Peer-reviewed version available at *Forests* **2018**, *9*, 126; doi:10.3390/f9030126

Article

Species Diversity of Oak Stands and Its Significance for Drought Resistance

Jan Kotlarz[*,1,2], **Sylwia Nasiłowska**[1], **Karol Rotchimmel**[1], **Katarzyna Kubiak**[1,3]

[1] Remote Sensing Division, Center of Space Technologies, Institute of Aviation, 02-256 Warsaw
[2] Faculty of Physics, Warsaw University, 5 Pasteura Street, 02-093, Warsaw
[3] Department of Forest Protection, Forest Research Institute, Sękocin Stary, 3 Braci Leśnej Street, 05-090 Raszyn
[*] Correspondence: jan.kotlarz@ilot.edu.pl; Tel.: +48-737-452-114

Abstract: Drought periods have an adverse impact on the condition of oak stands. Research on different types of ecosystems has confirmed a correlation between plant species diversity and the adverse effects of droughts. The purpose of this study was to investigate the changes which occurred in an oak stand (Krotoszyn Plateau, Poland) under the impact of the summer drought in 2015. We used a method based on remote sensing indices from satellite images in order to detect changes in the vegetation in 2014 and 2015. A positive difference was interpreted as an improvement, whereas a negative one was treated as a deterioration of the stand condition. The Shannon-Wiener species diversity was estimated using an iterative PCA algorithm based on aerial images. We observed a relationship between the species indices of the individual forest divisions and their response to drought. The highest correlation between the index differences and the Shannon-Wiener indices was found for the GNDVI index (+0.74). In addition, correlations were observed between the mean index difference and the percentage shares in the forest divisions of species such as Pinus sylvestris (+0.67 ± 0.08) and Quercus robur (-0.65 ± 0.10). Our results lead us to infer that forest management based on highly diverse habitats is more suitable to meet the challenges in the context of global climatic changes, characterized by increasingly frequent droughts.

Keywords: drought; diversity; oaks; remote sensing

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1. Introduction

Drought affects all forest ecosystem properties. It is therefore essential to improve drought monitoring by understanding its spatial diversity with relation to tree species diversity, resilience, and resistance [1]. Apart from light, water availability is the most important factor determining tree growth [2]. Water shortage influences the biophysical properties of the vegetation, and the dimension of the negative effect is related to the duration of scarcity. For example, water stress results in reduced photosynthesis rates and stomatal closure, thereby inhibiting the growth of all plant cell types [3].

In forest management, it is therefore crucial to obtain up-to-date information about the actual tree habitat condition and its changes caused by drought.

A comparison of remote sensing images of vegetation indices from two periods can indicate a spatial distribution of changes. However, adequate change detection is a challenging issue. Several methods are available to not only determine differences between images, but also to designate an

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appropriate threshold to distinguish regions with and without changes [4]. Of these methods, image differencing is the most popular one, where an image from one period is subtracted, pixel by pixel, from an image from another period [5].

Research on the impact of drought on ecosystems, taking into account different variables, is important not only for the Central European areas examined in this study, but also for other moderate climate zone regions, including Scandinavian countries, in which adverse impacts of drought on species mortality [6] and distribution [7] of forest complexes have been observed. For example, a 10-year summer drought cycle in southern Finland halted the growth of a 12-year-old oak (Q. robur) stand, irrespective of the health class [8]. It is therefore important to enhance the long-term resistance of such stands to water stress, especially as species ranges shift to northern Europe (Scandinavian countries) and to greater longitudes [9] in the context of global climatic changes. It is expected that in the timeframe of several dozen years, the mean drought duration in Europe will become considerably longer. Climate models indicate that at present, in northern Europe, the mean period without precipitation increases and that from 2070 to 2099, droughts will be markedly longer than in 1961 to 1990 [10]. For example, the maximum duration of the period without precipitation in eastern Finland may increase from 27 to 39 days (as an average from four models) [11].

This article analyzes the relationship between the stand response to drought and the species diversity measured by remote sensing methods. It is assumed that species diversity is an important element influencing stand resilience to different stressors [12]. Variations in the water regime and the related water shortages caused by reduced precipitation levels are some of the most important factors which contribute to the development of fungal diseases of trees [13-14]. Fungal infections, such as the one caused by the genus Phytophthora (the HESOFF Life+ project), or the Dutch elm disease caused by invasive fungal species [15-16] (ELMIAS Life+ projects), pose some of the greatest threats to natural habitats with ecological and economic values. For this reason, it is important to explore the specific behavior of individual habitats in response to a drought-affected season.

To analyze the stand response to drought, 15 forest complexes were designated and, using remote sensing techniques, their species diversity and the changes in vegetation indices between 2014 and 2015 were measured. Subsequently, taking into account the species diversity index and other habitat variables, the impacts of drought on the condition of the examined stands were analyzed.

2. Materials and Methods

2.1. VI change threshold

A comparison of remotely sensed data for various points in time demands the use of normalized data, where errors and discrepancies caused by sensor and sun locations as well as atmospheric, plant, or soil components are eliminated [17]. The method was found to be efficient for land-cover changes [18] or the mapping of crop plantations [19]. The technique based on differential images was successfully used and recommended for operational application in forests, using the vegetation indices calculated from surface reflectance level products [20] in a habitat suffering from oak dieback [21-22]. The use of the multiplicity of the standard deviation as a change/no (+-σ) change threshold is also a popular approach [5, 23].

In our research, the following four steps were carried out [22] for images located on path 190, row 24, of the Landsat system.

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For further analysis, a set of 10 commonly used remote sensing vegetation indices was prepared: Enhanced vegetation index EVI [24], Modified Soil-adjusted Vegetation Index MSAVI [25], Normalized Burn Ratio NBR [26], Normalized Burn Ratio 2 NBR2 [26], Normalized Difference Moisture Index NDMI [27] Normalized Difference Vegetation Index NDVI [28], Soil-adjusted vegetation index SAVI [29], Green Normalized Difference Vegetation Index GNDVI [30], Atmospherically resistant vegetation index ARVI [31], and Blue-normalized difference vegetation index BNDVI [32]. Of these, NDVI is the most popular index used for drought analysis, based on both low-resolution and medium-resolution data [12, 23, 33, 34], as it uses the basic channels registered from the satellite ceiling, i.e., red and near-infrared.

The mean values of the vegetation index images for selected forest areas for 2015 were subtracted from those for 2014 to determine the differences between these years. For 2015, the following images were taken, as described with a Julian day and a growing season day in brackets: 111(14), 127(30), and 223(126), while for 2014, they were 92(6), 140(54), 156(70), and 188(102). A cloud mask was used to eliminate the influence of pixels which were not covered by vegetation, and their shadows were taken into account [35]. For all pixels, the mean and the standard deviation were calculated.

