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Impact of Site Conditions on *Quercus robur* and *Quercus petraea* Growth and Distribution Under Global Climate Change

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Abstract: Climate change has significant natural and economic implications, but its extent is particularly challenging to assess in forest management, a field which combines both of the previous aspects and requires the evaluation of the impact of climate change on tree species over a 100-year timeframe. Oaks are among the tree species of significant natural and economic value in Europe. Therefore, the aim of this study was to analyze all oak stands in Poland and verify the hypothesis regarding differences between *Quercus robur* and *Quercus petraea* stands in terms of soil type, annual total precipitation, average annual air temperature, and the length of the growing season. Additionally, this study aimed to analyze the impact of these differences on the growth rates of both oak species and test whether climate change may affect oak stands. A database containing 195,241 tree stands, including different oak species with varying shares in the stand (from 10% to 100%), was analyzed. A particular emphasis was placed on *Q. robur* and *Q. petraea*. The results show that, although both oak species have a wide common range of occurrence, there are clear differences in their habitat preferences. Based on the ordinal regression analysis of selected oak stands, it was concluded that an increase in air temperature of 1 °C could impair the growth of *Q. robur* and slightly improve the growth of *Q. petraea*. This may indicate the possibility of expanding the geographic range of sessile oaks towards the east and northeast under warming climatic conditions, provided that appropriate moisture conditions are maintained.

Keywords: pedunculate oak; sessile oak; soil; climate; NDVI

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1. Introduction

The selection of tree species composition of stands is the starting point for all activities related to forest management, and therefore it is necessary to know the habitat requirements of trees and predict the role of tree species in changing global climate conditions [1]. *Quercus robur* L. (pedunculate oak) and *Quercus petraea* (Matt.) Liebl. (sessile oak) belong to the most important native tree species of Central Europe [2]. It is reported [3] that the oldest wooden structure in the world (in Czechia) was built of oak wood approx. 7200 years ago. Among the oldest settlements in Poland, the most famous one is Biskupin, a construction made of oak wood cut down nearly 3000 years ago [4]. Despite the fact that oaks have accompanied humans for thousands of years, and their general requirements are well known, information on the detailed habitat data differentiating both oak species is still rather poor. Thus, for example, in the synthesis of the state of knowledge about *Q. petraea* and *Q. robur* in Poland [5], the country lying in the middle of the range of *Q. robur* and on the eastern edge of the range of *Q. petraea*, data on habitat conditions of both oaks is very sparse and mostly comes from studies before 2000 [6–13]. Bugała's monograph does not

present the results of investigations on *Q. robur* and *Q. petraea* habitat conditions in Poland but compares both species on the basis of ecological index numbers after Zarzycki [14]. Generally, there is no synthetic data on habitat conditions of *Q. robur* and *Q. petraea* in Poland. Therefore, the aim of the study was to analyze all oak stands in Poland and verify the following hypothesis:

- Site conditions of *Quercus robur* and *Quercus petraea* stands differ in terms of soil type, annual total precipitation, average annual air temperature, and the length of the growing season;
- Under similar site conditions, *Q. robur* and *Q. petraea* do not differ in terms of growth rate class;
- Climate change may affect the geographical range and the dynamics of the growth of *Q. robur* and *Q. petraea*.

Selected data regarding the habitat requirements of *Q. petraea* and *Q. robur* in Poland is provided by Rutkowski [15] indicating water shortage as the main factor contributing to the deterioration of the oaks growth and distribution. Similar conclusions were provided with regard to *Q. petraea* and *Q. cerris* by Móricz et al. [16], but this fact seems obvious for all living organisms.

The habitat requirements of *Q. robur* and *Q. petraea* are described the European Atlas of Forest Tree Species [17], stating that both species prefer fertile and moist soils and that the tendency for pedunculate oak is to grow on heavier soils in a more continental climate. The same authors also state that the sessile oak is more tolerant to droughts and prefers more acid soils. However, Kohler et al. [18] note that generally pedunculate and sessile oaks are rather drought-tolerant compared with other common tree species.

According to Diaz-Maroto et al. [19], *Q. petraea* habitats characterized by higher precipitation, more variable soil properties and a higher degree of humidification than in *Q. robur*. In turn, Röhrig et al. [20] showed that *Q. petraea* prefers rather drier and warmer sites with acidic soils than *Q. robur*.

Most of the papers on the habitat requirements of oaks deal with climatic factors. Kelly et al. [21] analyzed pedunculate oak rings dating back to 1868 and showed positive response of oak growth to precipitation rather than temperature. Becker et al. [22] dealt with long-term increase in the wood production rate of forest ecosystems, connected this fact with the change in climatic factors, and joined the mainstream of research on determining pointer years in dendroclimatological studies [23–27]. These studies are especially useful in understanding the causes of the decline in oak stands, e.g., [28] and predicting the future of oaks in the context of global warming. They help to understand the complex relationships between climate and other site conditions. Some studies have been conducted on young trees [29,30], but for ensuring conservation and fulfilling the rules of sustainable forest management [31], it is necessary to analyze oak stands in different site conditions and various stand development phases. Therefore, this paper deals with all oak stands in Poland and discusses soil and climatic conditions influencing on *Q. robur* and *Q. petraea* forests.

2. Materials and Methods

2.1. Database and Selection of Oak Stands Included in This Study

The study was conducted on the basis of a database obtained—with the agreement of the General Director of Polish State Forests—from the Polish Forest Data Bank [32]. The database contains 195,241 tree stands with the presence of different oak species, with the different share in the stand (from 10 to 100%) and with different role in a stand (as a main tree species in the upper layer or in the lower layer of the stand, including lower oak layer under other tree species, e.g., pine in upper and oak in lower layer). These 195,241 tree stands cover 654,206.06 ha. This is equivalent to 7.1% of Poland's total forest cover and 9.2% of forests under State Forest management. After excluding from the database records with the other tree species as a dominant species in the upper layer of the stand and the geographically alien oak species in Polish flora (*Q. rubra* L.—1612 stands, *Q. cerris* L.—2 stands and *Q. coccinea* Münch. 1 stand), 106,677 records were left. Finally,

only those stands were selected for the analysis in which oaks occur in the upper layer of the stand as the main species, with a share of at least 60%. Thus, 95,906 oak stands covering 257,846.32 ha (2.8% of Polish total forest cover and 3.6% of forests under State Forest management) were preliminary analyzed. Out of 95,906 oak stands, 920 (645.90 ha) did not have soil data and were therefore excluded from the analysis of oak stand–soil type relationships.

