Monitoring effects of drought on nitrogen and phosphorus in temperate oak forests using machine learning techniques

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Abstract: Oak is a European tree species highly sensitive to drought. If declining symptoms appear they are often detectable at the crown (such as dieback) enabling monitoring using aerial images and remote sensing methods. Here, we analyzed the impact of short and long-term drought on oaks located in central Poland, between the years of 2014 and 2017. We used leaf nitrogen (N) and phosphorus (P) concentrations measured in the laboratory, aerial images collected in the range of 460-880 nm and machine learning techniques to estimate nutrient concentrations on the > 4000 oaks growing on gleysoil in the study area. We determined a negative impact on N and P concentrations during both types of drought stress (-23% and 19% for N concentration in leaves; -27% and -10% for P concentration in leaves) and an inconsiderable impact on N:P values (3% increase of N:P ration during short and 7% decrease of N:P ration during long-term drought stress). We found that the long-term drought impact was spatially diverse, possibly depending on the presence of drainage ditches and competing species.

Keywords: drought, oak, nitrogen, phosphorus, remote sensing, machine learning

1. Introduction

Forsts are the most vulnerable terrestrial ecosystems in terms of a loss of health due to climate change, which is projected to be a dominant stressor on terrestrial ecosystems in the second half of the 21st century [1]. Increasing temperatures and drought stress have negative impacts on forest diversity, structure, function, health and distribution [2], as well as services to humanity (i.e. economic value) [3]. Forest growth rates are significantly correlated to climate [4], and strongly influenced by water availability [5].

Oak is one of the European tree species more sensitive to drought, and may show decline symptoms at the crown [6]. Oak forest stands in Europe and America were repeatedly reported as sensitive to drought phenomena [7–14]. It is expected that within the next 50–100 years, the mean drought duration in Europe will become considerably longer, the drought period frequency and duration variability will increase and extreme climate events will be more common [15]. In Poland, examples of the local drought impact on forest ecosystems are investigated for the Primeval Forest of Białowieża [16], the Niepołomice oak forest [17], the oak stands of the Krotoszyn Plateau [9] and the Silesian Beskid mountain range area [18]. The projected changes in climate may occur much faster than the rate at which species and ecosystems are able to adapt [19], and as a result, present forest ecosystems will be affected by new environmental conditions. This raises the question of whether ecosystems will be able to adjust, or if their health will decay, resulting in deforestation [20] and changes in specie distributions [21].

The results of measurements carried out by terrestrial and laboratory methods in the literature unambiguously confirm the occurrence of drought phenomena in Poland during the 2015 growing
season. The effects of agricultural drought were the greatest in the Wielkopolska district (west Poland),
with a duration of 100 days. The effects on the soil from the drought were also the greatest in this
area compared to the rest of the country, and the soil water deficit lasted for more than 30 days [22].
The sum of the monthly precipitation measured during the 2015 growing season was 55% lower than
during the 2014 growing season, 25% lower than during the 2016 season and 45% lower than in 2017
(see Figure 1). Field surveys during summer 2016 confirmed huge water shortages in the previous
season (2.5 times lower water levels, on average) [23].

The effects of predicted climate changes on nutrient availability for forests ecosystems are still
not fully understood [25–27], but most climate scenarios forecast that much of the global land area
will experience increasing aridity [28]. In general, nitrogen and phosphorus capacity, as well as other
nutrients, will increase under elevated CO2 levels [29]. Predicted atmospheric CO2 concentration
elevations will result in a warming of an average of 1–3.5°C for mid-latitude regions [30], with more
frequent and longer droughts. This plant stress factor strongly affects the growth, gas exchange, cells
division, phytohormones production, and the metabolic and transport processes in plants [19,31].

Nitrogen (N) and phosphorus (P) are critical determinants of plant growth and productivity. Both
N and P are important nutrients for the structure, processes and functions of the ecosystem, as their
availability limits biomass production [32,33]. An increase in the frequency of drought is likely to
reduce the supply and uptake of nutrients and change their redistribution in soils [34,35]. The amount
of available N and P limit plant growth, and thus understanding the N and P cycles under new climatic
conditions, including forests' response to droughts, becomes very important.

