Monitoring forest biodiversity and the impact of climate on forest environment using high-resolution satellite images

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Abstract
The main objectives of the research work were to determine the usefulness of Landsat and SPOT data for monitoring various forest parameters, and to assess the impact of changeable climatic conditions with the use of vegetation indices derived from remotely sensed data. Vegetation indices describing various aspects of plant condition and vegetation structure were derived from satellite images, and their values were analysed in a temporal profile in different vegetation seasons, in conjunction with meteorological parameters. The results of analyses proved that dedicated vegetation indices of water stress in plants – the disease water stress index (DSWI) and normalized difference infrared index (NDII) – are able to detect changeable climatic conditions, especially the impact of drought on forest ecosystems. The indices are also useful for characterising types of forest site and tree stand mixture, in particular differentiating dry, fresh and humid forest sites. Results of analysis of satellite-based indices were supported by conclusions drawn from a study of vegetation parameters obtained in the course of field campaigns.

Introduction
The use of remote-sensing techniques for forest monitoring is an important topic, both globally and regionally. On the global scale, there have been many initiatives aimed at applying low- and medium-resolution satellite data to derive information on the state of forests and changes therein (Blackard et al., 2008; Asner, Knapp, Balaji, & Paez-Acosta, 2009; Boyd & Danson, 2005; Hansen et al., 2008; Lambin, 1999; Soudani et al., 2008). The most important international projects dealing with this topic were TREES, REDD, Geoland Forest Monitoring, GLOBBIOMASS and others (Bicheron et al., 2008; Gibbs, Brown, Niles, & Foley, 2007; Le Toan et al., 2011). However, alongside forest monitoring on a global scale, numerous projects have been conducted to apply high-resolution satellite images to forest mapping and to estimating forest parameters (Huang et al., 2010; Kimes, Nelson, Salas, & Skole, 1999; Kozak, Estreguil, & Ostapowicz, 2008; Masek et al., 2008; Miettinen, Stibig, & Achard, 2014; Morton et al., 2011; Puzzolo, De Natale, & Giannetti, 2003; Souza, Firestone, Silva, & Roberts, 2003). Different types of satellite data, including both optical and microwave images, have been used for this purpose. Various aspects of forest monitoring were taken into account, starting from forest type mapping, through inventory of forest changes and characteristics of environmental conditions, to assessment of forest biomass and productivity (Dong et al., 2003; Fiorella & Ripple, 1993; Franco-Lopez, Ek, & Bauer, 2001; Hall, Skakun, Arsenault, & Case, 2006; Joshi, De Leeuw, Skidmore, van Duren, & van Oosten, 2006; Lu, 2005; Mon, Mizoue, Htun, Kajisa, & Yoshida, 2012; Toomey & Vierling, 2005; Wolter, Townsend, & Sturtevant, 2009). In parallel, numerous studies on interactions between climate change and the status of various ecosystems, including forests, have been performed (Bonan, 2008; Millar, Stephenson, & Stephens, 2007; Moore & Allard, 2008; Theurillat & Guisan, 2001). Some of these studies were aimed at assessing the impact of climate change on forests with the use of remote sensing (Borgniet et al., 2013; Shahid & Joshi, 2015; Zoran, Dida, & Zoran, 2014). The authors of these studies pointed out the usefulness of long series of vegetation indices derived from satellite data (NDVI type) for monitoring the decline of forest ecosystems due to drought conditions, but their works were primarily based on the application of medium- or low-resolution satellite images.

Although several practical conclusions on the applicability of remotely sensed data for forest monitoring have been already drawn, nevertheless, due to the complexity of forest environments and their differentiation through various climatic zones, there is still a need to...
further develop and improve the existing methods. The presented work supports that process, concentrating on the use of optical high-resolution satellite images to characterise various forest parameters and to study the impact of climate changes on forest behaviour in a temperate zone. The main rationale for including two aspects in the research work (study of forest biodiversity and climatic impact on forest ecosystem with the use of remote sensing) was based on the hypothesis that various environmental components – tree species, type of forest site and stand mixture – can modify vegetation indices derived from EO data, thus having an impact on the relations between climate change and vegetation indices. So, in the first stage of the works, it was decided to thoroughly study particular vegetation indices derived from high-resolution satellite data, taking into account different environmental aspects in order to determine to what extent they are sensitive to particular forest characteristics. While stating the range of sensitivity of indices at the second stage of the works, analysis of relationships between the EO-based indices and meteorological-based index characterising drought conditions was performed and conclusions were drawn on the usefulness of remote-sensing-based parameters for monitoring drought in forest environments.