The database available in Poland only partially differentiates oaks between pedunculate and sessile oaks. Out of the 95,906 analyzed stands, 67.85% (65,076) belonged to an undefined species, meaning that they could be either *Q. petraea* or *Q. robur* stands or both oak species in one stand. The almost 32% remaining samples consisted mostly of *Q. robur* stands (25.66%; 24,611 records), with 6.49% (6220 records) being noted as *Q. petraea* instead. A detailed analysis of the habitat conditions was conducted only for those stands where the oak species (*Q. petraea* or *Q. robur*) had been determined (30,831 stands).

All data were listed in the form of an Attribute Table saved in ArcGIS 10.1 software and have been attached as Supplementary Materials to the paper. ArcGIS software was used by the authors according to the License Agreement (E203 04/24/2012) between the Poznań University of Life Sciences and the Environmental System Research Institute, Inc. ("ESRI"), where all the maps presented in the figures in this paper were prepared.

2.2. Determination of the Diversity in Habitat Conditions of Pedunculate and Sessile Oaks

Data on humidity and temperature were collected using the R Studio environment and the "climate" library [33]. Meteorological data were collected using the meteo_imgw function, contained the "climate" library, utilizing the following parameter settings: interval = "monthly" for 2000–2020. The data included information such as: the city where the meteorological station was located, latitude and longitude, average monthly temperature, and humidity. The downloaded data were saved to Excel software format, and incomplete data were deleted. Subsequently, the average temperature was calculated over the entire analyzed period. In the next step, the data were loaded into the Surfer 8 software to prepare the distributions of the analyzed parameters in Poland. Spatial interpolation from the point data was performed using the "minimum curvature" method [34]. The preparation of maps containing spatial distributions of temperature, humidity, and rainfall was accomplished in the ArcGIS program.

Data on vegetation period were presented based on Krużel et al. [35] for 1981–2010.

2.3. Using the Height Rate Index to Assess the Effect of Habitat Conditions on the Growth of Pedunculate and Sessile Oaks

To present the effect of habitat conditions on the growth of oaks, the height rate index was used.

In the Polish system for assessing the height rate of oaks, there are four growth classes: 1st is the highest, and the 4th is the lowest. The presented data on growth rate classes are based on real stand height measurements conducted in all forest stands included in the Polish Forest Data Bank.

2.4. Using NDVI to Assess Changes in Habitat Conditions

The influence of atmospheric precipitation and soil differentiation on the condition of stands was analyzed based on NDVI (Normalized Difference Vegetation Index) for one of the largest pedunculate oak complexes in Poland, located in the Krotoszyn Forest District (the area about 5300 ha).The share of oaks in the selected stands reaches 100% in each stand, which allows us to avoid the influence of other species on the NDVI value. The average age of the analyzed stands is about 150 years. The NDVI was calculated and presented for growing season (June-September) in 2018. Image data from the Sentinel-2 (A) satellite of the European Space Agency (ESA) were imported into Google Earth Engine (GEE) and were used for the calculations. Data from the Level L2A product were used for the analysis. L2A means that each pixel of the image for the spectral band contains

a calibrated reflectance on the earth's surface, and was created as a result of geometric correction taking into account the radiation changes in the atmosphere. In GEE, images with a cloud ratio of less than 10% with a defined INF area were selected. For this purpose, the SCL (Scene Classification Layer) was used. In this layer, areas with the following values were identified: shadows—3, clouds with low probability—7, medium—8, high—9, cirrus clouds—10. Areas with medium and high probability were excluded if the number of pixels was greater than 50.

2.5. Statistical Analyses

A statistical analysis covering the relationship between oaks and soil conditions, using ordinal regression analysis, was carried out on stands with pedunculate and sessile oak, where each oak stand had more than 100 replications in a given soil type.

A separate statistical analysis was performed for rusty soils, which have the highest share of all soil types (36.2%), with the aim of testing the hypothesis on the influence of precipitation, air temperature, the length of the growing season, or all of these factors jointly on the growth rate of oak stands. For this purpose, all oak stands growing on rusty soils were linked to maps of air temperature differentiation and the sum of annual precipitation. The relationship between the NDVI value for a given oak stand and the air temperature at its location was calculated. It was assumed that the lower the NDVI value, the worse the condition of the stand. The adoption of one soil type allowed for eliminating the influence of soil conditions.

3. Results

3.1. Distribution and Diversity of Habitat Conditions of Pedunculate and Sessile Oak Stands

Poland is located on the eastern edge of the *Q. petraea* range and in the middle of the range of *Q. robur* (Figure 1). Oak stands are dispersed throughout of the country. Figure 2 shows their location on the background of maps of the distribution of total annual precipitation, average annual air temperature and the length of the growing season.