The meta-analysis of 155 plant observations from 25 papers prepared by He & Dijkstra in
2014 confirmed that drought stress (DS) duration results in negative effects on N (-3.73%) and P
concentration (-9.18%), and a positive effect on plant N:P (+ 6.98%) [36]. In response to drought stress,
enhanced N and P limitation on plant growth (P more than N) may affect plant growth, yet these effects
are stronger during short-term drought (less than 90 days) and are transient [37]. During long-term
drought stress, water availability is the main factor of limiting plant growth [37].

Plant N and P have been used to indicate whether plant growth is limited [38]. Meta-analysis
done by He & Dijkstra indicates that drought stress generally decreases plant N and P, but increases
plant N:P. The increase in soil available N and decrease in soil available P may contribute to the increase
in plant N:P in response to DS, but number of soil observations in those meta-analysis was limited.
DS may enhance N and P limitation on plant growth (P more than N), but that these effects may be
only transient. Plant growth may be limited by N and P with increased long-term DS; instead, water availability may become the main driver for reduced plant growth with increased long-term DS [36]. In the present paper, the effect of drought on the nutritional status of oak (*Quercus robur* L.) is demonstrated. We collected data during three growing seasons: 2014, 2015 (drought season) and 2017.

Using in-situ data collected in 2015, aerial images from 2014, 2015 and 2017, and machine learning algorithms, P and N concentrations were estimated for oak stands located on the Krotoszyn plateau; the region where forests stands were affected in 2015.

2. Materials and Methods

2.1. Temperature and precipitation monitoring

Meteorological data was obtained from the meteorological data sharing service at the Institute of Meteorology and Water Management — National Research Institute in Warsaw [24]. Average temperatures and sums of precipitation were calculated for each month, between 2014/01 and 2017/12 (see: Figure 1).

2.2. In-situ and remote sensing data

The N and P concentrations in the leaves of 54 oaks (*Q. robur* L.) selected on the experimental area, near Krotoszyn (51.7037 N, 17.5650 E), Wielkoposka region, were investigated in-situ during the course of the growing season in 2015. Oak stands cover a total surface of 11,200 acres, with gleysoil and fresh type soil moisture. Common oaks are mainly observed: 123 –133 years old on the north and west part of the area and 60–75 years old on the south and west part and 89 years old pine on the east side. All oak heights were found to be between 29– 30 m.

Oak leaves were taken from the luminous part of the crowns by alpinists. The leaves were secured in plastic bags and transported at 4°C to the laboratory. Chemical analysis of the oak leaves was carried out in the chemical laboratory of the Department of Agricultural Chemistry at the Life Sciences University in Warsaw. Soil samples were collected two times during the growing season in 2014 and 2015 (May and July). Each sample was collected under the selected oak tree from a 0.5 m depth, placed into plastic bags and transferred to the Chemical and Agricultural Station in Warsaw, where the chemical analysis of the soil samples was performed.

In 2014, 2015 and 2017, photogrammetric flights over the HESOFF Project test areas was performed using the QUERCUS.6 multispectral platform [39]. Three optical (460, 550 and 640 nm) and two near-infrared bands (730 and 820 nm) were used to make measurements during the flights. From the collected data, three 5-color orthophotomaps were prepared using ArcGIS software, with a 0.25 m resolution.

In the years of 2014-2015, flights over the research areas were carried using the Cessna 152 and Cessna 182 aircrafts, while in 2017, an ultra-light VL3 platform was used. The images were acquired with a block of non-metric cameras designed for remote sensing applications within the spectral range of 400-1000 nm. This had no influence on the quality of the data, as the usefulness and interpretative potential of the studies is no worse than in the case of using typical pre-calibrated cameras [40]. The loading parameters were selected based on the available parameters of the platform, i.e. the geometric and time resolution (particularly important for the channels at 760 and 850 nm). It was decided that the ground sampling distance (GSD) sufficient for remote sensing tests was 0.25 m, with single image dimensions of 1200 x 804 pixels. Due to the high shooting height, the focus was set as infinity. The total error values of the obtained orthophotomaps did not exceed 0.1 m [41].

2.3. Tree crown separation

The segmentation of tree crowns consisted of determining single crowns from the differential elevation model nDSM (calculated by subtracting the digital terrain model (DTM) from the digital surface model (DSM)). This model was generated from a point cloud established using ArcGIS Desktop...
Software from the matching of the acquired images, using the QUERCUS.6 platform with a GSD of 0.25 m [41]. The watershed algorithm operating on the nDSM was used for the segmentation of tree crowns [42].

