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Extreme droughts' impact on Scots pine net primary productivity in the European temperate zone in the period 2002-2023

Kinga Kulesza[1], Oliwier Zając[2]*, Agata Hościło[1]

[1]Institute of Environmental Protection – National Research Institute, National Centre for Emissions Management, 32 Słowicza Street, Warsaw, Poland

[2]Department of Geoinformatics, Cartography and Remote Sensing, Faculty of Geography and Regional Studies, University of Warsaw, 30Krakowskie Przedmieście, 00-927 Warszawa, Poland, e-mail: o.zajac5@student.uw.edu.pl

* corresponding author

Abstract:

Severe drought episodes significantly influence the productivity of trees in many parts of Europe. This paper shows in detail the influence of the most severe drought events on the productivity of the most important forest-forming tree species in European temperate zone – Scots pine (*Pinus sylvestris L.*). We identified four months with most severe drought conditions that occurred in Poland in 2002-2023: July 2006, April 2009, August 2015 and June 2019. To quantify trees' net primary productivity (NPP) we used Moderate Resolution Imaging Spectroradiometer (MODIS) NPP, which was further correlated with temperature, precipitation, evapotranspiration and climatic water balance. The identified summer droughts had considerable effect on pine forest productivity: August 2015 had the lowest NPP of all Augusts in the study period (0.033 $kgC\cdot m^{-2}\cdot month^{-1}$), similarly July 2006 (0.055 $kgC\cdot m^{-2}\cdot month^{-1}$) and June 2019 (0.096 $kgC\cdot m^{-2}\cdot month^{-1}$). Relationship between drought severity and pine's productivity depends on the time during the year, when the drought occurs. Summer droughts, with their peak in June, July or August, resulted in significantly decreased

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productivity of trees, while spring droughts, tend to have an initial positive impact on pine's condition. For summer droughts cases, weather conditions influence the decreased productivity of pine forest for a long time, e.g. a prolonged negative relationship between NPP and temperature for drought cases in June 2019 and July 2006. Such long response of spectral indicator's value of pine is not clearly visible for droughts occurring either on the beginning (April 2009) or second half (August 2015) of the growing season.

Keywords:
Net primary productivity, MODIS, ERA5-Land, drought, Scots pine

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1. Introduction

Forest constitutes the main terrestrial ecosystem on Earth. Approximately 75% of the gross primary production within the Earth's biosphere originates from trees (Pan et al., 2013). Therefore, this ecosystem plays a key role in climate regulation, as it is involved in evaporative cooling processes on both local and global scale. Forests are also crucial for carbon sequestration, making their contribution to mitigating climate change undeniable (Xue et al., 2022). However, continuous rise of temperature and increasing frequency of extreme meteorological events affect condition and productivity of forest (IPCC, 2021; del Castillo et al., 2024). This concerns both biological functioning and structure of this ecosystem (Price et al., 2013).

Forest stress, caused by prolonged and severe droughts, already appeared in several parts of Central Europe (Buras et al., 2020). It is likely that droughts and heatwaves will occur more frequently, which may lead to ecological transition in forest and loss of biodiversity. Events such as forest fires, droughts and other extreme meteorological conditions contribute to decline in vegetation productivity or its damage (Nepstad et al., 2008; Pontes-Lopes et al., 2021). Detecting changes in forest condition is thus very important in the context of assessing their vulnerability to climate change (Navarro-Cerrillo et al., 2023).

Global warming induces changes in atmospheric circulation, resulting in prolonged heatwaves, and periods with low precipitation sums. When these periods overlap, a so-called "hotter drought" emerge (Allen et al., 2010; Buras et al., 2020). The increasing number of such events is one of the main factors determining the condition and productivity of trees. Ionita et al. (2017) indicated several years in which droughts occurred in Europe: 2003, 2010, 2013 and summer of 2015. This series of adverse hydroclimatological conditions was extended due to the drought of 2018 (Schuldt et al., 2020), 2019 (Boergens et al., 2020; Hari et al., 2020) and 2022 (Buras et al., 2023; Wang et al., 2023). The influence of these droughts on vegetation

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condition was already analysed in many papers (Ganey et al., 2021; Kulesza & Hoscilo, 2023; Gharun et al., 2024; Kulesza & Hoscilo, 2024b; Pompa-García et al., 2025; Zhao et al., 2025). Researchers suggest that hotter droughts result in a range of negative impacts on ecosystems, e.g. reduced productivity, indicated as lower vegetation greenness by remote sensing data (Ciais et al., 2005; Allen et al., 2015; Orth et al., 2016; Choat et al., 2018). They also notice that the response to drought vary significantly between different land cover types, particularly between grasslands and forest (Wolf et al., 2013; Kulesza & Hoscilo, 2024a). However, only few papers deal with the response to droughts of specific species. For instance, Moravec et al. (2021) observed significant impact of the 2018 drought on the Scots pine (*Pinus sylvestris L.*) stands in small area in Germany. The authors stressed that the main cause of dieback of trees were periods of low precipitation and high temperature during 2014-2018. Also, Popa et al. (2024) noted that Norway spruce (*Picea abies L.*) in the Eastern Carpathians showed growth losses during the 2003 drought.

Remote sensing techniques can be a useful tool for analysing the condition of forest vegetation, especially for processing large data at a regional scale. One of the satellite-based datasets providing information about the new biomass produced by vegetation is MOD17A2 Gross Primary Productivity (GPP) product (Running et al. 2015). It is based on measurements provided by Moderate Resolution Imaging Spectroradiometer (MODIS), onboard Terra and Aqua satellites, which are operated by National Aeronautics and Space Administration (NASA). In addition to GPP, the MOD17A2 product contains also a Net Primary Productivity (NPP) layer, which is referred to as Net Photosynthesis (the NPP equivalent). Terrestrial NPP is defined as the difference between the energy fixed by autotrophs and their respiration (Dunham, 2012). It is related to the net carbon sequestration, which is crucial for both ecology and environmental conservation. NPP plays an important role in providing food and fibre to support the expanding human population (Running et al., 2004; Xiao et al., 2019) . It serves as

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a source of energy and essential substances for various biological processes. NPP is often associated with the production of organic matter (the balance between the carbon absorbed through GPP and the carbon emitted during plant mitochondrial respiration) per unit of land area and time ($gC \cdot m^{-2} \cdot year^{-1}$) (Clark et al., 2001; Collalti et al., 2020). Although NPP is a derivative of GPP, prepared on the basis of GPP and modelled respiration (simulated with little sensitivity to droughts), it is used in many papers. Terrestrial NPP is one of the components of the global carbon cycle and a key indicator of land ecosystem dynamics (Chen et al., 2022). That is why NPP is recognized as the most relevant variable to characterize forest ecosystems since it serves as the primary energy source and drives the most critical ecosystem services (Martínez et al., 2022). So far primary productivity was coupled with meteorological conditions in some papers in e.g. Central Asia (Nanzad et al., 2021) and Europe (Ciais et al., 2005; Fu et al., 2020). In the latter cases, GPP was used to assess productivity reduction in eastern and western Europe during 2018 and 2003 drought.

