

Dear Editor,

Thank you very much for giving us the opportunity to respond to the reviewers' remarks, suggestions, etc. We are very grateful for all their opinions and suggestions, which were usually very helpful and constructive. All passages where changes in the article have been made are also placed in the text below.

All changes in the text are marked in red fonts. For clarity the reviewers' texts are in black and our answers are in blue. Corrected attached passages are shown in italic.

We would kindly like to inform you that the following alterations have been made to the text regarding the reviewers' comments, suggestions and opinions:

## **Anonymous Referee #1**

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Dear authors, I highly appreciate the approach of combining and complementing available tree-ring width chronologies, written documentary accounts and instrumental data to investigate droughts, i.e. their occurrence, frequency and intensity, in Poland back to ca. 900 CE. An amazing 200 documented drought accounts for the period 1451–1800 were collected and categorized into three classes of severity. In addition, 22 tree-ring width chronologies were used to detect years of extreme low annual growth, so-called negative pointer years, which were attributed to drought events. The extension into the industrial period was done using the Standardized Precipitation Index (SPI) with different seasonal lengths and which was calculated on eight long precipitation records.

Overall, the comprehensive analysis of drought events and duration using existing proxy data is needed, especially under current climate change. However, the amount of statistical approaches applied make the study partly difficult to understand. Moreover, there are several shortcomings in the manuscript regarding the structure and content. Substantial improvements should be made prior to publication and I strongly recommend that the English be revised by a professional service or a native Englishspeaking scientist working in the field.

The entire text was corrected by a native speaker.

General comments

- The title is not reflecting the study very well, maybe include that a multi-proxy approach was used or highlight the main result, for example.

Answer: was changed according to the reviewer's suggestion.

Final title: *Droughts in the area of Poland in recent centuries in the light of multi-proxy data*

- The abstract needs shortening and a clear structure by including a motivation of the study which is followed by data, methods, results and conclusion/significance of the study. The abstract should not be too long and should not include references.

Answer: was shortened and all remarks of the Reviewer were taken into account

Final text of Abstract: *The history of drought occurrence in Poland in the last millennium is poorly known. To improve this knowledge we have conducted a comprehensive analysis using both proxy data (documentary and*

*dendrochronological) and instrumental measurements of precipitation. The paper presents the main features of droughts in Poland in recent centuries, including their frequency of occurrence, coverage, duration and intensity. The reconstructions of droughts based on all the mentioned sources of data covered the period 996–2015. Examples of megadroughts were also chosen using documentary evidence, and some of them were described.*

*Various documentary sources have been used to identify droughts in the area of Poland in period 1451–1800 and to estimate their intensity, spatial coverage and duration. Twenty-two local chronologies of trees (pine, oak, and fir) from Poland were taken into account for detecting negative pointer years (exceptionally narrow rings). The longest chronology covers the years 996–1986 and was constructed for eastern Pomerania. The delimitation of droughts based on instrumental data (eight long-term precipitation series) was conducted using two independent approaches (Standard Precipitation Index (SPI) calculated for 1-, 3-, and 24-month time scales, and new method proposed by authors). For delimitation of droughts (dry months), the criteria used were those proposed by McKee and modified for the climate conditions of Poland by Łabędzki.*

*More than one hundred droughts were found in documentary sources in the period 1451–1800, including 17 megadroughts. A greater-than-average number of droughts was observed in the second halves of the 17<sup>th</sup> century, and of the 18<sup>th</sup> century in particular. Dendrochronological data confirmed this general tendency in the mentioned period. The clearly greatest number of negative pointer years occurred in the 18<sup>th</sup> century and then in the period 1451–1500. In the period 996–2015, a total of 758 negative pointer years were recorded.*

*Analysis of SPI (including its lowest values, i.e. droughts) showed that the long-term frequency of droughts in Poland has been stable in the last two or three centuries. Extreme and severe droughts were most frequent in the coastal part of Poland and in Silesia. Most droughts had a duration of two months (about 60–70%), or 3–4 months (10–20%). Frequencies of droughts with a duration of 5 and more months were lower than 10%. The longest droughts had a duration of 7–8 months. The frequency of droughts of all categories in Poland in the instrumental period 1722–2015 was greatest in winter, while the documentary evidence (1451–1800) rarely mentions droughts in this season. The occurrence of negative pointer years (a good proxy for droughts) was compared with droughts delimited based on documentary and instrumental data. A good correspondence was found between the timing of occurrence of droughts identified using all three kinds of data (sources).*