**Study areas**

Three forest areas located in north-eastern Poland have been selected as pilot sites for the presented research work. These are the Bialowieska Forest, the Knyszynska Forest and the Borecka Forest. Northeastern Poland, where the sites are located, is under the influence of a continental climate, characterised by the impact of polar air masses, a shorter vegetation period than the rest of Poland and quite high temperature fluctuations. There are some differences in climatic conditions between the sites – the Borecka Forest is slightly influenced by oceanic climate, which has a certain impact on vegetation development. The selected forest areas are different, as far as tree species and forest sites are concerned. The Bialowieska and Borecka Forests mainly consist of deciduous and mixed stands – with hornbeam, oak, alder and birch as the dominant species – while the Knyszynska Forest comprises mainly coniferous stands – with pine and spruce as the dominant species. Also, forest sites differ within particular forest areas, as influenced by geology and landscape type. The Bialowieska Forest, located mainly on a flat plain of clay bottom moraine, is characterised by humid and fresh forest sites. The Borecka Forest, situated mainly on a hilly, moraine area, includes predominantly fresh forest sites related to deciduous and mixed deciduous stands, with numerous peatlands associated with humid forest sites. The Knyszynska Forest, located mainly on poor, sandy and podsollic soils, is characterised by a high contribution of fresh and dry forest sites, with conifers dominating the majority of the forest area (Zaręba, 1986). The locations of the study areas are presented in Figure 1.

![Figure 1. Location of forest study areas.](image-url)
Materials and methods

Three types of high-resolution satellite images have been used for the research works in the presented study – SPOT 5, Landsat 5 TM and Landsat 8 OLI images. SPOT 5 images were collected in the 2015 vegetation season within a Take 5 experiment, which made it possible to acquire satellite data in a 5-day cycle (precursor of Sentinel-2 activity). Due to cloud cover, 7 out of 14 images were finally collected for the Bialowieska Forest; they covered the vegetation period from the beginning of April till mid-September. They were registered in 10-m ground resolution (multispectral mode), including four bands covering the green, red, near infrared and shortwave infrared parts of the spectrum.

Landsat 5 TM images were collected in 2006 for the Bialowieska and Borecka Forests – six images from April till the end of September for the Bialowieska Forest and seven images for the same period for the Borecka Forest. They were registered in 30-m ground resolution, including seven bands, from the visible blue region to thermal infrared.

Landsat 8 OLI images were collected for 2014, 2015 and 2016 covering three study areas: the Bialowieska, Borecka and Knyszynska Forests (five images in 2014, seven images in 2015 and four images in 2016 for the Bialowieska and Knyszynska Forests and six images in 2014, five images in 2015 and three images for 2016 for the Borecka Forest). The acquisition dates covered the vegetation period from the end of March till the end of October; the collected images included 8 spectral bands, from short blue (coastal) band to shortwave infrared.

Apart from satellite images, ground reference data have been collected for the regions of interest. The detailed digital forest maps prepared by the Forest Service have been compiled; they comprise comprehensive information on the forests, including species, stand mixture and type of forest site. Moreover, two field campaigns were undertaken in 2014 and 2015, in order to collect data characterising tree condition at ground level. The set of measurements for each main species existing within a study area included spectrometric measurements with the use of the ASD FieldSpec 4 with the PlantProbe, recording spectral reflectance in the 350–2500-nm range, fluorescence measurements and measurements of pigments in leaves/needles (chlorophyll, flavonoids, anthocyanins, nitrogen balance). Field measurements were used for estimating real plant condition at ground level and the results of analyses served as reference information for analysis of the satellite data.

There were two main goals of the presented study. The first objective was to determine to what extent some forest parameters – type of forest site, tree species and tree stand mixture – impact the values of vegetation indices, thus modifying relations with climatic changes and implying separate climate impact analyses for different environmental conditions. The second objective of the research work was to study to what extent variable climatic conditions characterised by changes in meteorological parameters influence forest condition, as expressed in the levels of the specific vegetation indices derived from high-resolution satellite data. In order to achieve these goals, at the preliminary stage of the works, it was decided to study various vegetation indices derived from SPOT and Landsat images to be able to find those which are the most suitable for differentiation of environmental conditions within forest areas. After initial analysis of numerous vegetation indices available in the literature, it was decided to study four indices which characterise different, complementary aspects of plant condition and vegetation structure:

Normalised difference vegetation index (NDVI) characterising general plant condition

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

Enhanced vegetation index (EVI) characterising structure of vegetation canopy

$$EVI = 2.5 \times \frac{(NIR - RED)}{(NIR + 6 \times RED - 7.5 \times BLUE)}$$ (2)

Normalised difference infrared index (NDII) characterising water content in plants

$$NDII = \frac{(NIR - SWIR)}{(NIR + SWIR)}$$ (3)