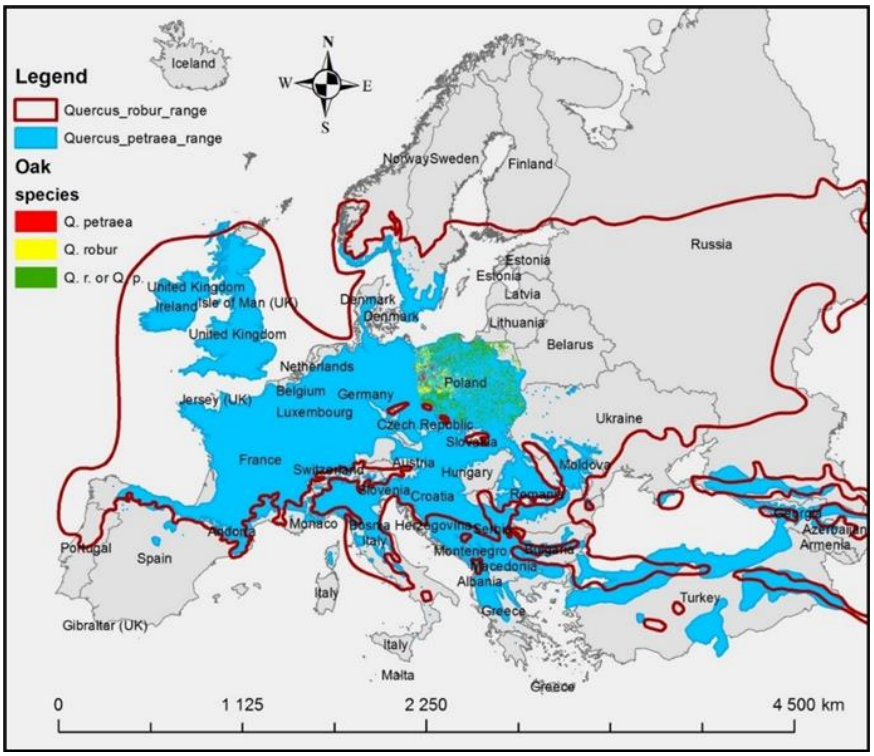


Figure 1. Distribution of oak stands in Poland (red—*Q. petraea*; yellow—*Q. robur*; green—*Q. petraea* or *Q. robur*) on the background of the ranges of both oak species in Europe (source of oak ranges—[36]).

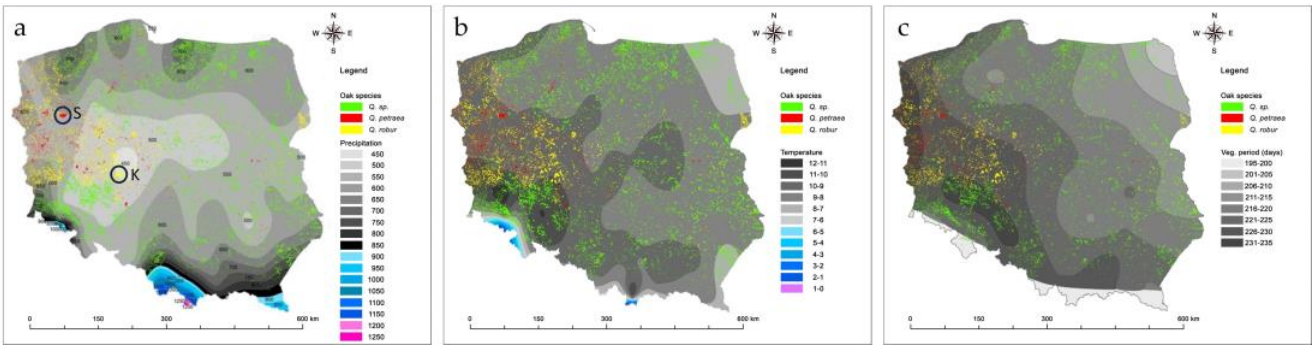


Figure 2. (**a**) Distribution of oak stands on the background of the year average sum of rainfalls in Poland during the period of 2000–2020. The green color shows undefined species, which means that the stands could be *Q. petraea*, *Q. robur,* or both oak species in one stand; the yellow shows *Q. robur* (24,611 stands), while the red shows *Q. petraea* (6220); and circles marked as S and K point to the most important oak stand complexes—K, *Q. robur* in the Krotoszyn Forest District, and S, *Q. petraea* in the Smolarz Forest District, respectively. (**b**) Distribution of oak stands on the background of a map of the average annual air temperature for the years 2000–2020. (**c**) Distribution of oak stands on the background of vegetation seasons in Poland during the period of 1981–2010 [35].

Oak stands are located in a rainfall zone for which the average annual values for the period 2000–2020 range from 450 to 800 mm (Figure 2a). In the zone of the lowest rainfall there is a visibly poorer presence of both oak species. However, it is also an area with generally low forest cover, so, on the one hand, this could be explained as a situation in which the precipitation limits the occurrence of forests, but we *could also* accept the theory that the lack of forests affects the low total rainfall.

Figure 2 also shows areas in southern part of Poland with a high total annual rainfall (over 900 mm) where there are no oak stands, where mountainous conditions limit their occurrence.

In terms of topography, both oak species occupy mainly lowland areas, what is correlated to the relief of Poland, where most of the country does not exceed the height of 200 m above sea level.

Oak stands in Poland occur in the area with an average annual air temperatures ranging from 6 to 12 °C (Figure 2b).

The length of the growing season in the lowland area of stands with pedunculate and sessile oak is variable, comprising from 196 to 200 days in the northeastern part of the country, to 235 days in the west of Poland (Figure 2c).

For both oak species, the dominant soil type in Poland is Brunic arenosols (in Polish classification soil classification system named rusty soils), but the difference between *Q. petraea* and *Q. robur* is clearly visible in favor of the sessile oak (Supplementary Materials, Figure S1). It is necessary to add however, that the domination of soils close to Brunic arenosols among oak stands could be connected to the general domination of rusty soils in Polish forests [37].

A complete list of soil types and subtypes as well as a detailed share of oak species in each texture soil group is provided in Table 1 and the Supplementary Materials (Figures S1–S3).

An artificial form describing the habitat conditions (soil, climate, and location) in Poland is the forest habitat type (FHT), differentiating them into lowland, upland, and mountain varieties and, in terms of humidity, into dry, mesic, moist, and swampy types [39,40]. The share of *Q. petraea* and *Q. robur* between the different FHTs is shown in Figure 3.

Table 1. List of soil types related to oak stands.

No.	Polish Soil Type Symbol	Soil Type Name [38]	*Q. petraea*	*Q. robur*	Total	
			Area (ha)			%
1.	RD	Rusty soils (≈Brunic arenosols)	11,726.53	17,075.81	28,802.34	36.20
2.	BR	Cambisols	3283.9	10,009.01	13,292.91	16.70
3.	P	Luvisols	2003.56	9602.6	11,606.16	14.60
4.	OG	Stagnosols	268.65	9088.3	9356.95	11.80
5.	MD	Fluvisols	75.97	3868.94	3944.91	5.00
6.	G	Gleysols	285.02	2664.37	2949.39	3.70
7.	B	Podzols	705.45	1810.2	2515.65	3.20
8.	M	Murshic Histosols	261.87	3161.23	3423.10	4.30
9.	CZ	Chernozmes	91.23	1578.94	1670.17	2.10
10.	D	Colluvic Regosols	110.14	586.93	697.07	0.90
11.	R	Leptosols	0.5	36.62	37.12	0.00
12.	AK	Anthrosols	35.6	262.36	297.96	0.40
13.	C	Umbrisols, Phaeozems	1.15	118.1	119.25	0.10
14.	AU	Technosols	52.82	222.96	275.78	0.30
15.	PR	Calcaric Regosols	41.89	58.93	100.82	0.10
16.	AR	Arenosols	62.68	149.5	212.18	0.30
17.	T	Histosols	16.08	195.18	211.26	0.30
18.	RN	Dystric/Eutric Leptosols	4.73	0	4.73	0.00
19.	PE	Pelosols (≈Leptosols)		5.59	5.59	0.00
20.	Mł	≈Sapric Endofibric	0	15.76	15.76	0.00
21.	IS	Lithic/Nudilithic Leptosols		12.39	12.39	0.00
22.	OC	Rubic/Chromic Arenosols	1.94	5.14	7.08	0.00
23.	MDM	≈Fluvisols (Coastal marshes)		4.85	4.85	0.00
		Total (ha)	**19,029.71**	**60,533.71**	**79,563.42**	**100.00**
		Share (%)	**23.9**	**76.1**	**100.00**	