- The introduction needs improvement by 1) removing unnecessary information e.g. reduce p.3, l. 17-20, 2) write in a more precise way e.g. p.2, l.10. “statistical analyses” of what?,

Answer: The Introduction part was corrected and the present version is as below:

*The increase in ~~rate in degree~~ rate of global warming that has been observed in recent decades also influences characteristic changes in the occurrence and intensity of precipitation (IPCC, 2013). Although precipitation totals are slightly greater from year to year in some regions, frequency of precipitation is getting lower, while its intensity is increasing. As a result, breaks between precipitation episodes are getting longer and longer, which significantly favours the occurrence of droughts. The majority of statistical analyses presenting results of frequency and intensity of droughts conducted averaged for the entire world (Dai and Trenberth, 1998; Dai et al., 2004; Dai, 2011a, b, 2013; IPCC, 2013) and its different regions (see, e.g., Held et al., 2005; Alexander et al., 2006; Bartholy and Pongracz, 2007; Łabędzki, 2007; Brázdil et al., 2009; Seneviratne et al., 2012; NAS, 2013; Miles et al., 2015; Osuch et al., 2016; Bąk and Kubiak-Wójcicka, 2017; Brázdil et al. 2018) usually confirm their rising tendencies, in particular in more frequency and intensity of droughts recent decades. On the other hand, However, some authors document that this change for the entire globe is not as big clear as is presented in some of the above-mentioned publications and depends among others on the drought metrics used (Sheffield et al., 2012; Greve et al., 2014 and references therein). For example, Sheffield et al. (2012) They argue that overestimation of the rate of change of global droughts is related to the shortcomings (simplifications) of the Palmer Drought Severity Index (PDSI) used for this purpose.*

~~Sheffield et al., 2012~~ They write: “The simplicity of the PDSI, which is calculated from a simple water-balance model forced by monthly precipitation and temperature data, makes it an attractive tool in large-scale drought assessments, but may give biased results in the context of climate change.” Thus, the reliable estimate of global tendencies in the occurrence and intensity of droughts still needs more research. Nevertheless, a greater or lesser increase in frequency of droughts in many regions ~~global scale~~ has been observed in recent decades. Moreover, climatic models project that this tendency will probably be more common and clear in the future world. ~~also be seen in the entire 21<sup>st</sup> century.~~ The IPCC (2013) report concludes ~~It is very likely~~ that droughts will be not only more frequent, but also more intense in many regions, but particularly in areas with dry conditions in today’s climate (IPCC, 2013). For this reason, the study of drought occurrence and its intensity is very important, in particular when its manifold negative socio-economic consequences are taken into account. Many aspects dealing with drought (definition; kinds – meteorological, agricultural, hydrological, socio-economic; quantitative ways of measurement; socio-economic consequences; etc.) were described recently in many publications (e.g. Wilhite and Glantz, 1985; Tate and Gustard, 2000; Herweijer et al., 2007; Mishra and Singh, 2010; Dai 2011a; Brázdil et al., 2013, 2018; IPCC, 2014; Fragoso et al., 2018; White et al., 2018) and therefore a brief overview is omitted here.

To estimate how unprecedented is the scale of climate drying in recent decades, a longer perspective is needed. Therefore, in recent decades quite a lot of drought reconstructions encompassing almost the entire millennium, or the shorter historical, pre-industrial period, were constructed for different greater or smaller regions (e.g. Inglot, 1968; Piervitali and Colacino, 2001; Cook et al., 2004, 2010, 2015; Herweijer et al., 2007; Pfister et al., 2006; Brewer et al., 2007; Domínguez-Castro et al., 2008, 2010; Woodhouse et al., 2010; Brázdil et al., 2013, 2016, 2018 (see references herein); Dobrovolný et al., 2015; Fragoso et al., 2018; Hanel et al., 2018).