2.4. Machine learning

Following this, the tree crown segmentations of all 54 oaks with known nitrogen and phosphorus concentrations in the leaves were selected. The average reflectance and reflectance variability was calculated for the five bands. This data was used as the learning set [43–48] in the linear regression with multiple variables (LRMV) machine learning algorithm [49–54]. Finally, by applying the gradient descent method with a step precision of $\delta = 3 \times 10^{-7}$, the N P leaf concentrations was calculated as:

$$h_\theta(\tilde{x}) = \tilde{\theta} \cdot \tilde{x}$$

where $h_\theta$ is calculated nutrient concentration in the tree leaves, $\tilde{x}$ is a vector describing tree reflectance and the standard deviation of the reflectance in the five wavelengths, defined as:

$$\tilde{x} = \begin{bmatrix} \hat{I}_{460 \text{ nm}}, \sigma_{460 \text{ nm}}, \hat{I}_{550 \text{ nm}}, \sigma_{550 \text{ nm}}, \hat{I}_{640 \text{ nm}}, \sigma_{640 \text{ nm}}, \hat{I}_{730 \text{ nm}}, \sigma_{730 \text{ nm}}, \hat{I}_{820 \text{ nm}}, \sigma_{820 \text{ nm}} \end{bmatrix}$$

is the scalar product and the $\tilde{\theta}$ parameter vector minimize the cost function $J$:

$$J(\tilde{\theta}) = \frac{1}{2n} \sum_{\text{tree}} h_\theta(x_{\text{tree}}) - V_{\text{tree}}^2$$

where $n$ is the number of the samples in the learning set (54 here) and $V_{\text{tree}}$ is the in-situ nutrient concentration of the tree.

2.5. Nitrogen and phosphorus concentration estimation

N and P concentrations in 2014, 2015 and 2017 were estimated using equation 1 for all tree crowns separated as detailed in section 2.3. All trees were categorized into three categories (nutrient concentration deficiency, sufficient concentration, optimal concentration) using nutrient concentrations values described in the Wawrzoniak report, page 77 [55]: N concentration deficiency below 15 g/kg, sufficient N concentration between 15 and 25 g/kg and optimal N concentration over 25 g/kg; P concentration deficiency below 1.0 g/kg, sufficient P concentration between 1.0 and 3.0 g/kg and optimal P concentration over 3.0 g/kg.

3. Results

The chemical analysis of the soil samples in July 2014 showed an average N content of 0.12 g/kg and P content of 3.14 g/kg. The following year, the concentrations of N and P were calculated as 0.14 and 4.3 g/kg soil, respectively. Note that data was not obtained from 2017. All of the trees selected for the training set for the deep learning algorithm belong to the north-west part of the stand (see: Figure 2), located within the 4 divisions of the Forest Data Bank described in Table 1. The machine learning training set for the P and N concentrations measured in 2015 and the corresponding remote sensing data are described in Appendix A.

Two linear models were determined using the machine learning algorithm. For phosphorus $\tilde{\theta}_p = [0.142, 0.345, -0.090, 0.130, -0.214, -0.219, 0.301, -0.021, 0.053, 0.014, -0.079]$ with a cost function of $J_P = 0.088$ and for nitrogen $\tilde{\theta}_N = [0.164, 0.503, 0.065, 0.0254, 0.170, 0.095, 0.056, 0.151, 0.255, 0.264, 0.185]$, with $J_N = 0.252$.

The watershed algorithm separated 4,721 tree crowns with an average area of 21.52 m$^2$. Results obtained from the deep learning algorithm and multispectral images indicate that the N concentration in oak leaves calculated using equation 1 were on average: 28.88(±5.03) g/kg in 2014, 22.11(±4.05)
Figure 2. A total of 54 oaks (Q. robur L.) belonging to the training set of the deep learning algorithm marked on the ortophotomap (false color: 730nm, 550nm, 640nm) obtained from QUERCUS 6 multispectral platform in July 2015. Forest divisions marked.

Table 1. Soil and forest parameters of the forest divisions used for the training set, containing 54 oaks.