The mean $\Delta VI_{14\text{-}15}$ difference, calculated as the first step, was reduced by the mean VI and divided by the standard deviation $\Delta\sigma$ of all the pixels resulting from the differential vegetation index of relative change:

$$\Delta VI = \frac{\Delta VI_{14-15} - \overline{VI}}{\Delta\sigma}$$

2.2. Determination of regions of interest (ROIs)

The forest properties were analyzed in 20 different habitats, which were selected on the basis of Landsat imagery, using Forest Data Bank (FDB) maps showing forest divisions according to dominant species as a reference. The regions of interest included Q. robur specimens selected for the HESOFF project: DBB 126, DBB 96, DBB 130c, and DBB 130a (Fig. 1). The other regions were selected to cover the ortho photomaps to a maximum extent and derived from photogrammetric products generated in the project [36]. Only 15 out of the 20 selected polygons were used to elaborate the research method (section 2.3). Of these, 10 were deciduous forests dominated by oak and five were coniferous (two larch forests and three pine forests). The analyzed stands were located in the Karczma Borowa Forest District, near the City of Leszno, in southern Wielkopolska (Poland). All 15 regions of interest (ROIs)are described in Table 1, providing information about the tree and understory coverage, the soil type of the forest habitat, and the properties of dominant tree species, such as age, diameter at breast height (DBH), height, and wealth (abundance of the stand). The name of the region was obtained from the Forest Data Bank. The dominant species, including age, were specified as follows: DBB for Q. robur, DBC for Quercus rubra, MD for Larix sp., and SO for P. sylvestris.

Table 1. Environmental tree parameters (Forest Data Bank). Dominant species name with its age: DBB for Quercus robur, DBC for Quercus rubra, MD for Larix sp., SO for Pinus sylvestris. Soil type according to the Polish forestry nomenclature: OGw – rain-dependent gley soil; Gw – groundwater-dependent gley soil; Pw - lessive soil; BRk – acid brown soil; RDbr – rusty brown soil; due to its mineralogical composition, it is most permeable in our analysis.

				Properties of dominant species			Age of tree species									
	Soil type	Tree coverage [%]	Understory coverage [%]	Tree DBH [cm]	Tree height [m]	Stock [m^3/ha]	*Quercus robur*	*Picea abies*	*Fagus sylvatica*	*Carpinus betulus*	*Quercus rubra*	*Larix sp.*	*Pinus sylvestris*	*Tilia sp.*	*Betula pendula*	*Pseudotsuga Carriere*
DBB126	Gw	100	60	42	33	509	126	126	-	-	-	-	-	-	-	-
DBB129	RDbr	80	70	46	32	550	129	-	129	101	-	-	-	-	-	-
DBB130a	RDbr	100	50	43	31	586	130	-	-	130	-	-	-	-	-	-
DBB130b	RDbr	100	40	44	31	466	130	130	-	-	130	130	130	-	-	-
DBB130c	RDbr	100	70	42	31	411	130	66	66	-	130	130	130	-	-	-
DBB139	BRk	90	60	49	32	554	139	139	-	139	-	81	139	-	-	-
DBB140	RDbr	100	40	45	33	118	140	0	140	-	140	140	-	140	-	-
DBB83	BRk	100	50	27	25	346	83	-	-	-	-	83	83	-	83	-
DBB96	RDbr	90	20	35	30	390	96	51	130	-	-	-	-	-	-	51
DBC120	RDbr	70	10	47	32	411	-	-	-	-	120	120	-	-	-	-
MD50	RDbr	110	40	25	26	194	-	-	-	36	-	50	50	-	-	-
MD79	RDbr	110	80	40	34	509	-	-	-	79	-	79	-	-	-	-
SO100	RDbr	110	10	34	28	309	100	26	-	-	-	-	100	-	-	-
SO105	BRk	90	30	39	28	386	105	-	-	105	-	105	105	-	105	-
SO27	OGw	110	20	11	14	152	27	27	-	27	-	27	27	-	27	-

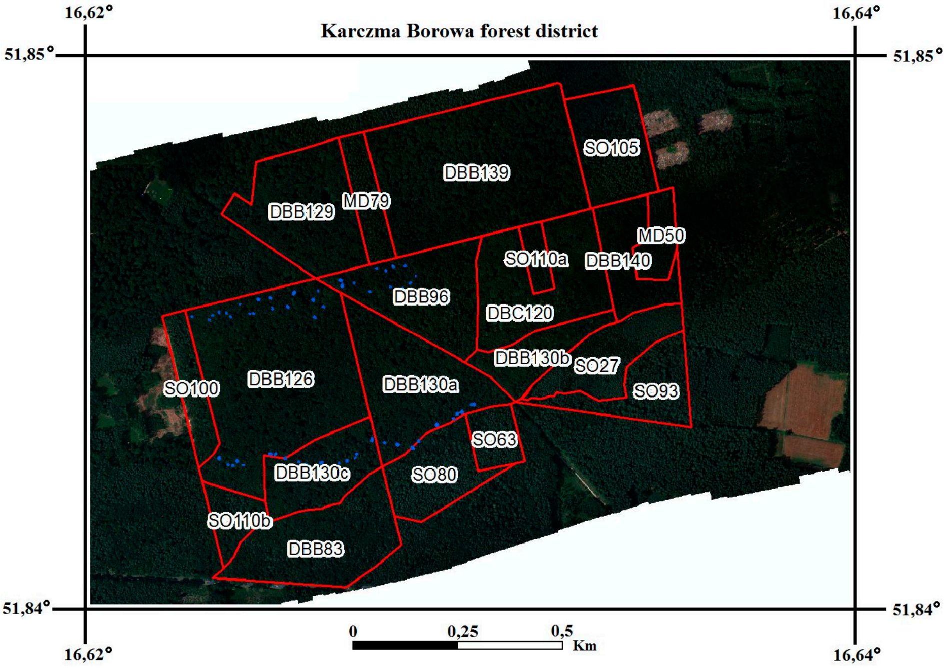

Fig. 1. Map of the research plot in the Karczma Borowa Forest District in the adopted WGS 84 reference system. The red colour denotes the ROIs adopted in accordance with the divisions of the Forest Data Bank (FDB). The blue colour denotes the positions of sample tress set out by the Forest Research Institute (Quercus robur).

2.3. Estimation of changes in the condition of forest complexes between 2014 and 2015

The satellite data from the Landsat-8 OLI series, products at the level of surface reflectance, were acquired from the ESPA server (https://espa.cr.usgs.gov/ordering/new/) and provided the basis for calculating the differences in indices between 2015 and 2014. These were multispectral data, imaging the land surface from visible light (400-760 nm) through near-infrared (750-1,500 nm) to mid-infrared (1,500-2,600 nm). The calculation of indices, on the basis of spectral channels registering the reflectance of particular wave types, is frequently applied to process the particular wave types, since their values are correlated with changes in the properties of the vegetation, rocks, or water. Knowledge of the specificity of the individual indices and their relationships with changes in the biophysical variables of vegetation enables the monitoring of its condition and, thus, of the specific impacts of stressors.