What is the state of knowledge about droughts occurrence and intensity in Poland – the area that is the object of our studies in the paper? It must be said that for the instrumental period, and in particular for the period after World War II, the knowledge is good. Papers have been published analysing: 1) classification of drought types and the development of drought indices (Bąk and Łabędzki, 2002; Łabędzki, 2007; Łabędzki and Kanecka-Geszke, 2009; Tokarczyk, 2013; Łabędzki and Bąk, 2014); 2) tendencies in drought occurrence and intensity (Farat et al., 1998; Magier et al., 2000; Łabędzki, 2007; Kalbarczyk, 2010; Bartczak et al., 2014; Radzka, 2015; Wypych et al., 2015; Bąk and Kubiak-Wójcicka, 2017); 3) monitoring of drought conditions (Łabędzki, 2006; Doroszewski et al., 2008, 2012; Tokarczyk and Szalińska, 2013; IMGW, 2014; ITP, 2014; Łabędzki and Bąk, 2014); and 4) drought hazard assessment for periods when observations are available (Łabędzki, 2009; Tokarczyk and Szalińska, 2014). In recent years the influence of future climate change on the occurrence of droughts in Poland in the 21<sup>st</sup> century has also been addressed (Liszewska et al., 2012; Osuch et al., 2012, 2016). On the other hand, little is known about drought occurrence in the pre-instrumental and early instrumental periods in Poland. Generally, only one ~~attempt~~ ~~team of researchers under the direction of professor~~

~~Stefan Inglot of Wrocław University was focusing on this issue, in the 1960s. As a result, a first attempted chronology~~ at a *chronology of droughts* for the 16<sup>th</sup> to mid-19<sup>th</sup> century was proposed based on documentary evidence (Inglot, 1968).

Drought is the one of the most stressful factors for trees (Vitas, 2001; Allen et al., 2010; Sohar et al., 2013). The measurement of tree ring widths is one of the ways to study the effect of climate parameters on trees (Zielski et al., 2010). Some factors such as frost or summer drought may have an immediate effect on ring width, whereas other factors, such as winter drought, may have a delayed effect on ring widths. This delayed effect occurs because the meristematic tissues are dormant during the winter months in temperate and cold climates. The effect of different factors is seen as variations in ring size and structure, which change systematically, or vary slowly throughout the life of the tree (Fritts, 1976). The effect of drought on tree rings is observed as narrow rings (Koprowski et al., 2012; Opała, 2015). The relationships are significant enough to reconstruct drought in temperate climate also in cold regions like Finland (Helama and Lindholm, 2003), Sweden (Seftigen et al., 2013) and Czech Republic (Dobrovolný et al., 2015). Therefore, we have assumed that information derived from tree rings can complement the existing knowledge about past droughts in Poland. According to studies by Somorowska (2016), the effect of drought extends from the south-west towards the centre of the country and, in some cases, to the north-east of Poland. Another study suggest that in the future some of the highest probabilities of drought occurrence may be in the central part, with the lowest probability in south-eastern Poland (Diakowska et al., 2018).

Although in the last three decades many climate reconstructions for the last millennium have been conducted for Poland (see Przybylak et al., 2005 or Przybylak, 2016 for a review), droughts were not analysed. Therefore, to fill this important gap we decided to investigate them in a more *detailed manner* than was done by Inglot's team. Moreover, for this purpose we used more sorts of proxy data (not only documentary but also dendrochronological). The reconstructions of droughts based on all the mentioned sources of data covered the period 996–2015. Thus, the main aim of the paper is to present the main features of drought occurrence, duration and intensity in the area of Poland in this period. Section 2 describes all the kinds of data used and their quality. Section 3 addresses the methods used in this study, including drought indices. Section 4 presents the results of three reconstructions of droughts derived from 1) documentary, 2) instrumental, and 3) dendrochronological data. Examples of megadroughts are also analysed here. The results obtained are discussed in Section 5, and main conclusions in the last section.

and 3) provide more information e.g. p.3, l.21. in which areas is drought the most stressful factor – to only provide a few examples.

Answer: We updated the text with information about areas with the most frequent occurrence of drought in Poland. The following passage was added:

*According to studies by Somorowska (2016) the effect of drought extends from the south-west towards the centre of the country and, in some cases, to the north-east of Poland. Another study suggest that in the future some of the highest probabilities of drought occurrence may be in the central part, with the lowest probability in south-eastern Poland (Diakowska et al., 2018).*

Also, I was wondering why the authors cite four lines of a publication on l. 18-21? This can be summarized.

Answer: Sorry, but in the mentioned lines there is no citing of publications in any of page in the entire manuscript? It must be a mistake?

- Structure of the Data and Methods chapters needs improvement. A straightforward description of the documentary data is missing. After reading the chapter 2.1, it is not entirely clear what data from whom were used. Maybe start with the summarizing paragraph (p.5, l. 30 – p.6., l.18) and add some (and only) important information from the paragraphs before.