Researchers emphasize that it is important to assess the impact of climate anomalies on tree dieback or decrease in forest condition using quantitative methods (Hammond et al., 2022). Thus, in this paper we integrate the meteorological observations with remote sensing approaches and reference ground data to form a synergistic dataset, leveraging modern technological solutions. This is currently a very important approach in forest ecology and management (Norman et al., 2016). Therefore, the main goal of this paper is to identify and assess the influence of the most severe drought events in last decades on the productivity of the most important forest-forming species in European temperate zone – Scots pine. We aim to identify the most severe droughts in years 2002-2023. Having these, we couple the NPP with meteorological elements in order to determine the correlations and time lags in the spectral response of pine forest to the influencing factors, during and after the severe droughts episodes.

2. Materials and methods

2.1 Study area

The study area consists of homogenous pine forest pixels within the administrative borders of Poland. Poland is the largest, predominantly lowland country in central Europe, with Baltic Sea to the north and the highlands and mountains to the south (Fig. 1). According to Köppen classification it is characterised by warm-temperate climate with oceanic influences in the west and continental influences in the north-eastern part of the country (Kottek et al., 2006). The western transfer of air masses prevails and therefore study area is influenced indirectly by the Atlantic Ocean (Ojrzynska et al., 2022). The multi-annual air temperature reaches 8.7°C (1991-2020), with the observed increase by 0.28°C per decade on average, within the last 70 years (Marosz et al., 2023). In terms of precipitation, the annual sums range between 500 mm in the central part of the study area to over 1100 mm in the far southern areas, which are mostly highlands and mountains (Wibig, 2024). The mean duration of the growing season in Poland in the period 1966-2020 was 222 days, with the beginning at ca. March 29th and the end at ca. November 5th (Szyga-Pluta et al., 2023).

2.2 Pine mask

Scots pine (*Pinus sylvestris L.*; hereinafter, pine) is the most widely distributed pine species in the world (Caudullo et al., 2016; Przybylski et al., 2021). In Poland, it constitutes 58.9% of the total forest area (State Forest... 2025). Pine is a fast-growing pioneer tree that thrives in both wet and dry conditions. It can grow on acidic and calcareous soils (Bigler et al., 2006). In Poland, it grows mostly in the lowlands, and often in a form of a planted monoculture (Konatowska et al., 2023). Such pine forest is present especially in the central region of the country. The progressing climate changes may significantly weaken these types of forest communities, causing a range of consequences and acclimation strategies, such as: lowering leaf area and enhancing water-use efficiency (Bose et al., 2024). Regional studies of pine are essential for understanding species- and site-specific dynamics that may be invisible on a global

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scale. Poland constitutes a climatic and ecological transition zone in Europe, where continental and Atlantic influences create diverse drought patterns. This makes it an adequate location to study the effects of drought under changing climatic regimes. Despite its wide distribution, pine shows a considerable variability in response to drought across its range, making local and regional studies important (Benisiewicz et al., 2024). In this study, we used only pine forest areas, not only because it is the most important forest-forming species in the European temperate zone (*Forest Europe*, 2020), but also because it forms suitably large clusters to be represented well in MODIS 500 x 500 m grid cell. Homogenous pine forest areas (polygons representing forest stands with 100% of pine) were derived from Polish Forest Data Bank (FDB) for year 2023 (FDB, 2023). Year 2023 (the final year in the considered period) was selected purposely, to exclude sanitation and planned felling areas throughout the whole study period. For each MODIS 500 x 500 m grid cell we calculated the percentage of a grid cell covered by homogenous pine forest areas. A MODIS pixel was considered as pine-masked, if homogeneous pine forest polygons covered at least 80% of its area. Generated pine mask allowed us to perform analyses only for area covered by this specific tree stands. The total number of MODIS pine mask grid cells was 20,618 (5,154.5 km^2). Most of the pine mask grid cells is located in the western part of Poland. The least of them is located in the south and north-east of the study area (Fig. 1).

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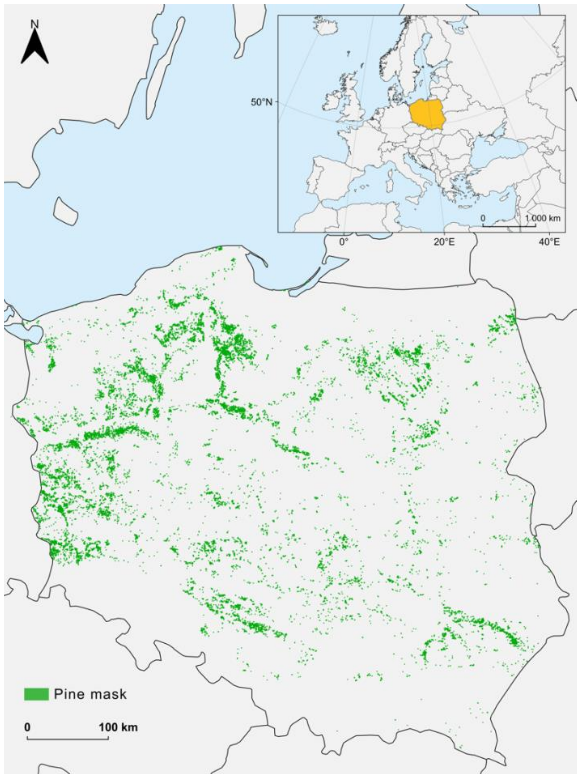

Fig. 1 Location of the study area and spatial distribution of pine mask in MODIS 500 × 500 m grid cells.

2.3 MODIS NPP data

We utilized the MOD17A2HGF V6 Terra GPP product to obtain information about NPP (Running et al., 2015). The dataset contains cumulative 8-day composites with 500 x 500 m spatial resolution. The algorithm to produce it is based on radiation-use efficiency concept, which assumes that the NPP of well-watered and fertilized annual crops is directly proportional to the amount of absorbed photosynthetically active solar radiation (APAR) (Wang et al., 2019), and MODIS has been providing consistent estimates of NPP since 2000. The data was downloaded from NASA Earthdata (https://www.earthdata.nasa.gov/) for the period 2002-2023. Each granule consists of 2400 x 2400 pixels, so three granules were needed to cover the area between 49ºN and 55ºN latitude and 14ºE and 25ºE longitude – corresponding to the spatial extent of Poland – and resulting in 3036 granules needed in total to cover the time period 2002-

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2023. For the year 2023, we used the MOD17A2HGF V6.1 dataset due to the decommission of V6 product version (Running et al., 2021).