Disease water stress index (DSWI) characterising stress of plants due to water shortage and damage

$$DSWI = \frac{(NIR - GREEN)}{(SWIR + RED)}$$ (4)

All indices were analysed in a temporal profile. In order to quantify their changes and to relate them to climatic conditions, a simple index characterising decrease of vegetation index was produced using the following formula:

$$\text{Decrease}_{\text{index value}} = \text{Max}_{\text{index value at peak season}}$$ (5)

Detailed digital forest maps were applied to select the set of samples of forest stands, considering three aspects of forest characteristics:

- Tree species
- Type of forest site
- Tree stand mixture

Regarding tree species, six species represented within the study areas were selected for analysis: two coniferous species – spruce (Picea abies) and pine (Pinus sylvestris), and four deciduous species – birch (Betula humilis), alder (Alnus viridis), oak (Quercus robur) and hornbeam (Carpinus betulus). Three types of forest site were taken into
consideration: fresh, humid and dry sites, in combination with various tree species – conifers and hardwoods. Tree stand mixture was analysed at three levels of mixing: pure stands (90–100% of dominant tree species), 70–90% of dominant tree species and 50–70% of dominant tree species. All polygons representing tree species, forest site and tree mixture were selected on the basis of the digital forest map in such a way as to give a good representation of the class. Each class was represented by 5 polygons, each of which included at least 30 Landsat pixels, in order to ensure proper further statistical processing of the data.

In order to study relations between vegetation indices derived from high-resolution satellite data and climatic conditions, meteorological information was compiled for the regions of interest, using the web-available database at http://en.tutiempo.net/climate/poland.html. This database includes various meteorological parameters, e.g. mean daily temperature and precipitation. These parameters were processed at the first stage of the works in order to produce the so-called hydrothermal (HT) index, which combines both temperature and precipitation information in a 10-day cycle, characterising drought conditions for the study area (Hutorowicz, Grabowski, & Olba-Ziety, 2008).

The methodical approach consisted of three main stages:

- Data collection: collection of high-resolution satellite data for the study areas (Landsat and SPOT), collection of in-situ spectrometric data characterising plant development compilation of meteorological data for the regions of interest.
- Data processing: generation of vegetation indices from the collected images (NDVI, EVI, NDI, DSWI), generation of vegetation indices on the basis of in-situ measurements, extraction of samples from the digital forest maps representing particular tree species, extraction of values of vegetation indices for particular samples, generation of HT index based on temperature and precipitation data for the 2000–2015 vegetation periods.
- Data analysis: analysis of vegetation indices in a temporal profile, comparison of usefulness of particular indices for differentiation of forest features: tree species type of forest site, tree stand mixture, statistical analysis of differences in vegetation indices due to tree species, type of forest site and stand mixture with the use of Student’s t test, correlation of vegetation indices with HT index, comparison of sensitivity of vegetation indices derived from satellite data to drought conditions, comparison of applicability of satellite-based and ground-based vegetation indices for drought detection.

In the first phase of the works, various vegetation indices derived from high-resolution satellite data – NDVI, EVI, NDI, DSWI – were analysed in a temporal profile throughout the growing season in order to find which of them are most suitable for differentiating particular tree species and for monitoring forest condition. The analysis was done for indices derived both from Landsat and SPOT data with the aim of comparing the usefulness of these two types of satellite images for forest studies. Statistical measure of class separability – Student’s t test – was applied to perform this assessment in a quantitative way. The test quantitatively assesses whether particular values of vegetation indices differ significantly.

At the next stage, the modified HT index characterising drought conditions was calculated for various years, representing dry, wet and normal growing seasons. The new index, called Cumulated Hydrothermal Index reduced to Drought level (CHID), was formed for each 10-day period, summing values of current HT index, which was next reduced to drought level (value of HT index = 1) with reduced values from previous 10-day periods, following the formula:

$$\text{CHID}_k = \sum_{i=1}^{n} (\text{HT}_i - 1)$$ (6)

The changes of CHID were analysed within the growing seasons 2006, 2014, 2015 and 2016. In order to determine if there is a statistical relationship between vegetation index derived from satellite data on the one hand and drought conditions characterised by HT index on the other, the DSWI index based on Landsat data was calculated for all vegetation seasons between 2000 and 2016 (depending on data availability). Next, differences between maximum and minimum DSWI value were determined and correlated with the various combinations of HT index derived for the years of interest: mean values for the first part of vegetation season (April–mid-June), mean value for the second part of the season (mid-June–September) and mean value for the whole vegetation season. The Statistica software package was used for conducting statistical analysis.