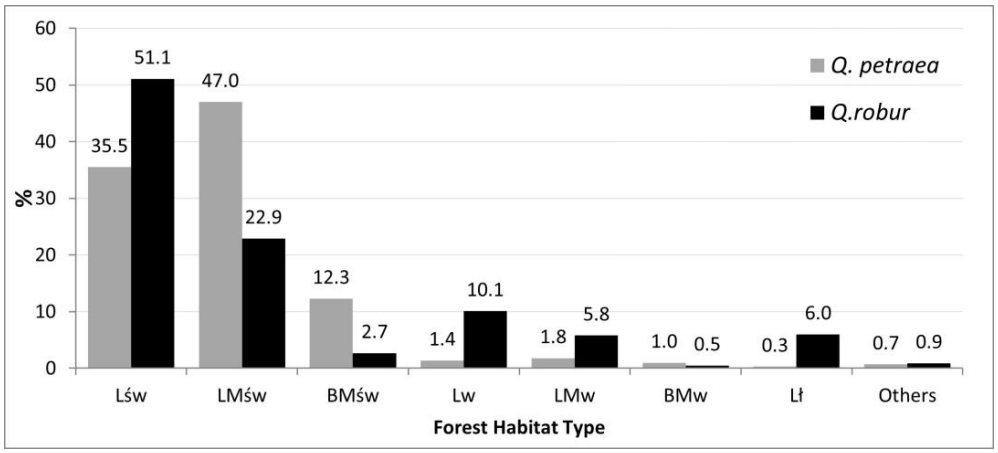


Figure 3. Share of pedunculate and sessile oaks stands according to forest habitat types. The chart shows only FHTs in which the share of oaks stands is higher than 1%. The original (Polish) symbols of the forest habitat types are used in the diagram: Lśw—fertile deciduous mesic forest; LMśw—mesotrophic, deciduous-dominated, and mixed deciduous–coniferous mesic forest; BMśw—poor coniferous-dominated and mixed coniferous–deciduous mesic forest; Lw—fertile deciduous moist forest; LMw—mesotrophic, deciduous-dominated, and mixed deciduous–coniferous moist forest; BMw—poor, coniferous-dominated, and mixed coniferous–deciduous moist forest; and Ł—alluvial forest.

Following the interpretation of the data presented in Figure 3, it should be noted that the dominance of the share of oaks in mesic habitats does not have to be the result of the preference of oaks only towards these habitats, but the effect of the general dominance of mesic habitats in Polish forests [41]. However, there are some differences between species that are worth noting. The presented data show that *Q. robur* dominates in fertile mesic (Lśw), fertile and mesotrophic moist (Lw and LMw), and alluvial (Ł) habitats. *Quercus*

petraea is more frequent in mesotrophic, deciduous-dominated, and mixed deciduous–coniferous mesic forest habitats (LMśw), while its presence is the poorest in deciduous tree species habitats in Poland, which, in general, correspond to coniferous-dominated, mixed coniferous–deciduous mesic (BMśw) and moist (BMw) forests. It is necessary to explain that coniferous-dominated mixed coniferous–deciduous mesic (BMśw) and moist (BMw) forests with oak stands should be interpreted as oak stands with the lowest height rate classes, usually preferred, in forest management, for potentially coniferous tree species (mainly *Pinus sylvestris*).

In order to minimize the impact of forest management, which could affects the species composition of the stands, in the assessment of the relationship between oak species and habitat conditions, the share of the oldest oak stands in Poland (>250 years, shown in Figure 4) between the various FHTs was also determined.

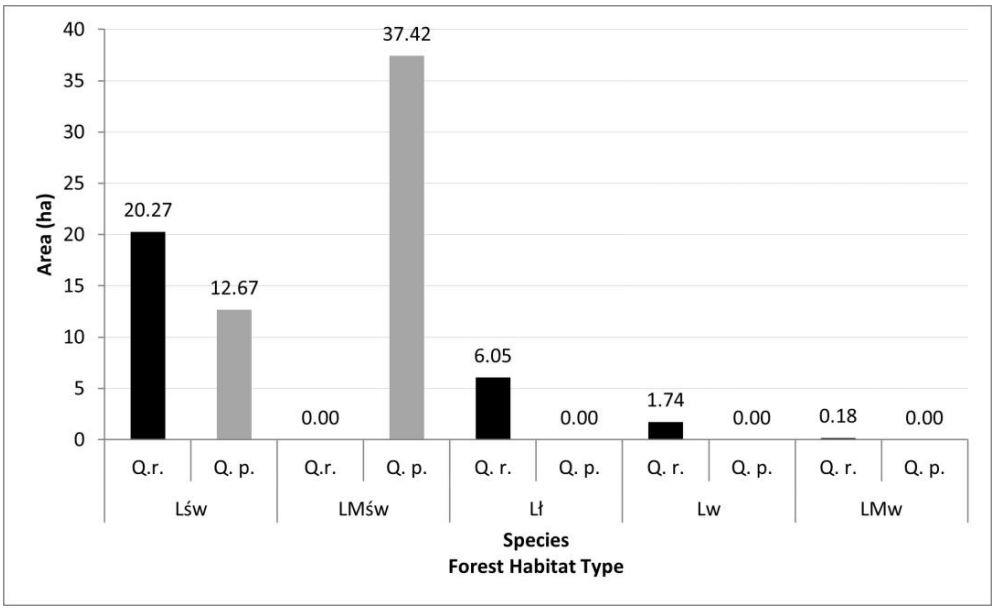


Figure 4. The area (in ha) of oak stands > 250 years old in forest habitat types. Q.r.—*Q. robur*; Q.p.—*Q. petraea*; Lśw—fertile deciduous mesic forest; LMśw—mesotrophic, deciduous-dominated, and mixed deciduous–coniferous mesic forest; Ł—alluvial forest; Lw—fertile deciduous moist forest; and LMw—mesotrophic, deciduous-dominated, and mixed deciduous–coniferous moist forest.