<table>
<thead>
<tr>
<th>Division</th>
<th>Stock [m$^3$ ha$^{-1}$]</th>
<th>DBH [cm]</th>
<th>Main species</th>
<th>Admixture species</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBS128</td>
<td>375</td>
<td>47</td>
<td>Q. robur (100%)</td>
<td>Carpinus betulus L., Tilia cordata Mill., Acer pseudoplatanus L.</td>
</tr>
<tr>
<td>DBS98</td>
<td>283</td>
<td>37</td>
<td>Q. robur (60%), Pinus sylvestris (20%), Carpinus betulus (20%)</td>
<td>Carpinus betulus L.</td>
</tr>
<tr>
<td>DBS134</td>
<td>385</td>
<td>42</td>
<td>Q. robur (100%)</td>
<td>Carpinus betulus L., Fagus sylvatica L.</td>
</tr>
<tr>
<td>DBS124</td>
<td>375</td>
<td>42</td>
<td>Q. robur (100%)</td>
<td>Carpinus betulus L., Fagus sylvatica L.</td>
</tr>
</tbody>
</table>
Table 2. Average nitrogen and phosphorus concentrations and N:P in oak leaves in separated divisions in 2014, 2015 and 2017, estimated using a deep learning algorithm and multispectral images acquired from the QUERCUS.6 platform.

<table>
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</thead>
<tbody>
<tr>
<td>DBS142</td>
<td>28.39</td>
<td>21.92</td>
<td>23.83</td>
<td>1.95</td>
<td>1.53</td>
<td>1.79</td>
<td>15.42</td>
<td>15.19</td>
<td>14.85</td>
</tr>
<tr>
<td>DBS134</td>
<td>28.39±(4.96)</td>
<td>22.02±(4.62)</td>
<td>22.70±(5.03)</td>
<td>2.01±(4.05)</td>
<td>1.58±(4.03)</td>
<td>1.87±(4.03)</td>
<td>15.17±(6.69)</td>
<td>14.78±(6.69)</td>
<td>13.19±(6.69)</td>
</tr>
<tr>
<td>DBS98</td>
<td>28.28±(4.86)</td>
<td>21.88±(5.03)</td>
<td>22.90±(5.13)</td>
<td>1.98±(5.03)</td>
<td>1.59±(5.03)</td>
<td>1.89±(5.03)</td>
<td>15.21±(5.31)</td>
<td>14.70±(5.31)</td>
<td>13.24±(5.31)</td>
</tr>
<tr>
<td>DBS128</td>
<td>28.81±(5.28)</td>
<td>21.97±(5.03)</td>
<td>23.53±(5.13)</td>
<td>2.10±(5.03)</td>
<td>1.55±(5.03)</td>
<td>1.74±(5.03)</td>
<td>14.86±(5.18)</td>
<td>15.06±(5.18)</td>
<td>15.09±(5.18)</td>
</tr>
<tr>
<td>Average</td>
<td>28.88±(5.03)</td>
<td>22.11±(5.03)</td>
<td>23.42±(5.13)</td>
<td>2.12±(5.03)</td>
<td>1.56±(5.03)</td>
<td>1.91±(5.03)</td>
<td>14.68±(5.13)</td>
<td>15.11±(5.13)</td>
<td>13.63±(5.13)</td>
</tr>
</tbody>
</table>

N concentration decreased in all tested forest divisions during drought periods by an average of 6.76±(±0.63) g/kg in 2015 and 5.45±(±0.63) g/kg in 2017. The largest decrease in 2015 was observed in the DBS128 division (average -6.83 g/kg). The other N concentration decrease was similar (-6.37 -6.47 g/kg) for the other three divisions. In 2017, the smallest reduction of N concentration was observed in leaf samples from the DBS134 division (-4.55 g/kg), with the other three divisions experiencing similar decreases (-5.28 up to -5.70) (Table 2).

Similarly, the P concentration in oak leaves decreased in all tested forest divisions during drought periods by an of average 0.56±(±0.65) g/kg in 2015 and 0.21±(±0.62) g/kg in 2017. The greatest decrease in 2015 and 2017 was observed in the DBS128 division (average of -0.55 g/kg in 2015 and -0.36 in 2017), with the other three divisions experiencing similar reductions(average of -0.39 up to -0.42 g/kg in 2015 and -0.09 up to -0.16 g/kg in 2017)(Table 2).
Figure 4. Classification of trees due to the phosphorus concentration in leaves before drought (2014), during short-term drought (2015) and during long-term drought (2017). P concentration: red — below 1.0 g/kg, blue — between 1.0 and 3.0 g/kg, green over 3.0 g/kg.