2.4. Segmentation of tree crowns in aerial images

The segmentation of tree crowns consisted of determining single crowns from the differential elevation model nDSM (Digital Surface Model DSM minus Digital Terrain Model DTM) (Fig. 2). This model was generated from a point cloud established from the matching of the acquired images, using the QUERCUS.6 platform with a GSD (ground sampling distance) of 0.25 m [36]. To acquire a differential model, a point cloud acquired from images taken outside of the growing season (deciduous trees had no leaves) was filtered, enabling terrain observations - this model was used to generate the DTM. The DSM model was generated from images taken in the course of the vegetation season; in this case, a cloud point represented tree crowns. The project did not include an accuracy analysis of the determined heights of single trees. In accordance with Pitkänen et al. (2004) [37], a systematic height error (with height representing the highest point of the crown) can be expected at

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a level of 1 m for data from airborne scanning (LIDAR). In the case of models originating from the matching of images with a GSD of 0.25 m, this error should be higher by a factor of about 1.5-2 for tall trees. In the investigated area, maximum tree height was about 30-40 m.

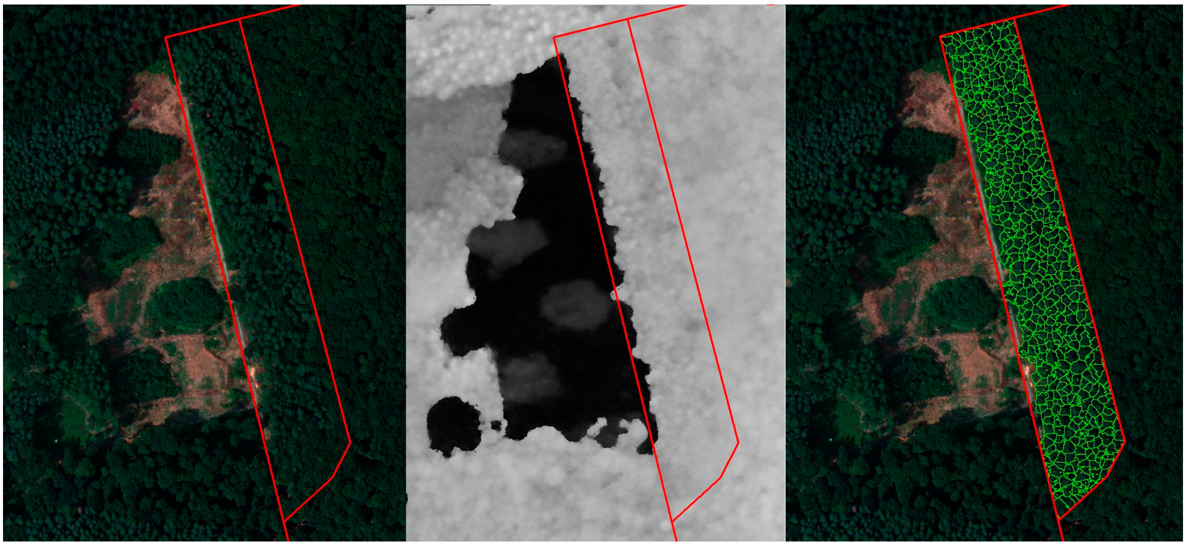

Fig. 2. Segmentation in the case of ROI SO 100 (Fig. 1.). From left: Orthophotomap – a RGB composition in natural colours. An elevation model acquired as a result of the matching of images. The particular tree crowns were determined using segmentation based on the watershed algorithm.

At present, several algorithms are applied to detect treetops and to determine the range of tree crowns. Among them, methods based on a search for local maxima prevail. In the research proposed here, the watershed algorithm [38] was used. The operating principle of this algorithm consists in reversing the crown model by multiplying the values recorded in the pixel by -1 (the tops become hollows). In the model thus created, the algorithm seeks out micro-catchments - imitating water spillage. The point with the lowest values is determined as the top. The boundaries of such a catchment are considered to be the boundaries of the tree crown [39, 40]. In addition, the variables determining the minimum height of the tree crown (only trees taller than 15 m were analyzed) and the minimum height of the tree crown were applied. In view of the variables applied, the results of the segmentation for areas dominated by coniferous trees were unsatisfactory. In light of this, further analyses omitted for regions SO110b, SO110a, SO93, SO63, and SO80 (Fig. 3b). Segmentation carried out in this manner ensures an effective estimation of the number of trees at a level of 70-80% [41]. This segmentation was used to determine species diversity (section 2.4).

2.5. Estimation of the species diversity index

The species diversity in a given ecosystem or in a designated area may be estimated by measuring two variables: (a) species richness (number of species) and (b) the evenness of individuals of a given species in an ecosystem. These two variables are reflected by the Shannon-Wiener diversity index, which is commonly used in ecological research [42].

The measurement of species diversity using remote sensing methods is based on both a factor analysis of multispectral images [43, 44] and digital modelling of the land cover [45]. Time-related

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analyses of changes observed in both reflectance [46] and in vegetation indices [47] play a special role in environmental studies.