2.4 Meteorological elements

To investigate an impact of meteorological elements on pine forest condition, we used ERA-5 Land reanalysis (Muñoz-Sabater, 2019). With spatial resolution of 0.1° × 0.1° it is a down-scaled product of ERA5 – the fifth generation of atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020). We used monthly values of the following meteorological variables: 2-metre temperature (T, in °C), precipitation (P, in mm), evapotranspiration (ETo, in mm). Next, the Climatic Water Balance (CWB, in mm) was calculated, based on a difference between precipitation and evapotranspiration (P-ETo; with negative values meaning more water goes out than comes to the surface) (Thornthwaite, 1948). Data was downloaded from the Copernicus Data Store (https://cds.climate.copernicus.eu/) for the period of 2002-2023, the same as the MODIS NPP data, and for the area of Poland. ERA-5 Land data was resampled to fit the MODIS grid cells using the nearest-neighbour interpolation method. Finally, only the pine-masked pixels of meteorological elements were used for further analyses.

2.5 Statistical analyses

In order to detect the most severe drought events in the area of Poland in the last two decades, the monthly mean T and CWB were used. Firstly, the values were detrended in order to detect the biggest anomalies of T and CWB, both in the beginning and in the end of the time series. Having monthly detrended T and CWB values for each pixel and for each month in the analysed period, we produced standardised values, i.e. z-scores. Because the course of monthly values of meteorological elements shows a natural annual cycle, the monthly detrended T and CWB values were standardised separately for each month (Eq. 1):

$$ZT\_dt_{m,i} = \frac{T\_dt_{m,i} - \mu_{T\_dt_{M,i}}}{\sigma_{T\_dt_{M,i}}} \quad (1)$$

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where $T\_dt_{m,i}$ is detrended monthly T in the *m*-th month (e.g. in a given January) and in *i*-th pixel; $\mu T\_dt_{M,i}$ and $\sigma T\_dt_{M,i}$ are the mean and standard deviation values of detrended monthly T values in all *m*-th months (e.g. in all Januaries) and in the *i*-th pixel. Z-scores for detrended CWB ($ZCWB\_dt_{m,i}$) were prepared respectively.

The months with the highest $ZT\_dt_{m.i}$ and lowest $ZCWB\_dt_{m,i}$ occurring simultaneously, are indicated as drought events. The bigger the sum of these two, the stronger the drought (Eq. 2):

$$Z\_dt_{m,i} = ZT\_dt_{m,i} + (-ZCWB\_dt_{m,i}) \quad (2)$$

In order to find months with the most severe droughts, the mean Z_dt_m value for the whole area of Poland was calculated using area-average of all pixels in a given month (Eq. 3):

$$Z\_dt_m = \frac{\sum_{i=1}^{n} Z\_dt_{m,i}}{n} \quad (3)$$

where *n* is the number of all pixels in the administrative borders of Poland. The monthly values of Z_dt_m were sorted in descending order. We indicated four months with the most severe drought conditions, and described the condition of pine vegetation (using NPP) in these and following months in detail. Such approach, based on data from the ERA5-Land, emphasizes the transparency and repeatability of procedures, while providing reliable results. Similar method was used by e.g. Buras et al. (2020).

In order to determine the multi-annual variability of NPP and meteorological elements, as well as the influence of the latter on NPP of pine forest, several research methods were used. In the first step, the appropriate z-scores were prepared. MODIS NPP data and meteorological elements (T, P, ETo and CWB) were standardised in a similar way as the variables for the drought selection, but without the initial detrending. For instance, standardised values of T were calculated as follows (Eq. 4):

$$ZT_{m,i} = \frac{T_{m,i} - \mu_{T_{M,i}}}{\sigma_{T_{M,i}}} \quad (4)$$

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where $T_{m,i}$ is monthly T in the m-th month and in i-th pixel; $\mu T_{M,i}$ and $\sigma T_{M,i}$ are the mean and standard deviation values of monthly T values in all m-th months and in the i-th pixel. Z-scores for P, ETo, CWB and NPP were calculated respectively.

Next, the time series of area-averaged values of ZNPP in the whole period was presented. To this end, the spatially averaged values of ZNPP data were used. Similarly, the spatially averaged values of meteorological elements' z-scores were used and served as a background to describe the ZNPP during the four episodes of drought.

To additionally illustrate the spatial distribution of ZNPP during and after the selected drought episodes, the maps of spatial distribution of ZNPP in the months with the most severe drought conditions and three months following them (1-, 2- and 3-month time lags) were prepared.

The relationship between ZNPP and z-scores of meteorological elements was measured using the Pearson correlation coefficient (Pearson, 1985). Firstly, the correlations were calculated on the basis of 22 correlation pairs, i.e. for the spatially averaged values of ZNPP and ZT, ZP, ZETo, ZCWB, each pair representing monthly value from individual year. This was prepared for Aprils, Junes, Julys and Augusts and presented on scatterplots. The linear regression lines, coefficients of determination R^2 and the statistical significance level p were also presented.

To examine further the relationship between ZNPP and z-scores of meteorological elements, the correlation coefficient with time lag was used. Four selected months served as "starting points" to calculate correlation coefficients with time lags. This time, the correlation was calculated at the pixel level, i.e. using all pixels at given month m. In order to investigate the delays in the spectral response of the pine forest to the triggering meteorological factors, the linear correlations with 0-, 1-, 2- and 3-month time lags were calculated. A 0-month delay means that the independent variable's values (ZT, ZP, ZETo, ZCWB) from month m were

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correlated with the ZNPP from the same month. In turn, a 1-month delay means that the independent variable's values from month *m* were correlated with the ZNPP values from the *m*+1 month. The significance of linear correlations was assessed at significance level of $\alpha = 0.05$. We deliberately adopted a bivariate approach to focus on theoretical understanding of the relationships between variables rather than predictive modeling. In order to explore and interpret the fundamental dynamics between NPP and key meteorological factors, a transparent and interpretable method was used, as implementing complex algorithms can lead to overfitting or false associations, especially in the case of oscillating climate drivers. With this in mind, the correlation-based approach allowed to directly link observed patterns to known ecological and climatological processes. A detailed methodology diagram is presented in Fig. 2.