The nitrogen to phosphorus ratio (N:P) in oak leaves from the divisions DBS124, DBS134, and DBS98 were the lowest in 2014 (average of 15.42 ± 4.77; 15.17 ± 5.11 and 15.21 ± 4.59, respectively), lowest in 2015 (average of 15.19 ± 5.02; 14.78 ± 4.87 and 14.70 ± 5.12, respectively) and the lower in 2017 (average of 14.85 ± 6.69; 13.19 ± 5.53; 13.24 ± 5.27, respectively). In the DBS128 division, a different situation was observed; N:P increased during the observation years. In 2014, an average 14.86 ± 5.31 was found, with the ratios in 2015 and 2017 having similar values (average of 15.06 ± 5.18 and 15.09 ± 6.70, respectively (Table 2, Figure 5).

4. Discussion

Forest stands constitute approximately 82% of terrestrial biomass and over 50% of terrestrial biodiversity. They fulfill many key functions in mitigating climate changes, provide the circulation of nutrients, carbon sequestration, water and air purification, and wood production. Forecasted changes in climate predict an increase in the frequency and elevated drought duration on a global scale, which may affect the availability of nutrients for tree growth and sustainability, productivity and the function of forest ecosystems [36].

Drought stress, in general, reduces nutrient availability in the soil, uptake by roots, transport from roots to shoots and partitioning in plants (because of restricted transpiration rates and impaired active transport and membrane permeability) [56–58]. Water stress reduces plant growth by affecting various physiological and biochemical processes, such as photosynthesis, respiration, translocation, ion uptake, carbohydrates, nutrient metabolism and growth promoters [59,60].

4.1. Machine learning model interpretation

Nitrogen deficiency in plants is associated with many negative effects, such as growth inhabitation, and the yellowing of the leaves, as a result of disturbed chlorophyll synthesis. Calculations from the machine learning algorithm model reflect this phenomenon with a positive factor related to the green wavelength (+0.254, 4th component of $\theta_\mathcal{K}$). Chlorophyll synthesis reduction also causes a fall in the infrared reflectance (over the “red edge”; the 880 nm optical band in our case). This observation is
Figure 5. Classification of trees due to the N:P value before drought (2014), during short-term drought (2015) and during long-term drought (2017). N:P values: green below 8.33, grey between 8.33 and 15.0, blue over 15.0.

Nitrogen (N) is a key nutrient for the growth and development of plants as it is involved in the synthesis of chlorophyll, amino acids, nucleic acids and proteins. Water stress can reduce the available N uptake, resulting in the reduced production of nitrogen compounds [63]. Phosphorus (P) is an important macronutrient that, in addition to its structural function, increases the ability of plants to tolerate drought stress [37,64]. Phosphorus contributes to the prolongation of the root system and causes modifications of physiological, morphological and biochemical processes, positively influencing plant growth during drought [33,65,66]. Most of the published studies investigate the relationship between drought stress and N and P uptake by agricultural crops plants. Much less attention has been paid to assessing the relationship between drought and conversion of N and P in forest trees; an interesting area of research as it is related climate change projections.

Extensive research on the impact of drought on the availability of N and P on the growth of woody tree species was carried out by He and Dijkstra in 2014. Drought stress manipulation was grouped into four types: constant-stressed type, drying and rewetting cycling type, prolonged drying type and intermittent drying type, and the average impact on N concentration for all of four types was then calculated [36]. The drought stress in 2015 from our research may be described as intermittent drying, short-term type. Precipitation was slightly higher in 2016 (see Figure 1), however still significantly lower than in 2014 and 2017. The 2017 case can be described as long-term intermittent drought stress. Below, our results are interpreted according to the categorization from He & Dijkstra.