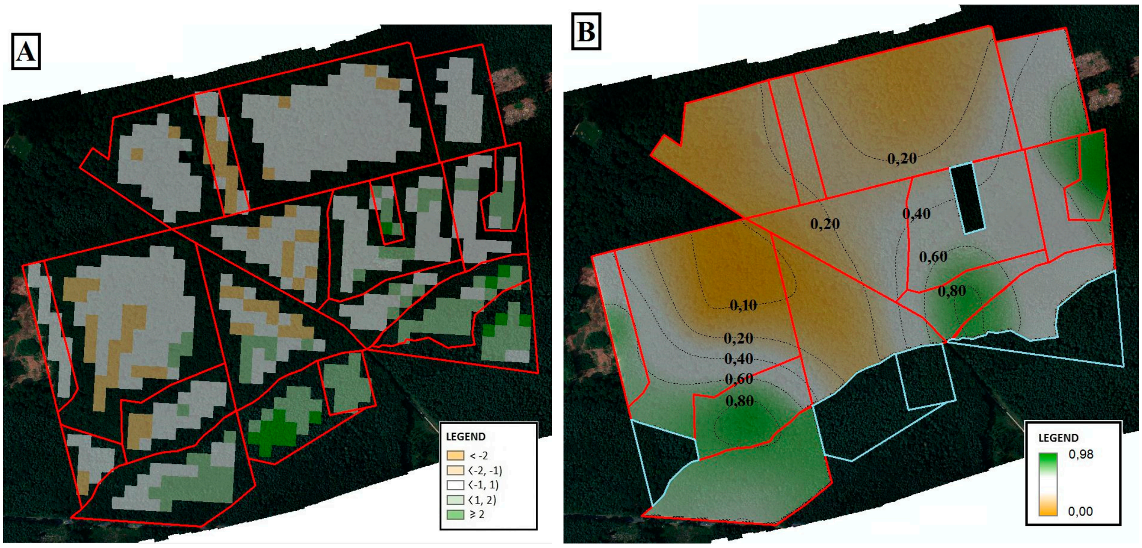

Fig. 3. Surface representation of the ΔGNDVI differential index between 2014 and 2015 (A). The mean value of the GNDVI differential index for 2014 and 2015 for all ROIs (B). The green colour denotes values exceeding 0, the orange colour represents those below 0. The blue colour represents the Shannon-Wiener diversity index for all ROIs. Products at the surface reflectance level (Landsat-8 OLI) were used as source data. The study did not consider mixed pixels at the boundary of divisions. An improvement in the condition of trees is represented by the green colour, while its deterioration is indicated by the orange colour.

In this paper, the method used to estimate the tree species diversity index in individual forest divisions was based on analysis of multispectral images acquired in July 2015, using the QUERCUS.6 multi-sensor platform [36, 48, 49]. Imaging was performed in six optical channels within the visible light and near-infrared ranges. An algorithm for an iterative application of a factor analysis of multispectral images was used in post-processing [22,48,50].

As a result of the image classification of an image, the following is determined: (a) the number of classes, including number n of classes with mean pseudo-signatures interpreted as biomass, and (b) the share of the quantity of the determined crowns attributed to a given species in all tree crowns. These data can be regarded as estimates of the variables determining the species diversity of the ecosystem in terms of (a) species richness and (b) species evenness. This provides the entire information needed to calculate the Shannon-Wiener diversity index H, which is defined as follows [51]:

$$H = -\sum_{i=1}^{n} p_i \ln(p_i)$$

where n is the estimate of species richness and p_i is the estimate of species evenness.

An iterative PCA analysis was carried out separately for each forest division to assign an appropriate tree species diversity index to each division.

2.6. A comparison of inventory-based stand characteristics in ROIs and their species diversity with the changes observed between 2014 and 2015

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A correlation analysis was carried out to identify the relationship between the occurred changes and the habitat variables related to the species diversity of the stands. Pearson´s correlation coefficient was calculated to determine the relationship with the species diversity of tree crowns H, the shares of particular species (Table 2), and the tree variables (Table 1).

In addition, to gain a better understanding of the specificity of the observed changes, the differences and the standard deviations between the indices in 2014 and 2015 were calculated.

3. Results

3.1. Habitat characteristics

In our study region, 10 out of 15 investigated stands grew on rusty brown soils. Two oak stands and one pine stand grew on acid brown soils; there were one pine stand and one oak stand on gley soils. Very dense tree cover dominated (with a median of 100%); most of the trees were older (with a median of 126 years for oaks and one of 100 years for pines). Table 1 shows the detailed results.

3.2. Species diversity indices of tree crowns in the particular forest divisions

In the evaluated forest divisions, tree crown classes corresponding to the following species or genera were determined: Q. robur (with a mean share in the biomass of a single ROI of 55.7%), P. sylvestris (21.2%), Larix sp. (11.6%), Q. rubra (8.2%), Carpinus betulus (1.3%), Picea abies (1.2%), Betula pendula (1.1%), Fagus sylvatica (0.8%), Pseudotsuga Carriere (< 0.1%), and Tilia sp. (< 0.1%). Divisions with the highest species diversity indices H included MD50 (0.882), DBB130c (0.860), and DBB130b (0.829). Here, the relatively high diversity indices resulted from large admixtures of red oak (10-20%) and larch (> 10%) in stands dominated by pedunculate oak (70-75%) or a substantial admixture of Scotch pine (> 30%) in stands dominated by larch (> 55%). The more homogenous divisions ($H < 0.100$) were dominated by pedunculate oak (DBB126, DBB129, DBB130a, and DBB 139). Table 2 shows the detailed results.

3.3. Coefficients of correlation between the characteristics of ROIs and their responses to drought

Table 3 presents the relative values of change in calculated differences for 10 well-known vegetation indices. The results are values which represent a relative improvement or a deterioration of the stand condition in the course of one year for the particular divisions. Values in the range from -1 [σ] to +1 [σ] are interpreted as the absence of a change in the examined stand [5,23]. Negative results indicate that the environmental conditions caused by drought have brought about an adverse change in the stand. Positive values correspond to stands which are more resistant to stressors. The most important factor which determines the stand response to drought is the forest type: forests dominated by coniferous species respond in a different manner (better) to water stress than deciduous stands do.

The statistics summing up the occurred changes include the mean and the standard deviation for all indices (Table 3). When calculated for the rows of the Table, i.e., for the particular forest divisions, they represent the mean response of the forest divisions to drought and the differentiation of this response for selected indices.

The results of the Pearson´s correlation between the observed changes in the stand condition and the environmental indices indicate the following relationships:

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Table 2. Shannon-Wiener species diversity index (H) and the shares of the identified species in forest divisions (the results based on analyses of aerial images, see section 2.4). Dominant species name with its age: DBB for Q. robur, DBC for Q. rubra, MD for Larix sp., SO for P. sylvestris.

FDB region	H [%]	Share of particular species in a forest division [%]									
		Quercus robur	Picea abies	Fagus sylvatica	Carpinus betulus	Quercus rubra	Larix	Pinus sylvestris	Tilia	Betula pendula	Pseudotsuga Carriere
DBB126	4.94	99.14	0.86	-	-	-	-	-	-	-	-
DBB129	8.06	98.64	-	0.91	0.45	-	-	-	-	-	-
DBB130a	6.39	98.83	-	-	1.17	-	-	-	-	-	-
DBB130b	82.94	72.86	1.18	-	-	17.70	1.18	7.08	-	-	-
DBB130c	86.03	74.40	0.88	3.06	-	11.16	10.28	0.22	-	-	-
DBB139	7.61	98.89	0.27	-	0.37	-	0.32	0.16	-	-	-
DBB140	53.30	87.23	3.19	6.91	-	0.53	1.60	-	0.53	-	-
DBB83	68.61	74.33	-	-	-	-	2.42	22.40	-	0.85	-
DBB96	25.53	93.54	5.17	0.90	-	-	-	-	-	-	0.39
DBC120	22.78	-	-	-	-	93.97	6.03	-	-	-	-
MD50	88.24	-	-	-	8.06	-	58.60	33.33	-	-	-
MD79	25.89	-	-	-	7.20	-	92.80	-	-	-	-
SO100	71.25	21.65	5.15	-	-	-	-	73.20	-	-	-
SO105	53.93	14.47	-	-	1.28	-	0.18	83.15	-	0.92	-
SO27	48.13	0.42	0.72	-	0.55	-	0.12	85.95	-	12.23	-

Table 3. Values of Differential Vegetation Indices for each forest region. Registered changes are bold and underlined.