The compilation shows that share of the oldest oak stands in FHTs is similar to the results presented in Figure 3, so it could be assumed that it reflects the natural preferences of oaks more than the effect of human selection of species composition. It confirms that *Q. robur* prefers fertile and moist habitats, while *Q. petraea* occupies drier and mesotrophic habitats. *Q. petraea* at the age of >250 years was not found in the alluvial forests (Ł), deciduous moist forests (Lw), and deciduous-dominated mixed deciduous–coniferous moist forests (LMw). These data are correlated to soil requirements given in Table 1 where list of soil types related to oak stands was shown.

3.2. Effect of Habitat Conditions on the Growth of Pedunculate and Sessile Oaks

The relationship between FHTs as a result of habitat conditions and the growth of oaks is presented in Figure 5. As it has been shown, the highest growth rate classes (GRC) are achieved by both oak species in upland habitats (the lower GRC value, the higher the average stand height), but it should be emphasized that both in upland and mountain conditions the data are provided by a small number of stands. However, this illustrates the preference of both oak species for lowland habitats.

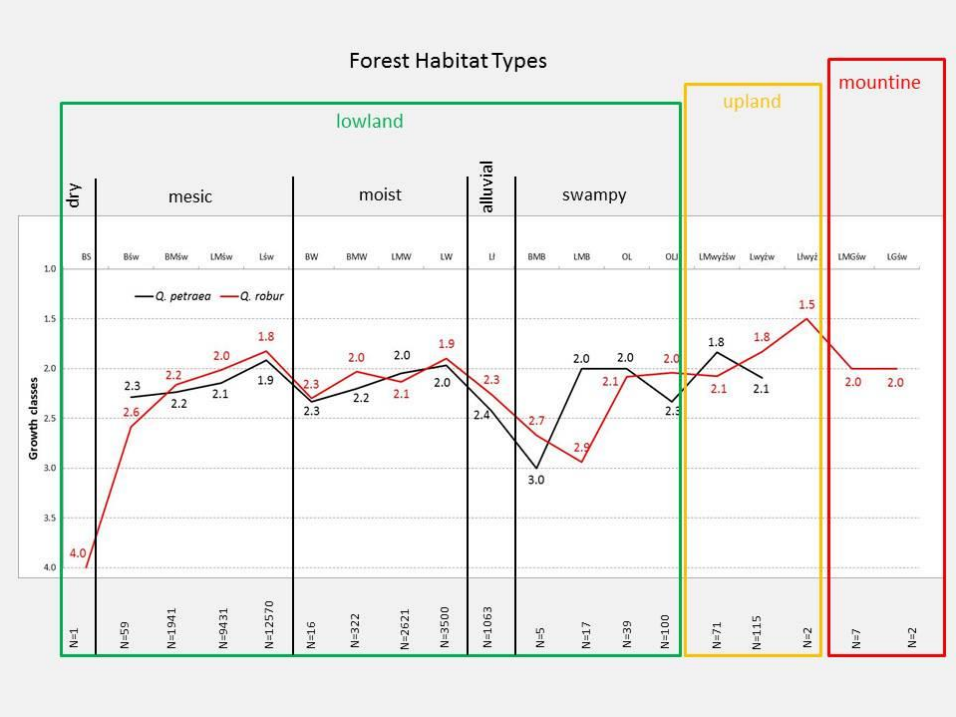


Figure 5. Differentiation of growth rate classes depending on the forest habitat types. On the bottom of the graph, the number of stands in the given FHTs is provided.

The lowest GRC was recorded in a dry forest habitat, represented by only one stand, which seems obvious as these are extremely unfavorable habitats for the growth of oaks, and theoretically it should not occur in such conditions at all. Generally dry forest habitats are covered in Poland only by pine forests.

Slightly better but still low GRCes were achieved for oak stands in boggy habitats associated with peat bogs, which are also very unfavorable conditions for the growth of both oak species. Generally *Q. robur* grows higher than *Q. petraea* (Figure 6), except in mesotrophic, deciduous-dominated, and mixed deciduous–coniferous moist forests (LMw).

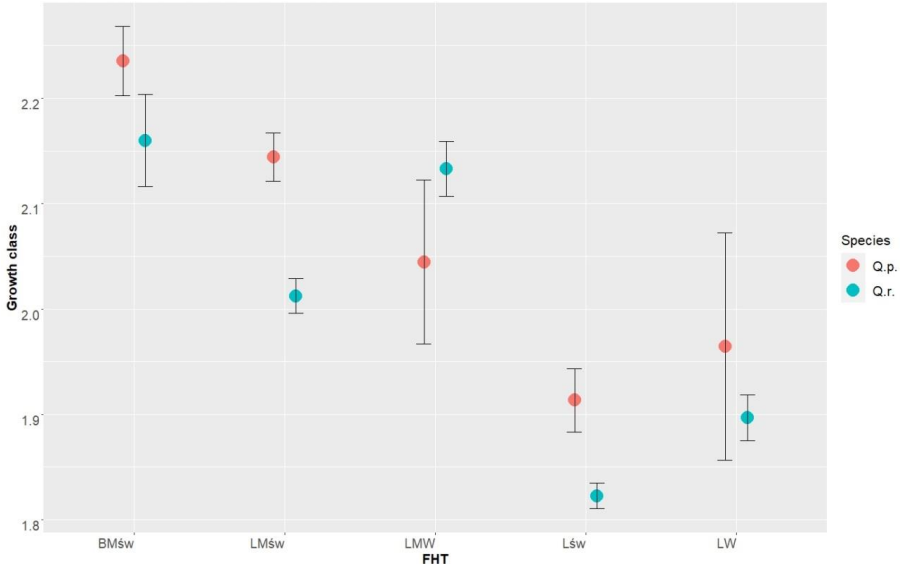


Figure 6. Growth rate classes in forest habitat types. Red dot—mean value for *Quercus petraea* (Q.p.); blue—mean value for *Q. robur* (Q.r.). The lower the growth rate class value, the higher the average stand height (i.e., stands with a value of 1.8 are higher than stands with a value of 2.2).