In order to confirm conclusions drawn from this analysis, vegetation indices derived from ground spectrometric measurements were also applied and their variability in two growing seasons – the dry year and the normal year – was analysed. Finally, the influence of some forests characteristics – type of forest site and tree stand mixture on values of vegetation indices – was studied in order to draw practical conclusions on the applicability of remote-sensing-based indices for studying drought phenomena.
The works related to analysis of satellite images were performed using the ENVI Ver. 5.1 software package. All analyses aimed at study of vegetation indices and meteorological data were carried out within Microsoft Excel. Statistical analyses were done using the Statistica 12 software package.

The workflow based on the methodical approach is presented in Figure 2.

Results and discussion

Analysis of usefulness of vegetation indices to species differentiation and sensitivity to variable climatic conditions

In the case of the most commonly used NDVI index derived from Landsat data, it was found that NDVI values for the four deciduous species are very similar through the whole growing season; the same applies to the two coniferous species – spruce and pine. This observation has been confirmed by analysis of SPOT 5 data. So, the conclusion is that NDVI index is not suited to the detailed mapping of tree species; it only differentiates two groups of forest stands – conifers and hardwoods. NDVI values for each group are characteristic – conifers demonstrate quite high values at the start of growing season, increasing from the end of March till mid-June, with quite stable values through the growing season and a slight decrease in September, while hardwoods have quite low values at the onset of the growing season, with a high increase till their peak in mid-June and a slight decrease till the end of the growing season. The NDVI changes for 2015 growing season are presented in Figure 3.
Similar conclusions were drawn while analysing enhanced vegetation index (EVI). High compatibility of EVI runs can be observed for hardwoods, with the exception of birch (which reflects higher values at the start of growing season resulting from earlier development of vegetation canopy than the remaining deciduous species). Coniferous species demonstrate slight changes in EVI index throughout the growing season, with somewhat lower values for pine than spruce in the mid-season. The EVI changes for 2015 growing season are presented in Figure 4.

While analysing NDII, high differences between particular deciduous and coniferous species can be observed at the onset of the growing season. These differences result both from different stages of plant development – more advanced for birch and early stage for alder – and from differences in forest sites. The NDII index separates alder forest from the remaining deciduous species, because of its lower values – especially in the first part of the growing season. Moreover, NDII values for all deciduous species decrease from mid-June till mid-September, which may indicate drought conditions in the second part of the vegetation season. The relation between decreasing NDII values and meteorological parameters will be studied further on in this chapter. The NDII changes for the 2015 growing season are presented in Figure 5.

![Figure 4. EVI changes for the Knyszynska Forest test site based on 2015 Landsat data.](image1)

![Figure 5. NDII changes for the Bialowieska Forest test site based on 2015 Landsat data.](image2)
The fourth analysed index – DSWI – revealed similar variations to those of the NDII index, but its changes were more pronounced. It also demonstrates differences between particular species at the beginning of the growing season, lower values for alder in the second part of the vegetation period and a quite distinct decrease in all DSWI values at the end of the analysed growing season. The DSWI changes for the 2015 growing season are presented in Figure 6.

The sensitivity of the DSWI index to differentiation of tree species was confirmed for the other study areas – the Knyszynska Forest and the Borecka Forest. In the case of the Knyszynska Forest, a larger difference between the two types of conifers – pine and spruce – is observed. In the deciduous group, hornbeam has lower DSWI values than the remaining species in the second part of the growing season (see Figure 7). A similar pattern can be observed for the Borecka Forest – lower DSWI values for pine than for spruce and higher values of DSWI index for oak than for the remaining deciduous species in mid-season.

Statistical analysis with the use of Student’s t test made it possible to quantitatively assess whether particular values of vegetation indices differ significantly. The results of this analysis proved that for tree species for which the graphs show different index values from the remaining species (e.g. alder from oak in Figures 5 and 6, hornbeam from oak in Figure 7), the
The statistical measure $t$ Stat of their separability is also high – it lies outside the ±$t$ critical two-tail range. In the case of tree species whose graphs show very similar values of vegetation index, the results of Student’s $t$ test analysis confirm that they are not statistically separable. The selected results of the statistical analysis related to significant differences are presented in Table 1.

Differences in DSWI values between the study areas result from the locations of particular tree stands within each study area; depending on type of forest site, humid, fresh or dry site, DSWI index values can differ. Various deciduous species situated within the same forest site reveal similar DSWI values throughout the second part of the growing season, but the other forest site implies a change in the index values. The same rule applies to coniferous species, although the shape of index curves within the growing season differs from that observed for deciduous species due to different types of phenological development.

Analysis of DSWI index for the 2006, 2014 and 2016 growing seasons demonstrated a smaller decrease than in 2015. Its changes for 2006 are presented in Figure 8.

Because both the DSWI and NDII indices revealed some decreasing trends in the second part of the vegetation period (but different in 2006, 2014, 2016 than in 2015), it was decided to verify whether these changes are related to the meteorological situation. For this reason, a statistical analysis was conducted.