FDB id	ΔEVI	ΔMSAVI	ΔNBR	ΔNBR2	ΔNDMI	ΔNDVI	ΔSAVI	ΔGNDVI	ΔARVI	ΔBNDVI	MEAN	σ
DBB126	-0.91	-0.92	-0.94	-0.79	-0.92	-0.93	-0.91	-0.83	-0.89	-0.99	-0,90	0.06
DBB129	-0.74	-0.76	-0.76	-0.73	-0.73	-0.81	-0.77	-0.67	-0.80	-0.78	-0.76	0.04
DBB130a	-0.54	-0.55	-0.34	-0.29	-0.32	-0.54	-0.54	-0.33	-0.47	-0.66	-0.46	0.13
DBB130b	0.67	0.66	0.72	0.80	0.59	0.36	0.62	0.63	0.42	0.28	0.58	0.17
DBB130c	0.30	0.27	-0.28	-0.08	-0.37	-0.05	0.31	0.20	-0.08	0.02	0.02	0.24
DBB139	-0.69	-0.71	-0.46	-0.58	-0.45	-0.39	-0.65	-0.65	-0.44	-0.30	-0.53	0.14
DBB140	0.16	0.13	0.34	0.50	0.13	0.42	0.20	0.46	0.42	0.41	0.32	0.15
DBB83	0.70	0.70	0.22	0.60	0.13	0.53	0.72	1.03	0.52	0.57	0.57	0.26
DBB96	-0.86	-0.87	-0.69	-0.72	-0.68	-0.76	-0.86	-0.78	-0.75	-0.79	-0.78	0.07
DBC120	0.70	0.72	-0.10	-0.06	-0.15	-0.23	0.62	0.03	-0.25	-0.12	0.11	0.40
MD50	1.29	1.28	1.64	1.45	1.54	1.52	1.31	1.01	1.52	1.42	1.40	0.18
MD79	-0.44	-0.36	-0.20	-0.43	-0.25	-0.20	-0.48	-0.80	-0.23	-0.25	-0.36	0.18
SO100	0.20	0.30	-0.10	-0.44	0.02	0.01	0.20	0.07	-0.08	0.21	0.04	0.22
SO105	0.42	0.42	0.98	0.64	1.00	0.86	0.41	0.28	0.89	0.70	0.66	0.26
SO27	1.70	1.74	1.46	1.41	1.59	1.46	1.69	1.24	1.45	1.49	1.52	0.16
MEAN	0.13	0.14	0.10	0.09	0.08	0.08	0.12	0.06	0.08	0.08		
σ	0.81	0.81	0.79	0.76	0.78	0.77	0.81	0.72	0.77	0.76		

Table 4. Pearson's coefficient of correlation between ΔVIs and the shares of particular species in forest divisions and for taxonomic data (* for p-value < 0.05, ** for p-value < 0.005).

	ΔEVI	ΔMSAVI	ΔNBR	ΔNBR2	ΔNDMI	ΔNDVI	ΔSAVI	ΔGNDVI	ΔARVI	ΔBNDVI	MEAN	σ
H	0.67*	0.66*	0.61*	0.64*	0.57*	0.66*	0.68*	0.73**	0.65*	0.68*	0,66	0.042
Q. robur	-0.67*	-0.69**	-0.46*	-0.15	-0.66*	-0.63*	-0.65*	-0.42	-0.61*	-0.64*	-0.61	0.083
P. abies	-0.1	-0.1	-0.1	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.17	0.034
Fagus sylvatica	-0.0	-0.0	-0.0	0.04	-0.1	0.01	-0.0	0.09	0.01	0.02	-0.01	0.061
Carpinus betulus	0.17	0.18	0.38	0.27	0.36	0.35	0.17	0.05	0.35	0.31	0.26	0.112
Q. rubra	0.23	0.23	-0.0	-0.0	-0.0	-0.0	0.20	0.03	-0.1	-0.0	0.03	0.140
Larix sp.	0.07	0.08	0.19	0.11	0.17	0.19	0.06	-0.0	0.18	0.16	0.12	0.083
P. sylvestris	0.60*	0.62*	0.65*	0.53*	0.72**	0.67*	0.61*	0.54*	0.66*	0.69**	0.63	0.061
Tilia sp.	0.01	-0.0	0.08	0.14	0.01	0.12	0.02	0.15	0.12	0.12	0.08	0.061
B. pendula	0.55*	0.56*	0.50	0.50	0.56*	0.52*	0.56*	0.48	0.52*	0.54*	0.53	0.029
Pseudotsuga menziesii	-0.34	-0.34	-0.28	-0.29	-0.27	-0.30	-0.34	-0.32	-0.30	-0.32	-0.31	0.027
Tree coverage [%]	0.29	0.30	0.40	0.37	0.41	0.46	0.31	0.35	0.45	0.44	0.38	0.064
Understory coverage [%]	-0.46	-0.47	-0.37	-0.31	-0.41	-0.33	-0.45	-0.39	-0.33	-0.37	-0.39	0.056
Age [years]	-0.62*	-0.63*	-0.64*	-0.58*	-0.68**	-0.67*	-0.62*	-0.51*	-0.66*	-0.67*	-0.63	0.052
Tree DBH [cm]	-0.66*	-0.67*	-0.64*	-0.63*	-0.68**	-0.7**	-0.67*	-0.65*	-0.69**	-0.7**	-0.67	0.025
Tree height [m]	-0.72**	-0.73**	-0.67*	-0.67*	-0.73**	-0.72**	-0.73**	-0.71**	-0.71**	-0.73**	-0.71	0.023
Tree stock [m3/ha]	-0.71**	-0.71**	-0.69**	-0.70**	-0.67*	-0.76**	-0.72**	-0.74**	-0.74**	-0.78**	-0.72	0.033

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- A strong positive correlation between the Shannon-Wiener species diversity of tree crowns and the particular ΔVIs; the mean value of the correlation is 0.66 (±0.083); the strongest correlation (+0.73, $R^2 = 0.54$; $p\text{-value} < 0.005$) occurred for the ΔGNDVI differential index (Fig. 4, up), while the lowest one could be observed for ΔNDMI (+0.57).
- A strong negative correlation between the percentage share of the tree crowns of the Q. robur species and the particular ΔVIs. The strongest relationship (with a correlation coefficient of -0.69, $R^2 = 0.48$) was found for the correlation with the ΔMSAVI index (Fig. 4, middle).
- A strong positive correlation between the percentage share of the tree crowns of the Pinus species and the particular ΔVIs. The strongest relationship (with the correlation coefficient of +0.72, $R^2 = 0.53$) was found for the correlation with the ΔNDMI index (Fig. 4, bottom).

