
<td>4.00</td>
<td>4.51</td>
</tr>
<tr>
<td></td>
<td>Feb</td>
<td>$OGS = -1.93 \times t_{\text{mean}} - 86.22$</td>
<td>0.74</td>
<td>2.81</td>
<td>3.18</td>
</tr>
<tr>
<td></td>
<td>Mar</td>
<td>$OGS = -2.31 \times t_{\text{mean}} - 93.69$</td>
<td>0.62</td>
<td>3.45</td>
<td>3.86</td>
</tr>
<tr>
<td></td>
<td>Jan-Mar</td>
<td>$OGS = -2.42 \times t_{\text{mean}} - 87.43$</td>
<td>0.87</td>
<td>2.03</td>
<td>2.30</td>
</tr>
<tr>
<td>Snow cover</td>
<td>Jan</td>
<td>$OGS = 0.69 \times sc - 87.01$</td>
<td>0.04</td>
<td>5.50</td>
<td>6.10</td>
</tr>
<tr>
<td></td>
<td>Feb</td>
<td>$OGS = 1.57 \times sc - 84.91$</td>
<td>0.45</td>
<td>4.12</td>
<td>4.54</td>
</tr>
<tr>
<td></td>
<td>Mar</td>
<td>$OGS = 2.58 \times sc - 85.87$</td>
<td>0.35</td>
<td>4.50</td>
<td>5.05</td>
</tr>
<tr>
<td></td>
<td>Jan-Mar</td>
<td>$OGS = 2.63 \times sc - 83.98$</td>
<td>0.42</td>
<td>2.02</td>
<td>4.75</td>
</tr>
</tbody>
</table>

The spatial variability of the coefficient of determination showed that the minimum air temperature from the period from January to March is the best predictor of the OGS dates for a major part of eastern Poland (Fig. 8a). The lowest values of the measure were recorded for the Baltic coast and the central-western part of the country ($R^2 <0.6$). Depth of snow cover accounted to 60-70% of the inter-annual variation of the OGS dates in north-western and north-eastern Poland and in the foreland of the Carpathians (Fig. 8b).
**Influence of the direction of air flow**

The OGS dates in Poland are considerably affected by the frequency of air advection from three directions, namely west, north-west, and east (Tab. 4). It was confirmed based on correlation coefficients that a higher frequency of advection of relatively warm air masses from the Atlantic Ocean in the cold season determined earlier onset of the growing season. An increase in the frequency of cold air advection from the interior of the Eurasian continent has a reverse impact. The lowest RMSE values (<3.5 days) were represented by the regression model where the number of days with westerly zonal flow (SW+W+NW) was the independent variable (Tab. 4). Furthermore, the NAO index showed that the variability of occurrence of the latest OGS dates in Poland is also strongly related to the variation of strength of the zonal circulation over the North Atlantic (Fig. 9). Other studies also confirm that high vegetation activity in early spring in Central Europe is considerably more dependent on zonal rather than meridional air flow in winter months [Scheifinger et al., 2002; Aasa et al., 2004; Menzel et al., 2005; Gouveia et al., 2008].

Table 4 - Relationships between the area averages of the OGS dates retrieved from the MODIS product (n=10) and air flow direction over Poland from December to March (2001-2010).