Table 1. Results of statistical analysis of class separability with the use of Student’s $t$ test.

| Date            | Statistical measure | DSWI Białowieska Forest Alder – oak | DSWI Knyszynska Forest Hornbeam – oak | NDII Białowieska Forest Alder – oak |
|-----------------|---------------------|-------------------------------------|--------------------------------------|-------------------------------------|
| 23 March 2015   | Mean value          | 0.52–0.67                           | 0.54–0.69                            | −0.05–0.05                          |
|                 | $t$ Stat            | −6.52                               | −11.31                               | −7.13                               |
|                 | $t$ Critical two-tail range | 1.97 | 1.96 | 1.97 |
| 9 April 2015    | Mean value          | 0.55–0.69                           | 0.60–0.72                            | −0.04–0.05                          |
|                 | $t$ Stat            | −6.37                               | −8.70                                | −7.36                               |
|                 | $t$ Critical two-tail range | 1.97 | 1.96 | 1.97 |
| 12 June 2015    | Mean value          | 2.07–2.22                           | 1.99–2.24                            | 0.44–0.48                           |
|                 | $t$ Stat            | −7.38                               | −8.42                                | −9.80                               |
|                 | $t$ Critical two-tail range | 1.97 | 1.96 | 1.97 |
| 5 July 2015     | Mean value          | 1.98–2.20                           | 2.00–2.27                            | 0.44–0.47                           |
|                 | $t$ Stat            | −8.21                               | −9.45                                | −8.60                               |
|                 | $t$ Critical two-tail range | 1.97 | 1.96 | 1.97 |
| 6 August 2015   | Mean value          | 1.82–1.99                           | 1.89–2.07                            | 0.40–0.44                           |
|                 | $t$ Stat            | −7.01                               | −8.93                                | −6.82                               |
|                 | $t$ Critical two-tail range | 1.97 | 1.96 | 1.97 |
| 31 August 2015  | Mean value          | 1.70–1.83                           | 1.56–1.89                            | 0.38–0.41                           |
|                 | $t$ Stat            | −4.30                               | −15.70                               | −5.21                               |
|                 | $t$ Critical two-tail range | 1.97 | 1.96 | 1.97 |
| 16 September 2015 | Mean value       | 1.38–1.53                           | 1.43–1.89                            | 0.64–0.67                           |
|                 | $t$ Stat            | −6.09                               | −25.82                               | −4.82                               |
|                 | $t$ Critical two-tail range | 1.97 | 1.96 | 1.97 |

DSWI: Disease Water Stress Index; NDII: Normalised Difference Infrared Index.

Figure 8. DSWI changes for the Białowieska Forest test site based on 2006 Landsat data.
For this purpose, the HT index, which informs on drought conditions, was calculated for four growing seasons – 2006, 2014, 2015 and 2016 – which had different climatic conditions. Its changes are presented in Figure 9. It can be seen from the graph that, in 2006, drought conditions, which are represented by HT index values below 1 (drought level line on the graph), appeared in 10-day periods 12–13, 17–19, 21 and 26–27, but with a high HT index in 22–25. In 2014, drought appeared in 10-day periods 10, 12, 15, 17–18 and 21–22. In 2015, drought was observed in 10-day periods 11, 16–19, 22–24 and 26–27, with a low HT index throughout most of the growing season. In 2016, drought appeared in 10-day periods 10, 13, 15–16, 18, and 25–26. Comparing the 4 years, it was found that the strongest drought conditions appeared in 2015; they were characterised by long drought periods from June till the beginning of July, and through August till the beginning of September.

In order to confirm that there are distinct differences between the analysed years, as far as drought conditions are concerned, the CHID was applied. The results of this analysis are presented in Figure 10. It can be observed from the graph that, in 2015, growing season drought conditions were much more pronounced than in 2006, 2014 and 2016. This was reflected by much lower end values of CHID and the descending 2015 curve, starting from the beginning of June, which was contrary to the remaining analysed years, which revealed much better growth conditions (higher HT index) in the second part of the growing season. So, analysing drought conditions, one should study the shape of the CHID curve throughout the whole growing season – if it descends for a longer time, especially in the second part of the vegetation period, it indicates drought conditions in a particular year.

In parallel, it can be observed from the graph that in the first part of the vegetation season (April–mid-June), growth conditions characterised by HT index were better for 2015 than for the remaining years. This resulted in the higher values of maximum

Figure 9. Changes of hydrothermal index in 2006, 2014, 2015 and 2016 growing seasons.