3.3. The Impact of Climate Change on the Growth of Pedunculate and Sessile Oaks

The hypothesis that a one-degree change in temperature leads to an increase or decrease in growth of oaks was tested with the use of ordinal regression. Furthermore, the hypothesis whether the result of a one-degree change in temperature is the same for the pedunculate oak (Q.r.) and for the sessile oak (Q.p.) was tested, too. The results of analysis are given on Figures 7 and 8.

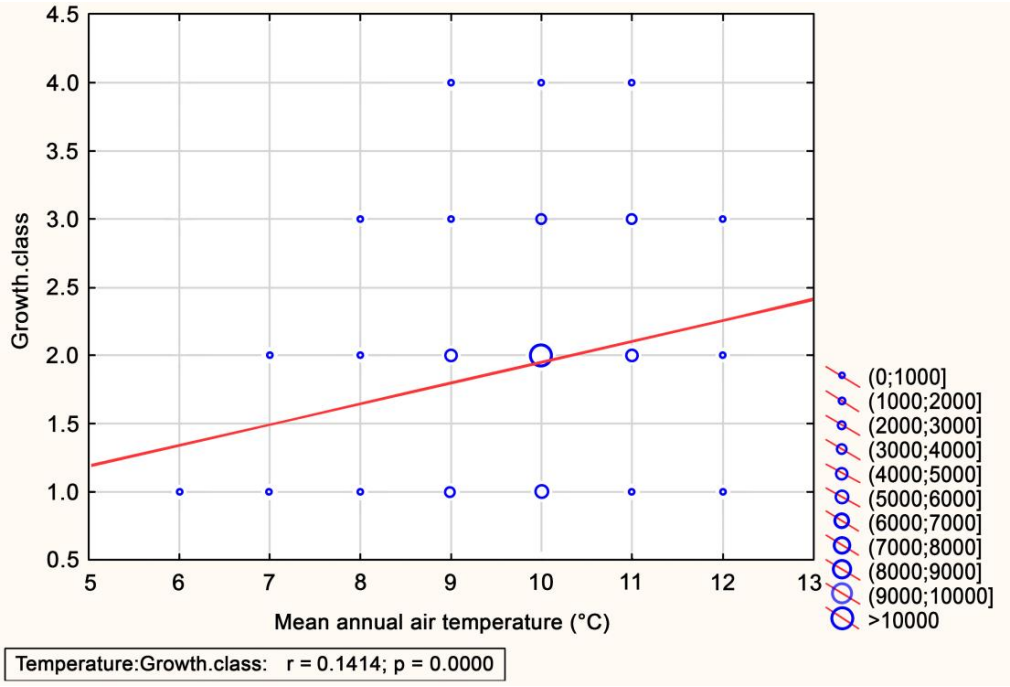


Figure 7. Scatterplot of growth rate class against temperature for *Q. robur*.

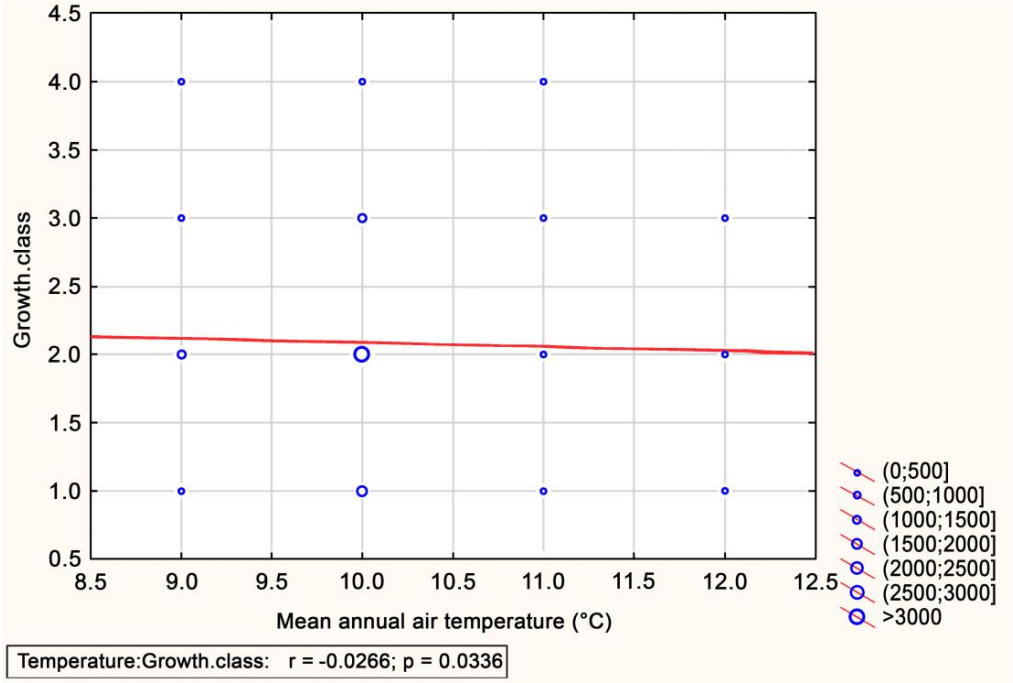


Figure 8. Scatterplot of growth rate class against temperature for *Q. petraea*.

The analysis of the relationship between the distribution of oaks in Poland and estimation using growth rate class ordinal regression on species and temperature indicates that,

generally, for both of oaks species (analyzed jointly—Supplementary Materials, Figure S4), an increase in temperature of 1 degree worsens their growth. However, in the current study, apart from the temperature factor, it was shown that pedunculate oaks had a statistically significantly higher quality than sessile oaks. Further separate analyses of both species presented in Figures 7 and 8 show that an increase in temperature of 1 degree may worsen mainly the growth of *Q. robur* and slightly improve the growth of *Q. petraea*.