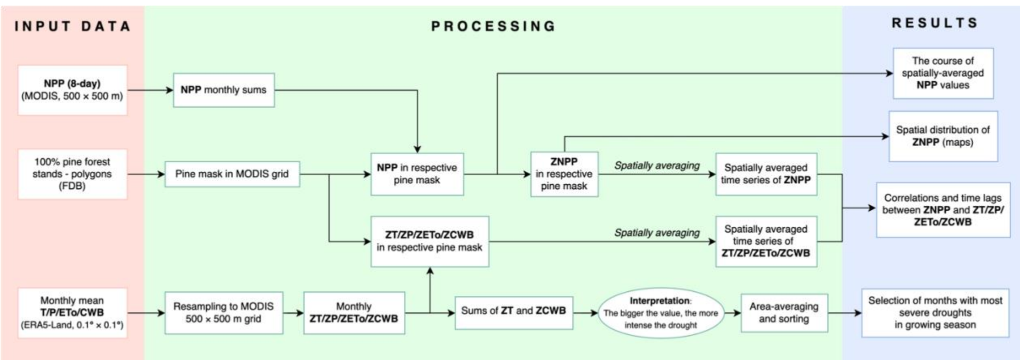

Fig. 2 Data and methodology used in the study.

3. Results

3.1 Detection of severe drought events

In the two decades of 2002-2023, the month that stood out with the biggest value of area-averaged Z_dt_m was June 2019 (Fig. 3). Meteorological conditions favourable for drought occurrence in this month appeared evenly across the entire country, mostly affecting its central part. The second most extreme case was July 2006, when the most severe drought affected western Poland. In April 2009, meteorological drought was observed equally across the

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country, with a slight predominance of its presence in the central and northern areas. The last of the four most drought-affected months was August 2015.

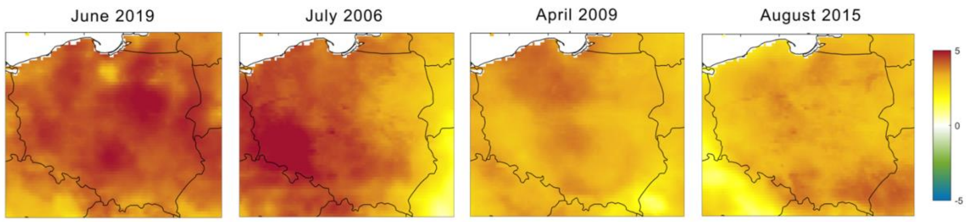

Fig. 3 Spatial distribution of the $Z\_dt_{m,i}$ index (sum of detrended T and detrended CWB) for selected months with the most extreme drought events in Poland in the period 2002-2023. The maps show top four of the most severe drought events (June 2019, July 2006, April 2009 and August 2015), ranked in descending order based on the area-averaged values of Z_dt_m. The values are expressed in standard deviation units.

3.2 Variability of NPP

The time series of area-averaged NPP in Polish pine forest in the period 2002-2023 shows a typical annual cycle of primary productivity fluctuations in the temperate zone of the Northern Hemisphere, with high values in the growing season (April-October) and low productivity in the winter season (November-March) (Fig. 4). The maximum value of area-averaged NPP equals 0.143 kgC·m^{-2}·month^{-1} for June 2010. The lowest one was observed for December 2021 (-0.004 kgC·m^{-2}·month^{-1}). Referring to the months in which droughts occurred, August 2015 was characterized by the lowest NPP of all Augusts in the multi-year period (0.033 kgC·m^{-2}·month^{-1}) (Fig. 5), similarly July 2006 (0.055 kgC·m^{-2}·month^{-1}) and June 2019 (0.096 kgC·m^{-2}·month^{-1}). In these cases, the presence of unfavourable meteorological conditions during the summer months had a significant impact on the productivity of pine trees. On the other hand, in April 2009 no decrease in NPP values – as compared to other Aprils' values – can be noticed.

Interestingly, the consecutive droughts of 2018 and 2019 resulted in very low values of NPP in 2019. In the following years the gradual increase of yearly maximum NPP values was observed – from 0.117 kgC·m^{-2}·month^{-1} in June 2020 to 0.134 kgC·m^{-2}·month^{-1} in May 2023.

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Another general observation is that in most years, the sinusoidal course of monthly NPP values shows a breakdown in July/August (Fig. 4). In some cases, the NPP decline is clearly visible, e.g. in July 2006 and August 2015 (drought months). Smaller decrease in NPP values can be seen also in July 2010, July 2014, and August 2022. It seems to be related with occasional needle shedding or browning processes caused by the normal decrease in precipitation and cloudiness that occurs in Poland in the end of July and in August.

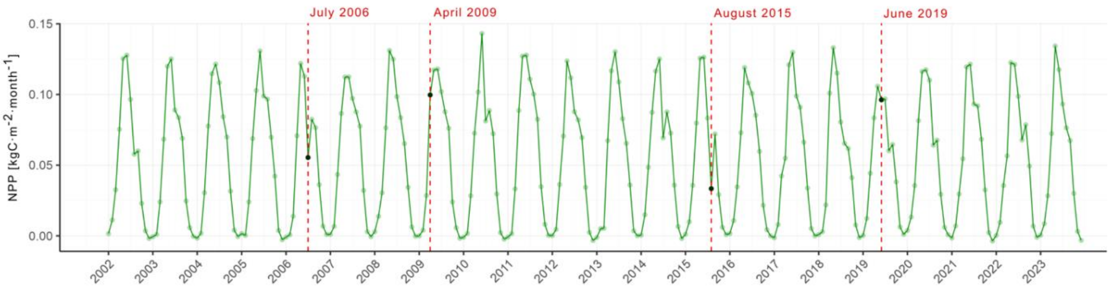

Fig. 4 Multi-annual course of area-averaged monthly NPP sums in the pine-masked pixels in Poland in the period 2002-2023. Dots and vertical red dashed lines present the selected severe droughts.

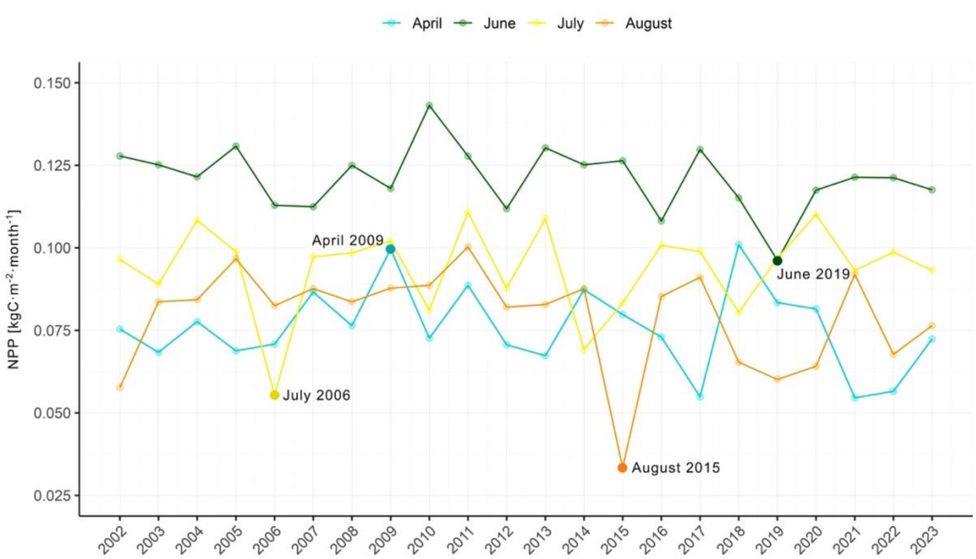

Fig. 5 Area-averaged monthly NPP sums in selected months (April, June, July and August) in pine-masked pixels in Poland in the period 2002-2023.