Figure 10. Changes of cumulated hydrothermal index reduced to drought level in 2006, 2014, 2015 and 2016.
vegetation indices, usually in mid-June, which can be observed when comparing Figures 6 and 7, which show DSWI values in 2015, with Figure 8 presenting DSWI index in 2006. This observation was supported through comparison of sums of CHID index within the April–mid-June period with maximum values of DSWI and NDVI indices reached in the study years. Results of this analysis are presented in Table 2.

It is seen from the table that 2015’s more favourable conditions for vegetation development, as represented by high summed Cumulated Hydrothermal Index, resulted in a higher value of DSWI and NDVI indices than for the 2006, 2014 and 2016 vegetation periods, which had less favourable growth conditions. The lowest values of both indices for 2006 result from unfavourable conditions of plant development at the beginning of the growing season – very low air temperatures at the end of March and the beginning of April.

At the next stage, it was decided to investigate more precisely whether the observed drought conditions are reflected in changes in vegetation indices derived from high-resolution data. These changes were analysed for the second part of the vegetation period (mid-June–September), when maximum and minimum index values, respectively, are reached. It was found that both indices related to water content in plants – DSWI and NDII – reflect drought conditions, especially for deciduous species (coniferous species are more resistant to drought conditions). At the same time, it was found that indices responsible for description of general plant condition (NDVI) and vegetation structure (EVI) do not significantly decrease at the end of the growing season. This means that drought conditions detected with the use of DSWI and NDII indices do not much affect the overall condition of forest canopies; these indices inform about decreased water content in leaves/needles and lower wetness of whole forest canopies.

The decrease in DSWI and NDII indices differs for the three analysed forest areas – the Białowieska, Borecka and Knyszynska Forests – being the largest for the Białowieska Forest. It is also different for both studied indices, being higher for the DSWI index. The degree of decrease differs between 2006, 2014, 2015 and 2016; it is highest for 2015, when the longest periods of drought appeared, as presented in

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**Table 2. Comparison of summed CHID index with maximum DSWI and NDVI indices in 2006, 2014, 2015 and 2016.**

| Year | Summed CHID | DSWI max | NDVI max |
|------|-------------|----------|----------|
| 2006 | 19.4        | 1.67     | 0.81     |
| 2014 | 9.6         | 1.83     | 0.87     |
| 2015 | 34.5        | 2.15     | 0.91     |
| 2016 | 12.1        | 1.83     | 0.85     |

CHID: Cumulated Hydrothermal Index reduced to Drought level; DSWI: Disease Water Stress Index; NDVI: Normalised Difference Vegetation Index.

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**Table 3. Decrease of DSWI index in 2006, 2014, 2015 and 2016 vegetation seasons based on Landsat data.**

| Species  | 2006 Decrease DSWI (%) | 2014 Decrease DSWI (%) | 2015 Decrease DSWI (%) | 2016 Decrease DSWI (%) |
|----------|-------------------------|------------------------|------------------------|------------------------|
| Alder    | 16.3                    | 7.5                    | 33.3                   | 11.7                   |
| Oak      | 12.2                    | 8.8                    | 31.1                   | 12.7                   |
| Hornbeam | 5.8                     | 6.0                    | 27.0                   | 6.6                    |
| Birch    | 2.4                     | 6.5                    | 23.2                   | 11.2                   |

**Figures 9 and 10.** The degree of index decrease (in %) in relation to the maximum value is presented in Table 3.

The results of correlation analysis between DSWI index and various combinations of HT index derived from the period 2000–2016 revealed that the best, quite strong relationship exists between DSWI vegetation index derived from remotely sensed data and the mean HT index representing the whole vegetation season (April–September) – the correlation coefficient r was equal to −0.723. The results are presented in graphical form in Figure 11.

The results of analysis of the DSWI index derived from Landsat 8 data in 2015 were confirmed by parallel analysis performed with the use of SPOT 5 images. Results of this analysis for the Białowieska Forest are presented in Figure 12; they reveal a progressive decrease in DSWI value from the beginning of July, resulting from drought conditions. The average decrease in DSWI index for four deciduous species is 18.5%.

In order to determine whether the observed changes in DSWI vegetation index due to meteorological conditions are related to real changes in plant condition, analysis of ground reference data was performed. The spectrometric data collected during field campaigns allowed reference indices to be derived characterising various aspects of plant development and behaviour. Four indices, which proved to change statistically significantly throughout the growing season and correlated with vegetation parameters, were selected: NDII sensitive to water content in plants;
simple ratio index (SR) characterising general plant condition; narrowband normalised difference vegetation index (NDVI 705), characterising chlorophyll content; and DSWI characterising stress of plants due to water shortage and damage. The results of analysis of these indices in two growing seasons – 2014 and 2015 – allowed it to be concluded that in the analysed years, there are differences in changes in these parameters which can be related to climatic conditions – a higher decrease in most indices appeared in 2015 (with the exception of birch). Hence, conclusions drawn from the study of ground-based indices support the results of analysis of high-resolution satellite images. A summary of the analysis of reference data is presented in Table 4.