A statistically significant correlation for some indices was found for B. pendula (e.g., for ΔMSAVI, with a correlation coefficient of +0.56); however, the quantitative representation of this species is relatively small, necessitating caution in interpreting the results.

Highly significant correlations were found for all differential indices in relation to the following four variables: age, DBH, height, and stock. This confirms the results of the previous research carried out in this area, which demonstrated the relationship between the age of a stand and its resistance to drought.

Table 4 shows the detailed results in terms of the correlation between the differential and environmental indices.

4. Discussion

Based on our results, we can draw conclusions about the impact of drought on stand resistance, assessed via the following factors: habitat conditions, species diversity, and the dominant species in the stand. The highest correlations between the differential indices and the Shannon-Wiener index were observed for GNDVI (+0.74), BNDVI (+0.68), and SAVI (+0.68). We found no relationship between the differential indices and the indices demonstrating tree and understory coverage. However, a statistically significant relationship was found for the variables characterizing the dominant species in a given stand for all analyzed ΔVIs. The resistance to drought increases with decreasing breast height (DBH), height, and abundance.

4.1. Species diversity

Divisions MD50 and SO27 were characterized by the highest resistance to drought. These habitats had the youngest stands and thus the lowest DBH, age, and abundance. At the same time, division MD50 showed the highest species diversity index (88.24%), while SO27 had the largest share of Scotch pine. It should be noted that Nasiłowska et al. (2017) [22] indicated both species diversity and the share of Scotch pine within a division as factors enhancing the response to drought. In turn, the values of indices decreasing within the ranges (-0.79, -0.99), (-0.67, -0.81), and (-0.68, -0.87) could be seen for divisions DBB126, DBB129, and DBB96, evidencing a negative trend in the development of the local vegetation. These were divisions with the lowest species diversity index values (all below 9.0%) and Q. robur as the dominant species.

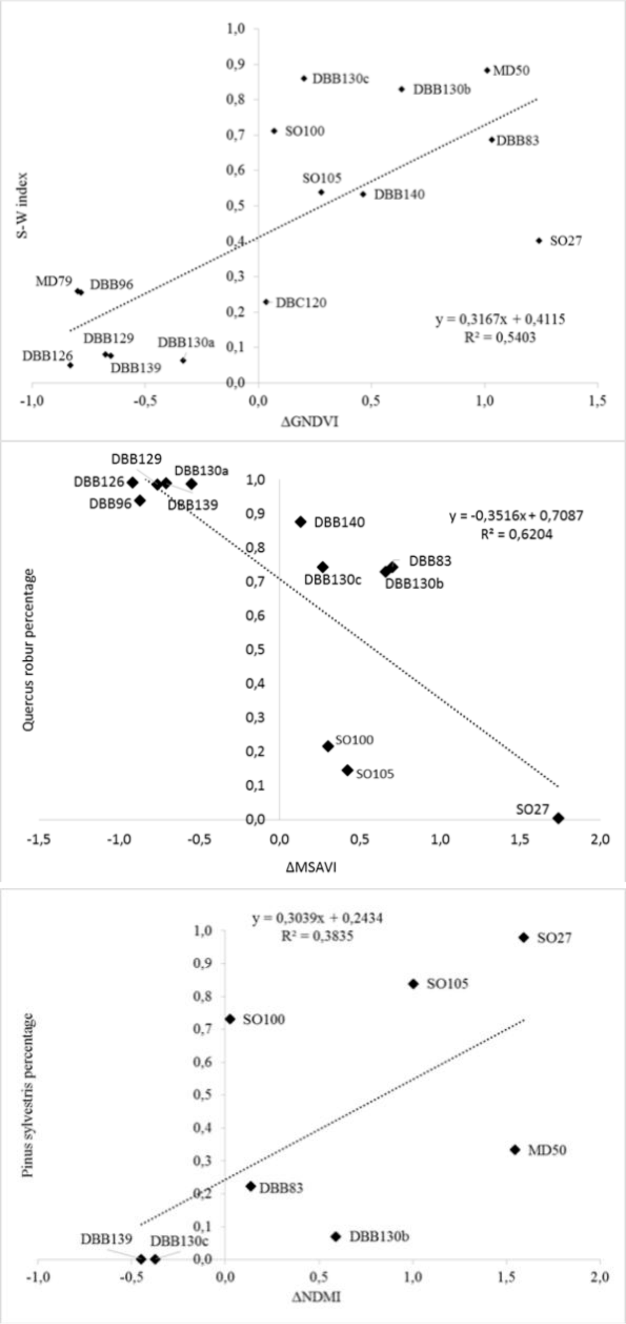

Fig. 4. Up: Diversity index H in relation to the value of the ΔGNDVI index; middle: percentage share of the Quercus robur species in relation to the value of the ΔMSAVI index; bottom: percentage share of the Pinus sylvestris species in relation to the value of the ΔNDMI index.

When comparing the indices *H* of all divisions with the corresponding differential indices, a mean correlation coefficient of +0.66 (±0.042) was obtained, confirming a decisive effect of *H* parameter on the stand response to drought. It should be pointed out that the study on the impact of species diversity on the stand response to drought could not fail to consider the simultaneous effects of factors such as forest type or dominant species, and it was only a simultaneous analysis of the index H and the other habitat variables that ensured a full description of the reasons for the behavior of stands under stress conditions. However, our results also show exceptions to this general trend. Two divisions with a low diversity index, i.e., DBB130a (*H* = 0.064) and DBB139 (*H* = 0.076),

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demonstrated higher drought resistance than a division with higher diversity, i.e. DBB96 ($H = 0.26$), did. This could have been caused by a poor understory in division DBB96 and s small percentage share of additional species in the oak stand (< 7.0%). This example shows that one must not interpret the index H uncritically, as it is sensitive to the number of scarce species in a stand.

4.2. Impact of the soil type

The lowest values of the differential indices, just below the interpretation threshold (-0.99 for the ΔBNDVI), were found in DB126, a 126-year-old homogenous ($H = 49.0\%$) oak stand. Among the analyzed oak divisions with low diversity, it was the only one situated on gley soils. In non-drought periods, these soils favor the growth of wet forests and cause the development of more shallow root systems as a result of gleying [52], creating ecosystems which are more vulnerable to water stress. During drought periods, these soils are characterized by an exceptional water deficit, leading to water stress in plants [53]. In addition, e.g. the biochemical soil composition emerging as a result of an excessive release of dissolved organic carbon (DOC) during drought periods [54] is unfavorable for plants. The carbon to nitrogen ratio (C/N) in leaves is a well-known variable indicating their nutritional status and the correct course of physiological processes or the health condition dependent on water availability [55]. Similar relationships were found in forest-forming deciduous tree species. Examining the responses of three oak species - Q. robur, Quercus petraea, and Quercus pubescens - to drought, [56] found that, under water deficit conditions, in all species, the quantity of dissolved nitrogen in leaves increased at the expense of structural nitrogen, contributing to a reduction in the C/N ratio.