3.3 Relationship between NPP and meteorological elements

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The course of the monthly z-scores of NPP (ZNPP) during the period 2002-2023 showed the dynamics of vegetation condition and its response to dynamics of meteorological elements. The biggest positive values of ZNPP occurred in 2009, 2010, 2011 and 2022, while the biggest negative ones in 2006, 2013, 2015 and 2019 (Fig. 6). In 2015, the negative phase of North Atlantic Oscillation (NAO) index recorded in July caused the 6^{th} biggest ZT value (2.29) in the analysed time period and big negative ZP value (-1.56) in August. As a result, August 2015 was the month with the lowest ZNPP (-2.97) in the period 2002-2023. The 2^{nd} lowest ZNPP value in the analysed time period was in July 2006 (-2.83), co-occurring with very big ZT (2.73) and very low ZP (-1.98). In June 2019, ZT (2.78) was the biggest in the whole time period. Combined with the very low ZCWB (-2.01), it resulted in 4^{th} lowest ZNPP (-2.56). Interestingly, the 3^{rd} lowest ZNPP value, which occurred in March 2013, did not coincide with the drought conditions. On the other hand, a drought episode detected in April 2009, manifesting itself in relatively big ZT (1.53) and exceptionally low ZP (-2.01), did not have much impact on this month's ZNPP, which was one of the biggest (1.92) in the analysed time frame.

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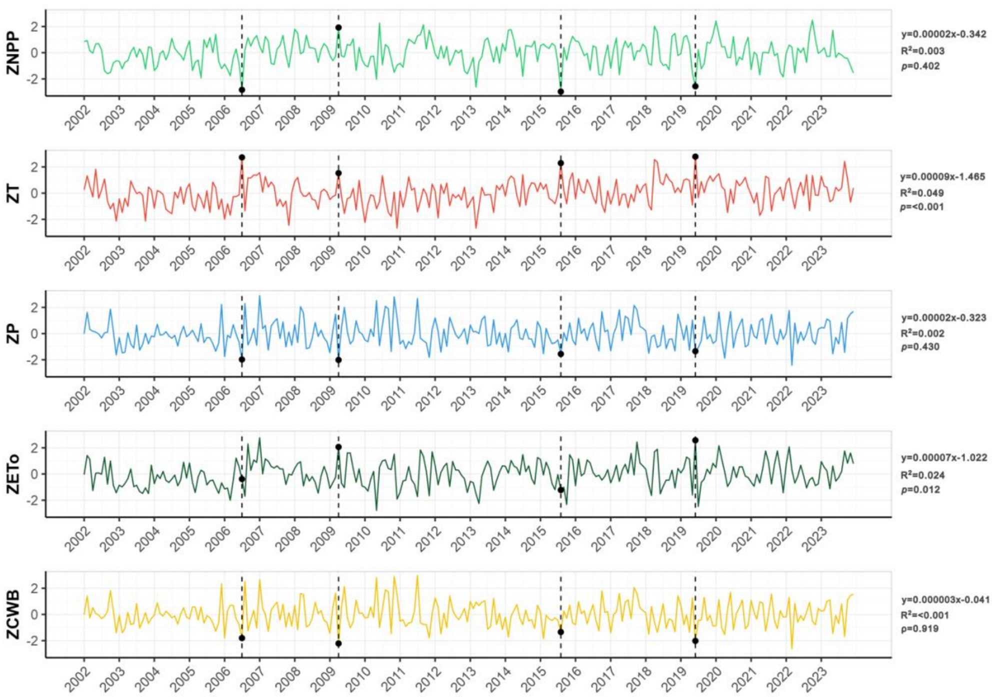

Fig. 6 Multi-annual course of area-averaged monthly z-scores: ZNPP and meteorological elements (ZT, ZETo, ZP and ZCWB) in pine-masked pixels in Poland in the period 2002-2023. Dots and dashed lines indicate the selected severe droughts. The graphs also show the linear trend equations, the coefficient of determination R^2 and the statistical significance level *p*.

Spatial distribution of ZNPP in the four selected months with most severe drought conditions and months following them, is presented in Fig. 7. In July 2006 the lowest ZNPP values were observed in central and western part of the study area. For 1-month delay (August 2006), the decreased productivity in pine forest remained in northern part of Poland, while for a 2-month delay (September 2006) - in western part of the study area. For 3-month delay, ZNPP values were mostly positive. In April 2009, the big, positive values of ZNPP were followed by reduced ZNPP values, observed in the north-central part of Poland 1 month later. After 2 months (in June 2009), the worst condition of pine forest was recorded in the north-east of the country, with ZNPP values ranging from -3 to -2. In August 2015, almost whole study area was covered with extremely low ZNPP values, with the worst condition noticeable mainly in the south-western part of the country. Regarding 1-month lag, ZNPP values remained low,

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primarily in the south-eastern areas. After 2 months (in October 2015), pine forest throughout the entire study area was characterized by negative ZNPP values. The 3-month delay showed a return to good condition in most areas, with exceptions in the north-eastern and south-eastern parts of Poland. In the last case (June 2019), poor condition of pine forest was observed mainly in western and southern part of the country. The 1-month delay brought relatively good condition of pine forest, with two regions of slightly lower ZNPP – central-southern and north-western Poland. In contrast, after 2 months ZNPP values dropped again, and ranged between -3 to 0. The last month (September 2019) shows diverse picture of ZNPP's spatial distribution, indicating the latitudinal variability of pine productivity, with the worst condition in the northern part of Poland.