Analysis of relations between vegetation indices, types of forest sites and stand mixture

Quite a high variation was seen in vegetation indices during analysis, depending on sample location. So, it was decided to investigate if there is a relation between type of forest site and the index value for the two main groups of forests stands – conifers and hardwoods. Three main types of forest site were considered in the analysis:

- humid sites, characterised by fertile soils, abundant understory with high shrubs, associated with deciduous and coniferous forests
- fresh sites, characterised by sandy and podsolic soils, associated with deciduous and coniferous forests
- dry sites, characterised by poor sandy soils and low groundwater level, associated with conifers

Three levels of stand mixture, both for conifers and for hardwoods, were considered:

- pure stands – 90–100% of dominant species
- less mixed stands – 70–90% of dominant species
- more mixed stands – 50–70% of dominant species

Initial analysis was performed for the NDVI index, but it did not deliver distinct differences between studied forest sites and levels of stand mixture. So, it was decided to thoroughly analyse the DSWI index, which had proven to be most valuable in the previous study. The analysis was performed for conifers and hardwoods separately, studying the impact of forest site and stand mixture on DSWI value. The selected results of analyses are presented in Figures 13–15.

In order to verify whether the observed differences in DSWI values are significant, a statistical analysis was done; as in the case of studying tree species differentiation, Student’s t test was applied. The results of this analysis confirmed the separability of the analysed classes in each date of the growing season. Selected results are presented briefly in Table 5.

Table 4. Analysis of ground reference data for the study area – decrease of indices in September in relation to July (in percent).

| Year | Species  | NDII (%) | SR (%) | NDVI_705 (%) | DSWI (%) |
|------|----------|----------|--------|--------------|----------|
| 2015 | Alder    | 27.9     | 21.0   | 9.8          | 10.3     |
|      | Oak      | 26.6     | 30.1   | 19.6         | 17.3     |
|      | Hornbeam | 23.8     | 19.4   | 16.0         | 8.1      |
|      | Birch    | 5.2      | 22.5   | 13.3         | 10.5     |
| 2014 | Alder    | 6.0      | 1.5    | 7.6          | 0.4      |
|      | Oak      | 3.4      | 8.2    | 8.2          | 3.0      |
|      | Hornbeam | 1.2      | 8.0    | 5.6          | 8.5      |
|      | Birch    | 20.1     | 25.2   | 20.0         | 19.2     |
The results of analysis enabled to draw the following conclusions:

- in case of pure conifers, there is quite distinct difference in DSWI index for dry site at first part of vegetation period (April–July); DSWI value for dry site is lower than for fresh site by 12%; there is no difference between fresh and humid sites (Figure 13);

- in case of pure hardwoods, there is distinct difference in DSWI index for fresh and humid site through almost the whole vegetation period; DSWI values for fresh site are higher than for humid site, reaching the highest difference in May – 21% (Figure 14);

- for less mixed conifers (70–90%), there are still differences between forest sites, showing DSWI values for dry site lower by 12%; for less mixed hardwoods (70–90%), differences between fresh and humid forest sites, expressed by DSWI values, are less pronounced than in case of pure hardwoods, reaching at maximum 9%; these differences are further diminished by higher mixing (50–70%);

- in case of conifers, the level of mixing has impact on DSWI value, for all types of sites (example for humid site in Figure 15). For humid site, less mixed conifers (70–90%) reveal in July DSWI values higher by 23%, while more

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**Figure 13.** Changes of DSWI index based on SPOT 2015 data for coniferous forest sites.

**Table 5.** Results of statistical analysis of class separability with the use of Student’s t test.

| Date       | Statistical measure | Coniferous species | DSWI          | Deciduous species | DSWI          |
|------------|---------------------|--------------------|---------------|-------------------|---------------|
|            | Mean value          | Dry site–fresh site|               | Fresh site–humid site |               |
| 9 April 2015 | t Stat              | 1.05–1.13          | 0.60–0.56     |                   |               |
|            | Critical two-tail   | 1.96               |               |                   |               |
| 19 May 2015  | t Stat              | 0.99–1.10          | 1.65–1.30     |                   |               |
|            | Critical two-tail   | −34.99             | 96.70         |                   |               |
| 8 June 2015   | t Stat              | 1.03–1.19          | 1.82–1.51     |                   |               |
|            | Critical two-tail   | −32.15             | 99.41         |                   |               |
| 3 July 2015   | t Stat              | 1.22–1.40          | 1.96–1.78     |                   |               |
|            | Critical two-tail   | −38.97             | 54.30         |                   |               |
| 18 July 2015  | t Stat              | 1.30–1.32          | 1.82–1.64     |                   |               |
|            | Critical two-tail   | −4.07              | 58.55         |                   |               |
| 7 August 2015 | t Stat              | 1.28–1.30          | 1.70–1.53     |                   |               |
|            | Critical two-tail   | −5.17              | 55.10         |                   |               |
| 31 August 2015 | t Stat             | 1.30–1.25          | 1.61–1.44     |                   |               |
|            | Critical two-tail   | 11.34              | 49.58         |                   |               |
|            |                     | 1.96               | 1.96          |                   |               |
mixed conifers (50–70%) over 30%. The same tendency was observed for conifers located on dry site; less mixed conifers reached in July DSWI values higher by 21% than pure coniferous stands;