4.2. Nitrogen and phosphorus concentration decrease: short-term drought case

According to the results of He & Dijkstra, the DS effect on N and P concentrations was a decrease in concentrations by 10.2 (±6.2)% and -18.1 (±8.9)%, respectively. In our study, a strong effect of drought...
on nitrogen and phosphorus levels in oak leaves was observed. The reduction in 2015 of nitrogen and phosphorus was -24% and -26%, respectively, compared to 2014 (without drought symptoms), while the soil amounts for both nutrients were sufficient (0.14 N and 4.30 P g/kg of soil in 2015). The uptake of nitrogen and phosphorus was disturbed because drought, decreased the soil water availability for external mycelium of mycorrhizal fungi in roots. The efficiency of nutrient uptake from soil is affected by the mycorrhizal community associated with fine roots of trees [67]. Ectomycorrhizal (ECM) communities play key role in belowground carbon flux and turnover, mycorrhizosphere microbial activity, organic matter, and have a significant effect on the ECM communities of oaks (Quercus petraea, Q. robur) throughout Europe [67–69]. ECM can improve nutrient acquisition, particularly phosphorus (P) and nitrogen (N) [69,70]. It is still unclear if fluctuations in nutrition availability directly affect the fungi, or whether changes in community structures are mediated via the host plant. Moreover, it has been concluded that nitrogen deposition can alter plant community composition by changing the community of mycorrhizal fungal symbionts [71]. Many studies have shown that the extent of ectomycorrhizal symbiosis within plant roots can be negatively affected by drought, with the effect of this impact noticed in the tree crowns [67,69,72].

Our results indicate a greater effect of drought on N concentrations than in the He & Dijkstra study (< -20%) in all four forest divisions. Under drought conditions, water saturated soil is a reduced chemical environment and may also shift to an oxidized state. During drought, nitrogen can be compromised by micronutrients combining with macronutrients, forming a perfect storm that adds strength to the basic stress effect. The soils of oak stands on the Krotoszyn Plateau belong to the Haplic Gleysol class, with the predominance of clay and low permeable parent rock, characterized by the highest content of C and N in surface layers (up to 40 cm depth), and groundwater at a depth of about 1 m [9,23]. A short but strong drought in 2015 resulted in a reduction of groundwater levels by 2-2.5 m (local consultation) and was a serious stress factor with the ability to significantly affect the microbial community associated with oak fine roots and nutrition uptake.

Studies on the impact of drought on European oaks depending on the type of soil were conducted by Hu et al in 2015 who observed a varied response of seedlings of three Central European oak species (ie Q. robur, Q. petraea, Q. pubescens) for drought depending on the length of its duration and type of soil (in example acidic and calcareous). In response to droughts, they found an increase of the potassium content and N-soluble N-protein concentration at the expense of structures of N compounds in the leaves of all three oak species, but the intensity of the stress reaction varied depending on the species and soil. Q. robur was the most sensitive to drought stress among the species studied. In all oaks, worse reactions were observed in the acidic soil for drought in comparison to the calcareous

Hu et al. (2015) [73] indicated that reaction intensity of foliar N metabolism to the drought-rewetting course was also highly dependent on soil substrate. They also observed that short drought event was not intense enough to induce significant changes, but the repeated drought event applied significantly induced the formation of more N-soluble protein and amino acids.

The dependence between the soil type and the intensity of the Central European oak response to drought stress was also confirmed by study Madeleine S. Günthardt-Goerget al, 2012 [74]. On the other hand, Li et al., 2012 did not notice any significant influence of drought and temperature increase on N content in Q. robur and Q. petraea leaves observed in Switzerland [75]. The researchers also found no influence of the provinces and soil types. Based on the results they obtained, they found that both Quercus species tested are less sensitive, because of their distribution covering a wide range of geographical and clear, moderate climate change in Switzerland and moderate global warming will not negatively affect N and carbon physiology of Q. robur and Q. Petraea [75].

Two oak divisions with almost the same trees parameters — DBS128 and DBS124 — were characterized by different N concentrations before drought. The main difference between them is the mixture species: pine, beech and hornbeam in DBS124 and hornbeam, lime and sycamore (A. pseudoplatanus) in DBS128. Inter-specific competition during drought stress periods between A.
pseudoplatanus and the other species results in the reduction of maple [19]. Our results may indicate the same process.

Our results have shown that P concentrations decreased in 2015 by 0.56 g/kg (19.9–26.1% less than observations from 2014). As in the previous case, the highest P concentration was observed in the DBS128 division and in this case, the highest decrease (-0.55 g/kg) was observed. Unlike nitrogen, the highest values in 2014 were observed at a distance of <50 m from the cultivated fields in the west part of the forest. The highest P concentration increase was observed in the divisions DBS98 and DBS132.