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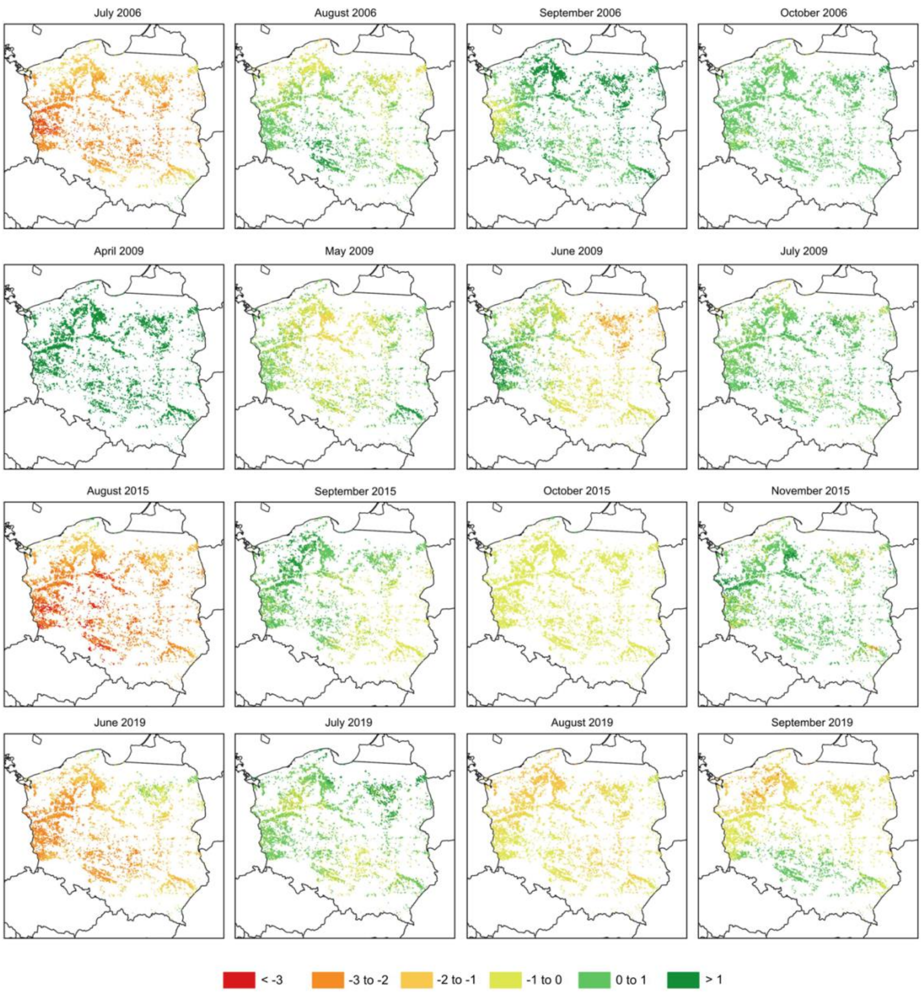

Fig. 7 Spatial distribution of ZNPP in pine-masked pixels over Poland in the four selected months with most severe drought conditions (July 2006, April 2009, August 2015 and June 2019) and three months following them.

Correlations for area-averaged ZNPP and meteorological elements (ZT, ZETo, ZP and ZCWB) showed a similar picture for summer months (June, July, August) and completely different for spring month (April) (Fig. 8). For ZT, summer months indicated negative correlation. The strongest one was observed for August (r = -0.88) and July (r = -0.85). Statistically significant correlation coefficient between ZT and ZNPP was also noted in June (r = -0.53). On the other hand, strong positive relationship between these variables was observed

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for April (r = 0.93). It is undoubtedly related to the beginning of the growing season in the temperate zone on the northern hemisphere. Furthermore, April 2009 was the second warmest of all Aprils and had the second highest ZNPP value. The remaining cases, which concern the summer months, were characterized by the lowest ZNPP and the highest ZT in these months, which highlights that increasing temperature in these months had a limiting effect on pine greening.

There was only one statistically significant, negative correlation between ZP and ZNPP – in April (r = -0.62). The reason for this may be increased cloud cover associated with greater precipitation during this month, which limits access to light and at the same time disrupts the photosynthesis process. For July and August, a positive correlation occurred (r = 0.30; r = 0.34), although statistically insignificant. In the case of ZETo and ZCWB, statistically significant correlation coefficients were observed only in April – a positive one for ZETo (r = 0.74) and negative one for ZCWB (r = 0.72).

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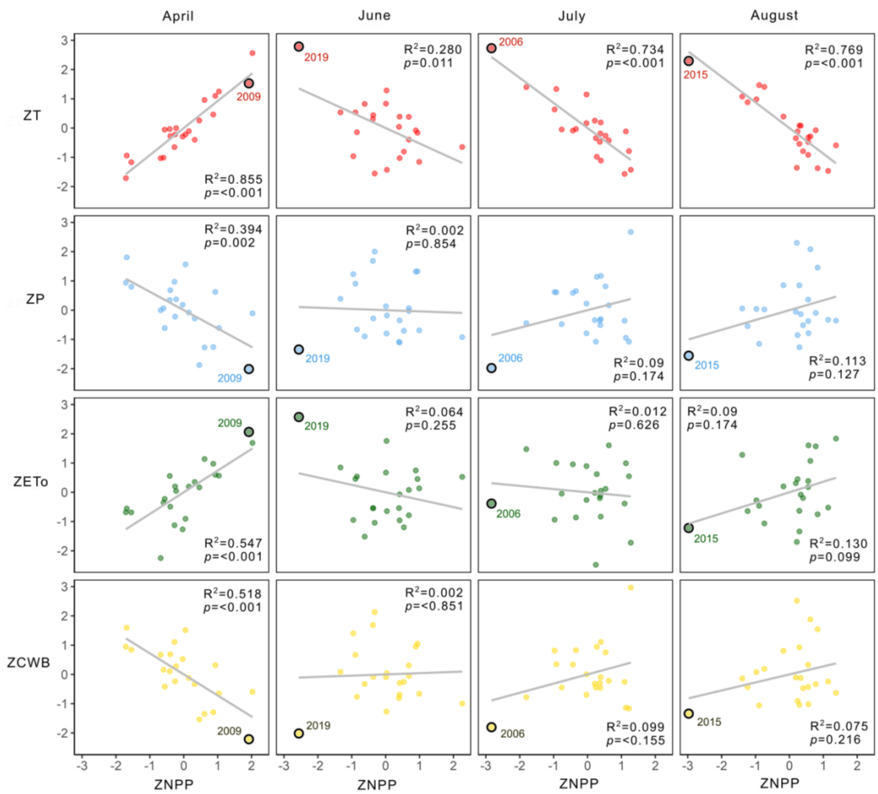

Fig. 8 Relationship between area-averaged ZNPP and meteorological elements (ZT, ZETo, ZP and ZCWB) for pine-masked pixels over Poland in individual months (Aprils, Junes, Julys and Augusts) throughout the period 2002-2023. Each graph consists of 22 points (one for each year), and also presents a linear regression (gray line), coefficient of determination R^2 and the statistical significance level p. Black-circled points indicate selected months with severe drought conditions.