- in case of hardwoods, the mixing level has influence on DSWI value for fresh forest site only, reaching in July DSWI decrease for less mixed hardwoods (70–90%) by 5%, while for more mixed deciduous stands (50–70%) by 10%. Deciduous stands located on humid site do not reveal significant DSWI differences, when mixed with conifers.

The conclusions drawn from analysis of SPOT 2015 data for Bialowieza Forest were confirmed by analysis of Landsat images for Knyszynska Forest. Results of this analysis are presented in Figures 16 and 17.

In case of Knyszynska Forest, the differences between DSWI index for dry forest site and for fresh/humid forest sites (Figure 16) are more pronounced than in case of Bialowieza Forest (Figure 13) – the DSWI decrease in July is 39% comparing to fresh site and 33% in relation to humid site. The decrease of DSWI value due to dry site conditions is more distinct due to better
representation of that type of site within the whole Knyszynska Forest area. The observation of DWSI changes throughout the growing season reveals that forests situated on dry sites are more resistant to drought conditions than those placed on fresh or humid sites – there is no decrease of DSWI values at the end of growing season.

In case of stand mixture, observations based on analysis of SPOT data for Bialowieska Forest were confirmed while studying Landsat images for Knyszynska forest. It was confirmed that mixing of coniferous stands with deciduous species increases values of vegetation index, accordingly to the level of mixture – less mixed conifers (70–90%) reveal DSWI increase in July by 16%, while more mixed coniferous stands by 25%. In consequence, sensitivity of highly mixed forests to drought conditions is higher than pure conifers.

The conclusions drawn from the analysis of relations between vegetation indices, types of forest sites and stand mixture have a practical influence on studies of the impact of changeable climatic conditions on forest ecosystems. In order to properly estimate that impact, the studied forest area should be stratified before analysis into homogeneous zones characterised by the same type of forest site and stand.
mixture. Such a stratification can be based on detailed digital forest maps produced by foresters as a result of forest inventory and supported with classifications derived from high-resolution satellite data.

**Final conclusions**

Forest areas are very complex ecosystems, characterised by many environmental parameters which can influence remote-sensing-based information derived from satellite data. The main objective of the study was to evaluate the usefulness of high-resolution satellite images for monitoring vegetation stress due to variable climatic conditions. The second goal was to assess the degree of impact of particular forest stand characteristics on satellite-based vegetation indices. The main conclusion from the presented study is that there are relations between changeable meteorological conditions and forest condition as expressed by remote-sensing-based indices, but these relations vary depending on type of forest site and degree of tree species mixture. It was found that vegetation indices derived from high-resolution satellite data, which include information on spectral reflectance both in near-infrared and shortwave infrared bands, can be effective for evaluating drought-related stress in forest stands. The second important conclusion is that some basic characteristics of forest stands – forest site type and degree of tree species mixture – have an impact on values of remote-sensing-based parameters, such as DSWI or NDII. Specifically, they modify the general relations between satellite-based indices and parameters characterising climatic changes and forest condition. The impact is diversified, depending on type of forest site, tree species and degree of stand mixture. While analysing relations between remote-sensing-based vegetation indices and forest characteristics, it was found that deciduous stands are more sensitive to drought conditions, as expressed by changes in DSWI index, than coniferous forests. Comparing forest sites, it was proven that coniferous stands on dry forest sites are more resistant to long-term drought than those on fresh and humid sites. Hence, due to the high spatial variability of environmental features in Polish forests, which affect remote-sensing-based indices, high-resolution satellite data should be applied in conjunction with a detailed forest map in order to derive effective, reliable information on forest condition. These conclusions open new possibilities for detailed forest studies and assessments but also indicate the complexity of analysis of satellite images, when applied to forest monitoring. So, finally, it can be concluded that optical, high-resolution satellite images are useful for assessing the impact of climate change and for analysing the main environmental features of forests, but in order to derive more information, e.g. on forest structure, the synergistic use of optical and microwave images should be considered.

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