The nitrogen to phosphorus ratio (N:P) for the three divisions DBS124, DBS134, DBS98 decreased in 2015 (compared to results from 2014), while for the DBS128 division, the N:P ratio increased. An increase in the N:P ratio due to drought stress was also observed by He and Dijkstra (2014) [36] and Sardans et al., 2008 [76]. This increase occurs due to the greater reduction in amount of phosphorus leaf levels compared to nitrogen. In contrast, Herzog et al., 2014 [77] did not observe a fall in P concentrations in pine forests due to drought stress.

4.3. Nitrogen and phosphorus concentration decrease: long-term drought case

We observed an increase N and P concentrations in all of the divisions increased in 2017; 1.31 (±3.53) g/kg for N and 0.35 (±0.54) g/kg for P. Yet this was not homogeneous for all forests divisions. According to the nutrient concentrations in 2017, the forests divisions were grouped into two main class:

1. DBS124 and DBS128, characterized by highest N concentrations (>23.5 g/kg), lower P concentrations (< 1.80 g/kg) and an N:P index close to 15.0.
2. DBS98 and DBS134 characterized by N concentrations < 23.0 g/kg, P concentrations >1.85 g/kg and an N:P index below 13.5.

It should be noted that the long-term drought stress impact on N concentrations was the lowest in the DBS124 division (average of -4.55 g/kg in 2017 according to basic 2014 value) and the N concentration increase between 2015 and 2017 was the highest (average of +1.91 g/kg). An interesting case is the DBS128 division, which was the most sensitive in terms of short-term drought stress, yet N concentrations between 2015 and 2017 also increased also significantly in this division (average of +1.56 g/kg). We can see that these two similar divisions reacted differently to short-term drought stress, yet similar observations were made for long-term drought stress. We can see in Figure 3 that in 2017, there were many trees with an optimal N concentration (over 25 g/kg) on the eastern parts of the two divisions, where drainage ditches are present. It is not possible to observe the dichotomy in the central divisions of the forest, as the area with the drainage ditch is in this division (DBS98) is overgrown with pine trees, not oaks. Our results may confirm the role of forest drainage for nitrogen and water availability [78,79].

In addition, phosphorus concentration changes are not homogenous. We may observe the long-term drought stress impact on P concentrations in DBS98, DBS124 and DBS134 as between an average of -0.16 and -0.09 g/kg. A different situation is observed in DBS128, as with the short-term drought stress case, P concentration negative change is stronger: an average of -0.36 g/kg. This value is more in line with the short-term drought stress case. As with the nitrogen concentration, we may observe a dichotomy in the DBS124 and DBS128 divisions, but a particularly large number of trees with insufficient P concentrations (an average of 5.9% of all trees in the division) was present in the DBS128 division along the drainage ditch (see: Figure 4).

In general, phosphorus concentrations increased between 2015 and 2017. Our results are consistent with the observations of He & Dijkstra, i.e. the long-term drought stress impact on P concentrations (given as -1% by He & Dijkstra and -9.9% in our study) is smaller than the short-term impact (-18% in He & Dijkstra, -26.6% in our study). Analyzing high spatial resolution aerial pictures is important for the selection of the sets of single trees with varying P and N concentrations due to additional factors, such as the occurrence of nutrients, competing species, soil type or drainage ditches.
5. Conclusions

1. Using laboratory N and P concentrations in leaf measurements as a learning set, multispectral aerial images of the whole forest stand, including trees for which measurements were performed and machine learning techniques, it is possible to estimate nutrient concentrations for significantly more trees regarding to 54 trees described in Training Set and observe phenomena for which spatial variability is an important factor.

2. During drought stress, N concentrations decreased by 23% in short-term drought stress and by 19% in long-term drought stress. Gleysoil negatively influenced N concentrations during drought by shifting the reduced chemical environment to an oxidized state, with the occurrence of inter-species competition or was affected by the mycorrhizal community associated with the fine roots of trees.

3. During drought stress, P concentrations decreased by 27% in short-term drought stress and by 10% in long-term drought stress. Our results were consistent with the He & Dijkstra meta-analysis.

4. The N:P value increased during short-term drought and decreased during long-term drought, in line with the results of He & Dijkstra, however with more stable N:P values (+ 3% and -7% respectively).

5. Our results are adequate to oak monocultures, and conclusions may not be suitable for more diverse forest stands.

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