The calculated correlation coefficients using all pixels at given drought month show a diverse picture, depending on which drought episode is analysed. Because selected four most severe droughts are located in different moments of the growing season (at the beginning – April 2009, in the middle – June 2019 and July 2006, and in the second half – August 2015), the spectral response of pine forest to triggering meteorological condition is significantly different in each of these cases. In June 2019 and July 2006, high ZT was strongly correlated with low ZNPP, resulting in correlation coefficients of -0.68 and -0.74 respectively (Fig. 9a and d). In the following months, the correlation coefficient remained negative. Simultaneously, in these two months low ZNPP was strongly correlated with low ZP, creating a positive correlation

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coefficients (r = 0.33 in June 2019 and r = 0.51 in July 2006), which also remained positive in the following months. This indicates that in these cases the drought, which occurred in the peak of the growing season, influenced the decreased productivity of pine forest for a long time. It is especially visible in spatial distribution of ZNPP in June 2019 and months following it (Fig. 7).

August 2015 was slightly different: although the drought in this month was strong, the spectral response of the pine trees productivity was not very extended in time. The correlation coefficients between ZNPP and ZT reached a value of -0.75 (with 0-month delay), and -0.55 (with 1-month delay), but changed significantly to high positive values at 2- and 3-month delays (Fig. 9c). This is also visible in the case of ZCWB, where strong negative correlations in August and September turn into strong positive correlations in October and November.

On the other hand, April 2009 presents a completely different picture. ZNPP is correlated positively with ZT, meaning that the higher the temperature, the bigger the productivity of pine trees (Fig. 9b). It is not surprising, taking into account that April is the beginning of the growing season. However, in the following months (1-, 2-, and 3-month delays), the correlation coefficient between ZT and ZNPP changed into negative, with a strong negative correlation coefficient (r = -0.70) in +3 month-delay. When it comes to ZP and ZNPP, the correlation, although strong positive in April (r = 0.40), changes into weak in the following months. Overall, the relationships between ZNPP and z-scores of all meteorological elements are relatively weak in 1- and 2-month delay.

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a) 2006

	July	+1 month	+2 months	+3 months
ZT	-0.74	-0.21	-0.74	0.31
ZP	0.51	0.31	0.57	0.06
ZETo	0.40	0.19	0.51	0.07
ZCWB	-0.06	0.04	-0.15	-0.05

b) 2009

	April	+1 month	+2 months	+3 months
ZT	0.76	-0.09	0.02	-0.70
ZP	0.40	0.27	0.01	-0.26
ZETo	0.26	-0.05	-0.05	-0.30
ZCWB	0.13	0.24	0.05	0.01

c) 2015

	August	+1 month	+2 months	+3 months
ZT	-0.75	-0.55	0.55	0.69
ZP	-0.20	0.22	0.64	0.23
ZETo	0.48	0.56	-0.07	-0.41
ZCWB	-0.67	-0.39	0.63	0.62

d) 2019

	June	+1 month	+2 months	+3 months
ZT	-0.68	-0.62	-0.37	0.03
ZP	0.33	0.28	0.15	0.18
ZETo	0.40	0.18	0.13	0.38
ZCWB	-0.05	0.13	0.04	-0.21

Fig. 9 Correlation coefficients with 0-, 1-, 2-, and 3-month delay, between ZNPP and ZT, ZETo, ZP, ZCWB, from all pine-masked pixels, for July 2006 (a), April 2009 (b), August 2015 (c), and June 2019 (d). All the coefficients are statistically significant (α=0.05).

4. Discussion

In the period 2002-2023, a significant number of severe, large-scale drought events occurred across Europe, affecting also the area of this study. This included years 2003 (Buras et al., 2020), 2013 (Ionita et al., 2017), 2015 (Ionita et al., 2017), 2018 (Boergens et al., 2020; Buras et al., 2020; Schuldt et al., 2020), 2019 (Boergens et al., 2020; Hari et al., 2020) and 2022 (Buras et al., 2023). In this study, we defined a *Z_dt* index to quantify the overall severity of drought in each month, resulting in months sorted according to their above-average T and below-average CWB sum. Hence, the most unfavourable meteorological conditions occurred in June 2019, July 2006, April 2009 and August 2015. Indeed, June 2019 with a positive ZT value of 2.78 (Fig. 6) was the warmest month not only in the study period, but since 1951

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(Ziernicka-Wojtaszek, 2021). The reason for this was the negative phase of NAO, which persisted for the whole growing season of 2019, and contributed to anticyclonic circulation and 2 to 2.5 times higher-than-average frequency of circulation from the south and south-east direction (1951-2018) (Ziernicka-Wojtaszek, 2021). In July 2006, the most severe conditions were recorded in western Europe, with the Netherlands, Belgium and Germany being the most exposed locations (Rebetez et al., 2009). However, the territory of Poland was also seriously affected. In turn, in 2015 the negative phase of NAO in July caused a severe drought that reached its peak intensity and spatial extent in August, affecting especially the eastern part of Europe (Ionita et al., 2017). Very low negative ZP values in June, July and August resulted in summer precipitation sum in 2015 being the lowest since 1901 over Central Europe (Orth et al., 2016; Ionita et al., 2017).

Drought event in April 2009 although very severe, lasted shortly. Although ZP was very low in this month (-2.01), which calculates back to approximately 14 mm (with an average sum of precipitation in April being 54 mm in 1971-2023), the precipitation sums in preceding (February, March) and following months (May, June, July) were above-average. Similarly, mean monthly temperature in April 2009 was 3° above average (ZT = 1.53), but other months in this growing season recorded normal values. However, after mostly positive values of ZNPP in April in whole Poland, negative ZNPP values were spread all over the study area in May and June (Fig. 7). Increased vegetation growth at the beginning of the growing season, caused by sudden warming and moisture accumulated in the ground, resulted in decreased forest's productivity in following months. Researchers confirm that fast depletion of resources (e.g. soil moisture) in the spring promotes and strengthens droughts in summer (Bastos et al., 2020; Somorowska, 2022).

A key aspect of the study was to assess the impact of climatic factors on the condition of pine to determine its potential vulnerability to climate change, including increasing

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meteorological droughts. Dyderski et al. (2025) highlighted that pine is one of the species that is predicted to lose most of its climatic suitability in temperate zone even under the IPCC's optimistic climate change scenarios, except for mountain ranges and Western Europe. This shows why the study of pine susceptibility to meteorological conditions and its behaviour in Poland, where it occurs both in the centre and at the border of its climatic tolerance, allows us to investigate potential early indicators of forest sensitivity to climate change, showing significant ecological consequences for both forest management and nature conservation (Dyderski et al., 2018).