The simultaneous presence of as many as four factors, namely (1) low species diversity, (2) a dominant species which is vulnerable to water stress, (3) the stand age, and (4) the presence of gley soil, explains the worse change in the vegetation indices among all divisions.

4.3. Dominant species

The percentage share of the determined tree species was significantly (p-value < 0.05) correlated with ΔVIs for most indices only for Q. robur (-0.63 ± 0.04) and B. pendula (+0.55 ± 0.02), as well as for all indices for P. sylvestris (+0.63 ± 0.096). This result indicates that the resistance of forest stands to drought increased as the percentage share of Q. robur diminished and the shares of B. pendula and P. sylvestris increased.

These observations are consistent with the literature data, since an assessment of the vulnerability of trees to drought is of major importance for improving the forecasts of the dieback of forests and species under the impact of climate change. Particular forest tree species demonstrate substantially different needs in terms of water supply. In particular, this is the case with oaks [57]. For example, a direct comparison between Quercus petraea, Q. robur, and Q. rubra has shown that Q. petraea is more resistant to drought than the other two species [58].

4.3.1. Q. robur

Compared with other oak species, such as e.g. Quercus petraea in the temperate climate zone, pedunculate oak (Q. robur) has higher water requirements and is more vulnerable to water stress [59, 60]. Q. robur can also be found on sites with low water availability, e.g., on sandy, nutrient-poor soils [61] or on plateaus and the exposed slopes of well-drained limestone hills [62]. In such habitats, pedunculate oak shows a high drought tolerance, which ensures its survival. Experimental data acquired under controlled greenhouse conditions also show good drought tolerance of pedunculate oak. The results indicate that under the conditions of progressive drought, plants demonstrate intensive adaptation mechanisms, consisting of the alignment of the physiological potential of leaves [63, 64].

In Q. robur, drought causes biomass allocation, leading to reduced foliage in favor of small roots. This seems to be the most important process of the acclimation of Central European oak species to drought stress. This is confirmed by the highest significance of the correlation between the percentage share of Q. robur and the NDMI differential index. At the level of leaves, the acclimation to drought stress consists in osmotic regulation to achieve resistance to dehydration. However, these processes generally occur under moderate drought stress rather than under strong drought stress [60].

Urli et al. (2015) [65] also assessed the ecophysiological response of Quercus ilex and Q. robur to drought and their vulnerability to dehydration stress under field conditions. Their research indicated that despite limited water availability, the abundance of Quercus ilex was comparable to that of the control stand, whereas the abundance of Q. robur dramatically fell as water availability deteriorated. These authors claimed that the different species responses might be caused by the differences in the structure and operation of the hydraulic system. Q. robur demonstrated the threshold water transport variables in contrast to Quercus Ilex, in which the transport level was satisfactory - this probably makes pedunculate oak extremely vulnerable to drought [65]. In the context of increased drought frequency and intensity, the findings by Urli et al. (2015) suggest that in the face of progressive climate change, the Q. robur population may be at risk.

4.3.2. Q. rubra

In Poland, Q. rubra is considered to be an alien species and characterized by a higher tolerance to drought and frost than native oak species. According to the literature, Q. rubra is a species with a low drought tolerance [66] and is best adapted to habitats with moderate or well-balanced moisture conditions [67]. In Polish stands, it usually constitutes a production or biocenotic admixture or may occur in the form of a homogenous stand [68]. Literature data indicate that pedunculate oak (Q. robur) is more vulnerable to water stress than Quercus petrea, which is popular in Polish forests [69, [69, 70] but copes better with drought than Q. rubra does [71]. However, our results cannot confirm this position. In areas DBB130b and DBB 130c, where Q. robur dominated with a share of Q. rubra (17.7 and 11.16%, respectively), a higher drought tolerance was found than in areas with higher biodiversity, such as DBB96. The increased drought tolerance of hardly diverse oak habitats may have been caused by the coexistence of pedunculate oak with an admixture of red oak, which has adapted to the limited water resources in a given habitat. Despite the fact that both Q. rubra and Q. robur are considered to be highly vulnerable to water stress, they can occupy habitats with varied water availability, although Q. rubra can also occur in extremely dry habitats [69, 72]. Genetic differences in drought tolerance can also be seen within a species from a specific geographical location. Research carried out in central Pennsylvania demonstrated that Q. rubra growing in extremely dry habitats had both physiological and morphological features of drought tolerance in contrast to the same species in habitats with higher moisture levels [72].

Under water deficit conditions, Q. rubra can demonstrate changes in hydraulic conductance to adjust stomata opening at values below -2.3 MPa [71]. Parker et al. (1982) compared the resistance of

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Q. alba and Q. rubra to water stress [73]. Both species responded with a change in the osmotic potential in leaves under the impact of drought, and the closing of stomata was triggered by a turgor potential of 0.2 MPa for Q. alba, whereas the respective value for Q. rubra was 0.4. Hinckley et al. (1978) also observed the closing of stomata at higher values of the osmotic potential in red oak than those for white oak, indicating that Q. alba had was more capable of adapting to drought than Q. rubra was [74]. Despite the fact that, as indicated in the literature, it is a typical species which avoids drought [75], our research demonstrated its positive effect on the drought resistance of habitats with addition of Q. rubra.

This study found that areas overgrown by pedunculate oak, with an admixture of Q. rubra (DBB130b and DBB130c), had a higher drought tolerance than areas without Q. rubra. This might also be related to the habitat requirements of both oak species. Q. robur is a species with high soil requirements as it prefers rich soils, such as brown and lessive soils and black earths, whereas Q. rubra develops well on poorer soils, such as clayey sands and sandy soils [76]. On the Krotoszyn Plateau, the areas under study were dominated by low-fertile gley soils, to which red oak was considerably better adapted than pedunculate oak. Vivin et al. (1993) found that the richness/fertilization of a habitat had a significant impact on the growth and development of Q. robur and Q. rubra under water deficit conditions [58]. Under the impact of a prolonged drought, the mortality of young Q. robur specimens was higher than that of Q. rubra and, on this basis, the authors noted that Q. rubra was a species with a higher tolerance to drought stress than Q. robur. They also found that both species coped better with drought stress if mineral fertilizers were provided, which was probably related to the osmoregulation mechanism in case of a low water potential [58].