3.4. Using NDVI to Assess Changes in the Condition of Oak Stands Depending on Precipitation

The condition and prospects of oak stands (and other species) ultimately, however, depend on atmospheric precipitation. This is shown on the example of the pedunculate oak complex located in the Krotoszyn Forest District (Figure 9).

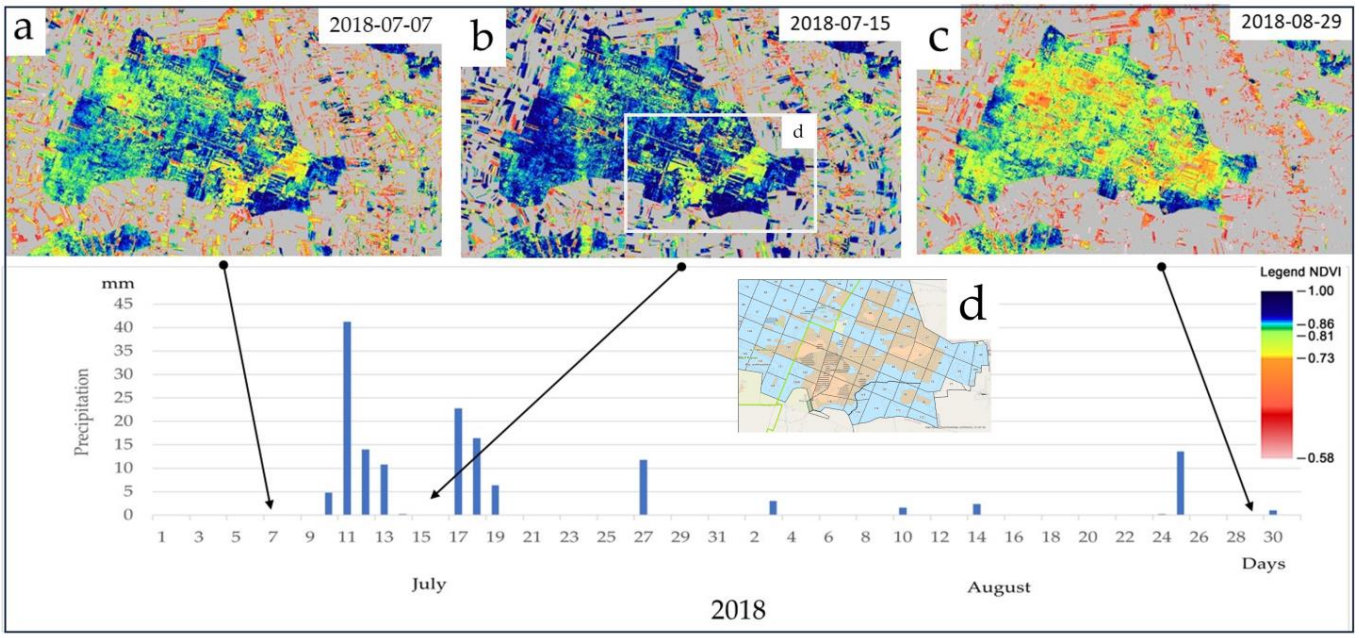


Figure 9. NDVI diversity images of pedunculate oak stands in the Krotoszyn Forest District for the following dates: 7 July 2018 (**a**), 15 July 2018 (**b**) and 29 August 2018 (**c**); in connection with precipitation in July and August 2018, for the Krotoszyn weather station (https://docs.google.com/spreadsheets/d/1baRDmFFOfIXxfel74otsDQLmUsYh8KM6aOc_BfMAlx8/edit?gid=1020198012#gid=1020198012; accessed on 29 September 2024); (**d**) presents a fragment of the soil map showing the difference between clayey soils (light blue) and sandy soils (brown); these differences are consistent with the NDVI, which has higher values in the clay area (**b**—dark blue) than in the sandy soils (**b**—yellow).

Figure 9 shows the changes in rainfall in July and August 2018. for the Krotoszyn weather station and the dependence of NDVI on rainfall. The figure clearly shows how oak stands react between 7 and 15 July to rainfall on 11–13 July (the intensity of the blue color indicating high NDVI increases) and how the NDVI value decreases after the drought in August 2018, which is marked by an increase in the yellow color. But the response of stands also depends on the soils they grow on. As shown in Figure 9d, among the dominant clay soils in the area shown in Figure 9, there are also small patches of sandy soils, where the NDVI values of the stands growing on them are significantly lower in each period shown in the Figure 9. It should be noted, however, that the area of sandy soils is covered mainly with pine stands, which also affects the NDVI value.

4. Discussion

As shown in this study, only 32% of the 95,906 analyzed oak stands had a specified species. The remaining 68% were stands of either pedunculate or sessile oaks or stands consisting of both species mixed in different proportions. The situation could be similar in

other countries. Hence, there may be a lack, in many papers [5,6,17,19], of unambiguous data that would allow researchers to definitively describe the habitat conditions of *Q. petraea* and *Q. robur*. Nevertheless, the analysis of 6220 stands of sessile oaks and 24,611 stands of pedunculate oaks in this study allowed us to show some differences between the habitat conditions of both oak species. The obtained data show that it cannot be unequivocally stated that both species "prefer fertile and moist soils" [17]. For both oaks, characteristic, sandy, mesotrophic, and mesic rusty soils were the dominant soil types (Table 1 and Supplementary Materials, Figure S1). In *Q. petraea* habitats, the domination of rusty soils over other types of soil was very high, while, in *Q. robur*, this percentage was much smaller. However, in pedunculate oak stands, a significant share of soils developed from loam was noted (Supplementary Materials, Figure S2), especially Stagnosols (OG—Figure S1), found mainly in one large complex of oak forests growing on this type of soil [42], described in detail in the monograph edited by Danielewicz [43]. In turn, the dominance of rusty soils in both oak species might have been the result of the general predominance of rusty soils in Polish forests [37], regardless of the type of stand.

It is also difficult to state unequivocally that *Q. petraea* prefers conditions of higher precipitation more than *Q. robur* [19], as both species of oak often appear in Poland in zones with the same sum of annual rainfall (Figure 2b).