In general, this study indicates an overall impact of meteorological condition on productivity of pine forest. There is strong negative correlation between ZT and ZNPP in summer months (June, July, August), while correlation between ZNPP and precipitation is negative and weaker. Similar results can be found in other studies (Tang et al., 2010; Martínez et al., 2022; Cui et al., 2025), e.g. Tang et al. (2010) noticed that NPP was negatively related to summer temperature, but positively related to temperature in April, May and October. In turn, Martinez et al. (2022) showed negative correlation between productivity of coniferous species and precipitation in Spain. They also proved that low-altitude evergreen needle-leaved forest is vulnerable to climate variations, and shows negative correlation with annual temperature (Martínez et al., 2022). Interestingly, the growth response of Scots pine, reflected by the degree of tree-ring width variation, in small study areas in Poland and Hungary showed a significant correlation with summer P, while decreasing association with T (Misi et al., 2019). Indeed, relationship between condition/productivity of trees and precipitation is much stronger on the yearly basis, than on the monthly basis (Kulesza & Hoscilo, 2024a).

However, apart from the instantaneous relationship between forest's productivity and climate, this paper shows that spectral response to the influencing meteorological factor might be extended in time, meaning that a significant time lag in correlation between ZNPP and

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meteorological element can occur. Such lags in the vegetation (mostly forest) response to the changes in weather elements are within the researchers' scope of interests (Mao et al., 2012; Moreira et al., 2019; Benisiewicz et al., 2024; Kulesza & Hoscilo, 2024a). Bigler et al. (2006) presented proof of the limiting effect of droughts on Scots pine stands in the southern Switzerland. The authors showed that strong droughts have a short-term effect on forest productivity, increasing a tree's risk of dieback. After such events a dynamic increase was observed, related to the effects of release after the death of neighbouring trees caused by drought (Bigler et al., 2006). As a result of this, extreme meteorological conditions may affect the productivity of forest ecosystems in a direct way and strengthen the probability of occurrence of pests (Hart et al., 2017; Bao et al., 2019). Yin et al. (2024) provided complex studies on response of NPP to poor meteorological conditions, showing that drought stress limits the growth of productivity in forest, and NPP anomalies gradually intensify as the degree of drought increases. In Amazon Forest, the ecosystems in post-drought recovery were found to have an approximately 13% lower NPP than the reference values derived from their pre-drought conditions or from regions unaffected by drought (Machado-Silva et al., 2021). In Poland, Kulesza and Hościło (2024a) noticed significant correlations between condition of coniferous forest vegetation and temperature for at least 3-month delay, while insignificant correlations for precipitation. However, the research in this paper is more case-oriented, as only the influence of the four most severe drought episodes on forest productivity is analysed. Because selected droughts are located in different moments of the growing season, the spectral response of pine forest to triggering meteorological condition is significantly different in each of these cases. The drought that occurred in the peak of the growing season, especially the one in June 2019, influenced the decreased productivity of pine forest for several months. Beloiu et al. (2022) highlighted that also in Central Germany tree crowns and young trees were severely affected by drought in 2019, and forest experienced long-term drought effects and consequently required

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a longer recovery time after drought. Schuldt et al. (2020) noted that also 2018 drought was very severe and led to unprecedented tree mortality across many species in Central Europe. The authors emphasized that unexpectedly strong drought effects, detected in 2019, came from enhanced drought stress, caused by two consecutive droughts of 2018 and 2019, making the forest vegetation more susceptible to secondary impacts like insect infestations or fungal diseases (Schuldt et al., 2020).

Interestingly, a different scenario was in the case of August 2015. After initial strong negative correlation between ZNPP and ZT, it turned positive with 2-month delay (Fig. 9). Although the drought of 2015 was severe and extensive, its consequences in terms of productivity decline were not long-lasting. This probably occurred due to the overlap with the natural forest productivity cycle – productivity decline in October and November.

The analysis performed in this study has also some limitations, first of which is the interpretation of the spectral indices' values. In remote sensing of forests, the coming spectral signal may reflect not only the tree's condition, but also the "noise" from the understorey or soil, as they are sensitive to atmospheric influence as well (Huang et al., 2021). Moreover, the changes in forest productivity can come not only from the drought-related factors. Indeed, droughts may induce e.g. wildfires or enhance the forest vulnerability to insects, pests or fungus pathogen attacks (Karlsen et al., 2017; Bryn & Potthoff, 2018; Morin et al., 2018), but there are other factors, such as forest site condition, age structure or forest management practices, which may drive the productivity of trees.

Another important issue refers to the underlying pine mask. It was prepared on the basis of FDB data for year 2023, in order to exclude planned felling throughout the whole study period. However, some trees might have died and been removed before 2023 (in sanitary cuts), and therefore the overall condition/productivity of forest reported in this study might be slightly overestimated.

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5. Conclusions

The results presented in this paper show in detail the influence of the most severe drought events on the productivity of the most important forest-forming tree species in European temperate zone – Scots pine. We identified four most severe droughts that occurred in Poland in the last two decades: in July 2006, April 2009, August 2015 and June 2019. To quantify trees' net primary productivity we used MODIS NPP, which was further correlated with selected meteorological elements, known for having a major influence on forest productivity dynamics: T, P, ETo and CWB.

Relationship between drought severity and Scots pine's productivity depends on the time during the year, when the drought occurs. While it is known that summer drought is impactful, this study quantitatively distinguishes the relative sensitivity of pine to drought across seasons, using remote sensing data for long-term assessment. This allowed to clarify not just that summer drought matters more, but how much more, and under which specific climatic conditions. By determining the pine's response time to drought, we provide a theoretical framework for understanding pine forest dynamics and its adaptation. Summer droughts, with their peak in June, July or August, result in significantly decreased productivity of trees, while spring droughts, tend to have an initial positive impact on pine's condition. Another important conclusion is the time lag in the response of trees to triggering drought conditions. For summer droughts cases, which occur in the peak of the growing season, weather conditions influence the decreased productivity of pine forest for a long time, e.g. a prolonged negative relationship between NPP and T for drought cases in June 2019 and July 2006. Such long response of spectral indicator's value of Scots pine is not clearly visible for droughts occurring either on the beginning (April 2009) or second half (August 2015) of the growing season.

The research presented in this study addresses the important issue of trees response to severe drought conditions. Identifying the drought-induced variability in the productivity of the

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most important forest-forming tree species in European temperate zone is particularly important in the context of recent climate change and trees' impact on mitigation of climate change. It gives a significant insight into Scots pine's vulnerability to drought-related disturbances. The decline of pine, the main forest-forming species and a species of great economic importance in Poland and Europe, is a significant problem of the upcoming deep transformation of ecosystems and species composition caused by climate change. In the future, similar analyses should be performed for more forest-dominating species and increasingly longer periods of time. Although MODIS NPP data proved to be useful for analysing Scots pine's primary productivity, its spatial resolution might be too coarse for analysing other tree species. Further studies should also involve satellite products with higher spatial resolution, e.g. Sentinel-2.

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Author contributions. KK: conceptualisation, methodology, writing (original draft), writing (review and editing). OZ: formal analysis, investigation, data curation, writing (original draft), writing (review and editing), visualisation. AH: conceptualisation, supervision, project administration, funding acquisition.

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