4.3.3. *P. sylvestris*

The results of the analysis of remote sensing indices also demonstrate that an enhanced share of Scotch pine increases the drought resistance of forest ecosystems, which has also been confirmed by the scientific community and forestry experiments. Scotch pine (P. sylvestris) is a species with a demonstrated ability to tolerate long-term and short-term changes in water availability. This is related to the morphology, phenology, and adaptability of this species. Under the conditions of increased water deficit, pine development is negatively impacted, resulting in changes in tree morphology, such as reduced height, changes in tree form, leaf shape, and size, and altered wood anatomy [77]. Prolonged drought decreases the growth rate of Scotch pine, which is reflected by its reduced DBH. In short drought periods, a reduced height may not be noticed. This is related to the phenology of the pine: needles remain on the tree for one to five years; therefore, seasonal drought may not have any adverse effects on tree development [78]. Moreover, pine often colonizes dry habitats, such as dunes. Pine species are adapted to such habitats since their roots are characterized by a taproot structure, enabling the trees to take up water, along with mineral salts, from deeper soil layers, thereby surviving short-term droughts.

4.3.4. *B. pendula*

The analysis of areas containing birch yielded disputable results. Although the obtained results concerned barely three out of the fifteen examined divisions, they indicated that the drought resistance of forest stands increased with increasing numbers of B. pendula. The literature sources point out that under natural conditions, silver birch often resides in cool and wet regions, including

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peat-bogs, stream and lake banks, cool and wet forests, and the slopes of cool bays [79, 80]. For this species, water deficit may cause significant stress and is dangerous for both adult individuals and nursery seedlings. Scientific research indicates that birch leaves are vulnerable to water stress [64], and the species demonstrated severely reduced growth as a result of mild water stress. In addition, in the course of a drought at daytime, birch leaves did not show any significant accumulation of dissolved substances, which caused a drop in the water potential in the leaves; we therefore assume that growth during daytime is constrained by low turgor. When subjected to water stress, the plants showed reduced growth and low stomatal conductance. No mechanisms for adapting stomata to drought stress could be seen. After water had been supplied to the plants, a slow regeneration of the stomata occurred [64]. In turn, Ranney et al. (1990) observed that stomata responded directly to water deficit in leaves [81]. Humphries et al. (1982) also found that B. pendula had a poorer water stress tolerance [82]. The authors found a higher mortality of B. pendula seedlings under less intensive water stress compared to that of B. davidii under more severe drought.

4.4. Monitoring water stress using differential indices

Among the analyzed indices, only ΔGNDVI accommodated the green channel and is thus the only index sensitive to the chlorophyll content in cellular structures. The chlorophyll content indicates the condition of the vegetation and its photosynthetic potential; the higher the content, the more energy can be absorbed and used for plant development. A reduced share of this pigment in cellular structures can be seen in the lower reflectance in green light. As indicated by the literature, its value should be independent of changes in pigments other than chlorophyll [30], which is responsible for light absorption; its efficiency depends on stressors. The ΔGNDVI showing the drought impact correlates most strongly with biodiversity; we therefore conclude that this green pigment and its quantity in the habitat that determine and differentiate the spectral response to a greater extent than other factors do.

In addition, this index should be independent of the impact of the soil visible between leaves or the impact of the atmosphere, which is particularly important for forest areas [30]. Moreover, its relationship with the diversity index H is stronger than that for classical indices, which are applied on a standard basis to eliminate the impact of the substrate (Table 4), such as SAVI [29] and MSAVI [25].

Considering all these factors, this index is increasingly used to investigate stress in vegetation [83 – 85]. Our results indicate that it is useful for forests and suggest that it should be used more frequently as an alternative to NDVI.

4.4.1. Quercus sp.

The ΔMSAVI differential index is distinguished by its strongest correlation, with the highest statistical significance, with the percentage share of the dominant species Q. robur. It has been designed to enhance its sensitivity to changes in the condition of the vegetation and, at the same time, to eliminate the soil impact, making it less dependent on the quantity of the biomass than the original SAVI was. This factor clearly affects the drought response of oak. However, when approached in general terms (Table 3), the variation of both ΔMSAVI and ΔSAVI is similar (with a standard deviation of 0.81). This indicates the greater usefulness of the ΔMSAVI index for investigating forest environments dominated by Quercus species.

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4.4.2. *Pinus sp.*

The percentage share of the species P. sylvestris showed the most significant statistical correlation with the ΔNDMI differential index. This coniferous tree species occurred in several analyzed habitats and dominated three of them, i.e. SO100, SO105, and SO27 (Table 1). Among the three analyzed indices based on mid-infrared, it demonstrates by far the strongest relationship with drought. Therefore, when comparing the results in Table 3, it can be considered that trends of change shown by ΔNBR and ΔNBR2 are less reliable than those calculated using ΔNDMI. Research performed to date has indicated the usefulness of indices based on mid-infrared for investigating coniferous forests [86-88]. The present study demonstrates that the index calculated on the basis of bands 5 (880 nm) and 6 (1,610 nm) more adequately shows the condition of a stand with a large share of pine than the other two indices (NBR and NBR2), considering the second reflectance maximum in mid-infrared of 2,200 nm (band 7). It is possible to better explore the behavior of these three indices and their usefulness for investigating drought impacts for a larger number of divisions including this species, whereas this study considers only three of them.

5. Conclusions

The particular differential indices have different degrees of usefulness, depending on the examined factor. In general, the sensitivity to green light is important for biodiversity research. The index MSAVI is most useful for investigating Q. robur, while NDMI is more adequate for P. sylvestris. It is important to note that such conclusions can only be drawn for species which dominate a given habitat. More detailed analyses require data with significantly higher spatial resolution than that of Landsat. It is therefore envisaged that further research will use data with a GSD of 0.25 m, acquired from the QUERCUS.6 aerial platform, which was used in the present study for image segmentation. This will allow the analysis of the spectral response of individual crowns, using six channels registered in the range from 400 to 1,000 nm. An additional advantage of high-resolution data is the ability to eliminate shadows and clearances between trees, facilitating the analysis of tree properties.

Despite all constraints, Landsat satellite images with a 30-m accuracy are suitable to obtain a quick and general overview of a situation. Their analysis is relatively rapid, and they are generally available for any time and place. The major constraints include cloudiness and correct radiometric adjustment. However, the present study demonstrates that, based on accurate knowledge of the quantitative shares of individual species, indirect conclusions can be drawn about their contribution to changes in the particular remote sensing indices. Their characteristics and interrelationships can also be assessed.

Acknowledgments: This research was performed under the HESOFF Project (Life 11 ENV/PL/000459), financed by the European Commission and the National Fund for Environmental Protection and Water Management.

Author Contributions: J.K. was responsible for tree crowns separation, estimation of the species diversity K.K. was responsible for particular species impact discussion S.N. was responsible for VI changes analysis K.R. was responsible for DTM preparation. J.K. and S.N. analyzed the data. J.K., S.N., and K.K. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Peer-reviewed version available at *Forests* **2018**, *9*, 126; doi:10.3390/f9030126

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