<table>
<thead>
<tr>
<th>Air flow direction (Dir)/sector (Sec)</th>
<th>Linear correlation coefficient</th>
<th>Frequency from 2001 to 2010 (%)</th>
<th>Model equation</th>
<th>R²</th>
<th>RMSE</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>−0.08</td>
<td>7.9</td>
<td>OGS = −0.12×Dir_N + 89.11</td>
<td>0.01</td>
<td>5.56</td>
<td>6.24</td>
</tr>
<tr>
<td>NE</td>
<td>0.42</td>
<td>6.0</td>
<td>OGS = 1.06×Dir_NW + 81.57</td>
<td>0.18</td>
<td>5.05</td>
<td>5.66</td>
</tr>
<tr>
<td>E</td>
<td>0.73*</td>
<td>6.9</td>
<td>OGS = 0.96×Dir_NE + 81.64</td>
<td>0.53</td>
<td>3.84</td>
<td>4.30</td>
</tr>
<tr>
<td>SE</td>
<td>0.37</td>
<td>7.5</td>
<td>OGS = 0.42×Dir_SE + 85.02</td>
<td>0.13</td>
<td>5.19</td>
<td>5.81</td>
</tr>
<tr>
<td>S</td>
<td>0.44</td>
<td>11.1</td>
<td>OGS = 0.57×Dir_SE + 81.73</td>
<td>0.20</td>
<td>5.01</td>
<td>5.58</td>
</tr>
<tr>
<td>SW</td>
<td>−0.24</td>
<td>15.9</td>
<td>OGS = −0.22×Dir_S + 91.95</td>
<td>0.06</td>
<td>5.41</td>
<td>6.03</td>
</tr>
<tr>
<td>W</td>
<td>−0.70*</td>
<td>25.8</td>
<td>OGS = −0.30×Dir_W + 96.51</td>
<td>0.49</td>
<td>3.98</td>
<td>4.44</td>
</tr>
<tr>
<td>NW</td>
<td>−0.67*</td>
<td>16.7</td>
<td>OGS = −0.84×Dir_NW + 103.49</td>
<td>0.45</td>
<td>4.12</td>
<td>4.61</td>
</tr>
<tr>
<td>NW+N+NE</td>
<td>−0.40</td>
<td>–</td>
<td>OGS = −0.37×SecNW+N+NE + 100.05</td>
<td>0.16</td>
<td>5.12</td>
<td>5.74</td>
</tr>
<tr>
<td>NE+E+SE</td>
<td>0.70*</td>
<td>–</td>
<td>OGS = 0.47×SecNE+E+SE + 78.46</td>
<td>0.49</td>
<td>3.98</td>
<td>4.39</td>
</tr>
<tr>
<td>SE+S+SW</td>
<td>0.22</td>
<td>–</td>
<td>OGS = 0.12×SecSE+S+SW + 83.69</td>
<td>0.05</td>
<td>5.44</td>
<td>6.09</td>
</tr>
<tr>
<td>SW+W+NW</td>
<td>−0.80**</td>
<td>–</td>
<td>OGS = −0.27×SecSW+W+NW + 104.93</td>
<td>0.65</td>
<td>3.31</td>
<td>3.69</td>
</tr>
</tbody>
</table>

*, ** – significant at \( p \leq 0.05, p \leq 0.01 \), respectively

![Figure 9 - Relationship between the NAO index (DJFM) and values of the 95th percentile of the average OGS dates in Poland.](image-url)
The role of geographical location and type of land cover

The applied non-parametric Mann-Kendall test revealed a statistically significant correlation between the OGS dates and the geographical location of the area. The average onset of the growing season was generally delayed in the north and east of the country, as well as with an increase in height above sea level (Tab. 5). Moreover, the coefficient of variation of the OGS dates decreased towards the east of the country, and with an increase in height above sea level.

Table 5 - Kendall tau rank correlation coefficients (n=653) between the characteristics of the onset of the growing season and pixels’ geographic coordinates with selected types of land cover (2001-2010).

<table>
<thead>
<tr>
<th>Character</th>
<th>Coordinates</th>
<th>Land cover</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Latitude</td>
<td>Longitude</td>
</tr>
<tr>
<td>The average OGS dates (2001-2010)</td>
<td>0.14**</td>
<td>0.15**</td>
</tr>
<tr>
<td>CV of OGS</td>
<td>0.02</td>
<td>-0.35**</td>
</tr>
<tr>
<td>( R^2 ) \text{min I-III}</td>
<td>-0.01</td>
<td>0.39**</td>
</tr>
<tr>
<td>( R^2 ) Sector \text{NE+E+SE}</td>
<td>0.14**</td>
<td>-0.37**</td>
</tr>
<tr>
<td>( R^2 ) Sector \text{SW+W+NW}</td>
<td>0.07**</td>
<td>0.21**</td>
</tr>
</tbody>
</table>

*, ** – significant at \( p \leq 0.05 \), \( p \leq 0.01 \), respectively

As previously concluded, among the analysed meteorological elements, the variability of the OGS dates was best explained by minimum air temperature averaged for the period from January to March. The determination coefficient values for this characteristic clearly increased towards the east, as in the case of \( R^2 \) values for the number of days with westerly zonal flow in the period from December to March (Tab. 5). The number of days with easterly air flow accounted for the variability of the OGS dates in the lowlands of western and north-western Poland to a greater extent.