As von Lüpke [30] and Collet et al. [29] demonstrated, the two oak species can occur in a mixture, often without obvious differences in growth rate and timber quality. This may be the reason why stands with undefined oak species dominate in the Forest Data Bank. The conducted research confirmed the theses contained in the studies of Höltken et al. [44], Neophytou et al. [45], Reutimann et al. [46], and Leroy et al. [47] that both species have a certain ecological niche in which their habitat requirements overlap.

It seems that the increase in the share of *Q. petraea* and *Q. robur* in Poland should be fostered by the observed climatic conditions. As suggested by Dyderski et al. [48], *Q. petraea* and *Q. robur,* in the context of climate change, are included in the group of "winners", while pines, which often replace oaks in mesotrophic habitats, are included in the group of "losers". Taking into account the distribution of oak stands in Poland in relation to the average annual temperature presented in Figure 2b, if the necessary minimum precipitation is maintained, their expansion into cooler regions of Poland could be expected, especially for *Q. petraea*, which currently reaches the eastern edge of Poland.

Our study may confirm the thesis of Friedrichs et al. [49] that *Q. robur* is more sensitive to climate warming than *Q. petraea*. As shown in the example figures from the Krotoszyn Forest District (Figure 9a–d), pedunculate oak stands growing on clayey soils dependent on precipitation (Stagnosols) react strongly to rainfall changes, a fact which is very well illustrated by the NDVI analysis.

The assessment of the impact of climate change on the growth and development of trees will always be difficult, due to their long life cycle, and, as Morin et al. [50] have shown, the phenological response of trees to climate changes may not be linear. The authors therefore suggest that predictions should not be built on extrapolations of currently observed trends. In this context, our research based on the analysis of stands in their natural conditions may be significant, especially since the oldest stands included in this study were over 250 years old. This means that these stands began to grow in conditions significantly different from the present ones. It can also be assumed that, in this context, our study stands out from other analyses of this type. Morin et al. [50] conducted their research on seedlings in controlled conditions. Similarly, Pilipović et al. [51] showed differences in the physiological response of pedunculate oak seedlings of different origins to drought. However, it can be assumed that, once water availability drops below the necessary minimum, individual differences cease to be significant, especially since, in natural conditions, one of the consequences of drought are forest fires. Interesting in this context are the results of the study by Kabaoğlu et al. [52], showing the differences in the response of *Q. pubescens* and *Q. cerris* to drought stress during the post-fire season. Both oak species covered by the study by Kabaoğlu et al. occur in Poland, but they were not

included in our study due to their incidental locations, which are statistically difficult to compare with *Q. robur* and *Q. petraea*. *Quercus pubescens* is present in only one location in Poland where it is considered natural, which is located at the western border of the country, while *Q. cerris* creates two stands each time and is considered a geographically alien species in Poland. Due to the status of *Q. pubescens* as a species under strict protection and its presence in only one location in Poland, it is difficult to conduct a wider range of studies comparing *Q. pubescens* to *Q. robur* and *Q. petraea*. However, in light of the results of the study by Kabaoğlu et al. and of the observed climate changes, the importance of *Q. pubescens* in Poland may increase in the distant future. The results of the study by Kabaoğlu et al. correspond to some results of Daas et al. [53], whereby the authors concluded that oak species from warmer regions would not display larger plasticity in response to increasing temperatures. However, the studies by Daas et al., similarly to the previously cited authors, are based solely on samplings tested in greenhouse conditions. In real conditions, the effects of climate change may differ over the long life cycle of trees. Therefore, studies conducted on stands across their entire ecological and age range are considered important.

It seems particularly important to establish criteria that determine the eastern limit of sessile oaks, which significantly differentiates them from the range of *Q. robur*. Bose et al. [54], analyzing tree rings of *Q. petraea* and *Q. robur*, showed that the growth of both oak species was more related to precipitation than temperature. However, when comparing the northeastern limit of the range of *Q. petraea* presented in Figure 1 with the diversity of climatic conditions in Poland (Figure 2), it seems that the northeastern limit of the range is more similar to the distribution of the length of the growing season (Figure 2c) than to atmospheric precipitation (Figure 2a). This is because there exists a zone in central Poland that has precipitation values similar to both the area of occurrence of *Q. petraea* and outside of it. Moreover, the sum of atmospheric precipitation in northeastern Poland is higher than in central Poland, which does not lead to the occurrence of sessile oaks.

The results of Konatowska et al. [55] show that sycamores (*Acer pseudoplatanus* L.), similar to the sessile oaks described in this paper, may expand their geographical range in Poland towards the northeast. The authors used NDVI, which seems to be a good tool for this type of analysis. NDVI was also used by Mašek et al. to conduct analyses [56]. This paper showed the negative response of NDVI to temperature, similarly to [57], which showed that NDVI is proportional to precipitation and inversely proportional to temperature. Our studies also show a positive response of pedunculate oaks to precipitation (Figure 9). Having said that, it seems obvious that water will always play a key role for living organisms, but only when the optimum temperature is maintained.

5. Conclusions

The analysis of the populations of pedunculate and sessile oaks in an area representative of Central Europe, such as Poland, showed that, although *Quercus robur* and *Q. petraea* have a wide common range of occurrence, there are clear differences in the habitat preferences of both species. *Q. robur* dominates fertile mesic, fertile moist, mesotrophic moist, and alluvial habitats. *Q. petraea* is more frequent in mesotrophic and poor mesic forests. This is reflected in the relationship between pedunculate and sessile oaks and soil types. *Q. robur* dominates in luvisols, stagnosols, fluvisols, gleysols, murshic histosols, and phaeozems. *Q. petraea* is more frequent in rusty soils (≈Brunic arenosols), acid cambisols, and podzols. This is connected to the soil texture. Pedunculate oaks prefer loam and loamy sands, while sessile oaks dominate sandy soils.

Our results show that, under similar site conditions, *Q. robur* grows higher than *Q. petraea*, except in mesotrophic, deciduous-dominated, and mixed moist forests.

Based on ordinal regression analysis and the analysis of chosen oak stands using the Normalized Difference Vegetation Index (NDVI), it was concluded that that an increase in air temperature of 1 °C may impair the growth of *Q. robur* and slightly improve the growth of *Q. petraea*. This may indicate the possibility of expanding the geographic range of sessile

oaks towards the east and northeast under warming climatic conditions, provided that appropriate moisture conditions are maintained.

6. Patents

The article was not created on the basis of any patents.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/rs16214094/s1: Figures S1–S4.

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