The impact of land cover types on the OGS dates was determined for each of the pixels. An increase in the photosynthetic activity of vegetation after winter was observed to be slower in areas with a higher share of wetlands and inland waters (Tab. 5). A reverse relationship was obtained for urban areas and agricultural land. Over the study period, a higher variability of the OGS dates was observed in areas dominated by artificial surfaces and forests, while lower variability was reported in agricultural areas and wetlands.

Minimum air temperature is the best predictor of the OGS dates in regions with a high share of agricultural areas, and also low share of forest, artificial surfaces, and inland waters. Similar patterns were observed in the case of regression models where the frequency of westerly zonal flow was an explanatory variable. Reverse relationships were observed for the number of days with easterly air flow (Tab. 5).

Based on the obtained results, it is generally concluded that depending on the land cover...
type, specific local thermal conditions may affect the photosynthetic activity of vegetation in early spring. A part of the energy reaching the surface is used for evaporation (latent heat), and some for warming the atmosphere (sensible heat). For example, in terrain with higher soil moisture (e.g. marshy areas), a higher amount of energy is used for evapotranspiration than for heating the atmosphere [Ban-Weiss et al., 2011]. Therefore, in late winter and early spring, the recorded air temperatures are lower than those in urban areas with an additional anthropogenic sensible heat flux [Voogt and Oke, 2003]. Slower heating of the soil and air in early spring in areas of damp ground may constitute the main cause of a slower increase in the photosynthetic activity of vegetation. This is exemplified by northern Poland, where the share of lakes in the structure of land cover is considerably higher than in the rest of the country. It should be emphasised, however, that various species of plants have different thermal ranges for the timing of an increase in the photosynthetic activity of vegetation after winter [Sparks and Carey, 1995; Clark et al., 2013]. It is therefore necessary to carry out more detailed studies on the subject.

Conclusions
The results obtained suggest that satellite data may be an important source of information on the temporal and spatial variability of the onset of the growing season in Poland. In the years 2001-2010, the earliest average OGS dates occurred in the western lowlands and central part of the country, and the latest in northern Poland and in the high mountain areas.

A strong correlation was determined between the OGS dates in Poland and thermal conditions in the first months of the year, and a weaker correlation with depth of snow cover. Among all of the characteristics of air temperature, the variability of the OGS dates was best explained by the minimum air temperature averaged from the period from January to March. The results also suggested a correlation with the strength of zonal flow in the cold season. The onset of the growing season occurred significantly earlier than normally when high winter mean values of the North Atlantic Oscillation index were recorded.

The study revealed that the onset of the growing season in this part of Europe is also influenced by geographical position, expressed by latitude, longitude, and altitude above sea level. Changes in the spatial characteristics of the OGS dates are particularly determined by longitude, reflecting the range of the impact of the relatively warm Atlantic Ocean in winter. Spatial variability of the OGS dates caused by diverse land cover types was also recorded.

The photosynthetic activity of vegetation after winter was observed to be weaker in areas with a higher share of wetlands and inland waters. A reverse relationship was obtained for urban areas and agricultural land. Further studies should concern the distribution and interannual variation of the OGS dates for the different land cover types. This would provide more accurate information about the analysed problem.

Meteorological data from the grid points proved useful for this kind of research, although with certain restrictions. In the case of Poland, this was determined by the diversity of land cover, affecting the development of thermal and snow cover conditions at a local scale. Hence, detailed research on the impact of thermal conditions on the growth of the photosynthetic activity of vegetation in spring should be based on meteorological data measured in situ.
References


Bartoszek et al. Onset of the growing season based on remotely sensed data


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