Answer: It seems to us that it is precisely written in the text from which historical sources weather excerpts were taken. The structure of the chapter 2.1 is typical from the historical point of view and therefore we have decided to leave the chapter as it is. At the beginning the published sources are described, divided into different types, and then the archival sources (not published). At the end of the chapter a short summing-up is given. It is rather difficult and in our opinion not appropriate to summarize this not-too-long chapter.

For the dendrochronological data, no information about the quality of the individual tree-ring width chronologies is provided. Information of the number of samples, inter-series correlation, mean segment lengths can be easily added in Table. 1. Information on the sample replication in a tree-ring width chronology is essential to evaluate drought events that were detected during a low replicated time period.

Answer: Table 1 was updated. We provided the information about number of samples, EPS and rbar.tot. In the case of Site 12 the EPS is extremely low; however, the chronologies were not used for climate reconstruction but for detecting negative pointer years. Pointer years confirmed the information from historical sources and show that drought can also affect the trees. It is also worthwhile to note after Buras (2017) that “EPS is a measure of how well a finite sample of tree-ring data represents an infinite population chronology, but it will not necessarily indicate whether a tree-ring chronology is suitable for climate reconstruction purposes.”

Table 1

Site number	Site name	Time span	Number of samples	EPS	rbar.tot	Species	Source
Region I (Baltic Province)							
Site 1	Koszalin	1782–1987	22	0.899	0.339	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 2	Gdańsk	1762–1986	45	0.887	0.192	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 3	Wolin	1554–1987	23	0.877	0.318	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)

Site 4	Gdańsk	1175–1396	13	0.579	0.388	Oak	Dąbrowski HP, unpublished
Site 5	western Pomerania	996–1986	205	0.907	0.250	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Region II (Masuria-Podlasie Province)							
Site 6	Gołdap	1871–1987	22	0.941	0.472	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 7	Suwałki	1861–1987	19	0.872	0.303	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 8	Hajnówka	1720–1985	19	0.851	0.314	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Region III (Greater Poland-Pomerania Province)							
Site 9	Poznań	1836–1987	17	0.904	0.385	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 10	Zielona Góra	1774–1987	19	0.876	0.330	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 11	Toruń	1714–2015	48	0.886	0.335	Oak	Puchałka et al., 2016 (updated)
Site 12	Tuchola	1249–1490	7	0.054	0.347	Pine	Dąbrowski HP, unpublished
Site 13	Kuyavia-Pomerania	1169–2015	247	0.816	0.195	Pine	Koprowski et al., 2012
Site 14	Chojnice	1100–1468	21	0.688	0.327	Oak	Dąbrowski HP, unpublished
Region IV (Masovia-Podlasie Province)							
Site 15	Warszawa	1690–1985	19	0.850	0.291	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Region V (Silesia Province)							
Site 16	Upper Silesia	1770–2010	80	0.880 (average)	correlation 0.530	Pine and oak	Opala and Mendecki, 2014
Site 17	Wrocław	1727–1987	22	0.870	0.327	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 18	Upper Silesia	1568–2010	178	0.850	correlation 0.510	Pine	Opala, 2015
Region VI (Lesser Poland Province)							
Site 19	Kraków	1792–1986	29	0.906	0.361	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 20	Kosobudy	1782–1989	22	0.937	0.448	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 21	Lesser Poland	1109–2004	238	No data	No data	Pine	Szychowska-Krapiec, 2010
Site 22	Lesser Poland	1109–2006	560	No data	No data	Fir	Szychowska-Krapiec, 2010

For the Method chapter, the examples of the individual drought classes in chapter 3.1 are quite long. Please, consider reduction to only 2 to 3 examples and place the remaining examples in the supplementary material.

Answer: the examples of the individual drought classes in chapter 3.1 were significantly reduced according to the reviewer's suggestion, see tables 3–5 below:

Table 3

Year	Description	Translation	Source
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1463	<p><i>[...] fuit magnus calor et arditas, ita quod sylvae, nemora et montana incenderentur, ex voragine ignis pro magna parte absumptae</i></p>	<p><del>[...] there were such great heat and drought that forests, groves and mountain vegetation burned, and were largely destroyed by the fire</del></p>	<p>Rocznik wroclawski dawny, MPH, vol. 3, p. 686</p>
1473	<p><i>[...] caumata et penuriam aquarum, adeo ut perennes aquae verterentur in aridam, et flumina Poloniae principalia ubique fuerunt permeabilia, insignis. [...] Fumabant in universis Poloniae regionibus sylvae, borrae, arbusta, saltus, irremediabili igne, nec ante rescindi flamma poterat, donec ignis etiam radicem arborum voraret, ex quo ubique fragor ruentium saltuum audiebatur. Apum quoque et alveariorum arbores plurimae deletae, segetes vernaes exterminatae siccitate.</i></p>	<p>[...] hot weather and a lack of water, to such an extent that the places where there had always been water dried up everywhere, and the main Polish rivers could be crossed everywhere. [...] Forests, woods, thickets and forested hills burnt with fire; there was no way to put it out, and it was impossible to extinguish the flame before the fire even devoured the root of the trees; from here you could hear the clatter of collapsing thickets. Very numerous bee and beekeeping trees were destroyed, and many spring crops were destroyed due to drought.</p>	<p>Długosz, vol. 12, p. 336</p>
1540	<p><i>[...] fuit in aestate horrenda siccitas adeo, ut silices, montes et valles quasi igne flagrarent, duravit haec siccitas usque ad hyemem.</i></p>	<p>[...] in the summer there was such a terrible drought that the rocks, mountains and valleys were burned down with fire; this drought lasted until winter</p>	<p>Archivum vetus et novum ecclesiae archipresbyteralis Heilsbergensis, in: MHW, vol. 8, p. 597</p>

1561	<p><i>Im Julio und Augusto war es sehr dürre und dürre Winde, dass das Wasser sehr austrocknete. Die Oder war klein, dass es keinem Mann gedachte. Viel Brunnen trockneten aus.</i></p>	<p>In July and August there were dry and very dry winds, so that the water completely dried out. The Odra became shallow as it had never been before. Many wells dried up.</p>	<p>Pol, vol. 4, p. 17</p>
1575	<p><i>At in Polonia inaudita fere siccitas vere, aestate, autumno et hyeme denique aestivalium segetum, quas arefecerat, penuriam fecit, amnium vero undas adeo minuit, ut iis passim fere privaretur ipsaque Vistula infra Dobrinum multis locis vadabilis fieret, unde nec sal e Russia per Sanum in Vistulam permeari potuit.</i></p>	<p>However, in Poland, a truly unbelievable drought, in summer, autumn and winter, along with spring crops that had dried up, caused poverty[;] the level of the water in rivers had fallen so much that everywhere the rivers almost disappeared, while the Wisła Vistula in many areas below Dobrzyń became quite shallow, and it was not possible to transport any salt from Ruthenia through the San to the Wisła Vistula.</p>	<p>Orzelski, in: SRP, vol. 22, p. 360</p>
1590	<p><i>Ist ein sehr heisser truckener Sommer gewesen, also, dass auch die Landflüsse, als der Bober, Queiss, Katzbach, Weida, Olau, Lohe, und andere mehr gänzlich ausgetrucknet. Die Oder ist auch so klein worden, dass man sie an allen Orten durchwatten können.</i></p>	<p>The summer was so hot [and] dry that <del>national</del> regional rivers like the Bóbr, the Kwisa, the Kaczawa, the Widawa, the Oława, the Ślęza [Silesia, auth. suppl.] and many others dried up completely. The Odra also became very shallow, so you could cross it anywhere.</p>	<p>Pol, vol. 4, p. 156</p>



	<p>38 Wochen regnete es nicht. Die Flüsse trockneten aus.</p> <p>Zacken und andere Flüsse trockneten völlig aus</p> <p>Der Bober trocknete infolge starker Hitze ganz aus.</p>	<p>It did not rain for 38 weeks. The rivers dried up.</p> <p>The Kamienna and other rivers dried up completely.</p> <p>The Bóbr dried up completely due to severe drought.</p>	<p>Reinhold, 1846, p. 143</p> <p>Bergemann, J.G., 1830a, p. 84</p> <p>Bergemann, J.G. 1830b, vol. 3, p. 85</p>
1653	<p><del>In Monath Maii fiel ein dürres Wetter ein, und dauerte biss Ende August. Die alle Bäche vertrockneten, auch Flachs und Gerste verdorrete.</del></p>	<p><del>In the month of May the dry weather began and lasted until the end of August. All streams dried up, as did flax and barley.</del></p>	<p>Gomoleke, p. 53</p>
1676	<p><del>Tego roku straszne Panowały Susze, że zboża wypalało w polach.</del></p>	<p><del>That year a terrible drought took place so that crops burnt in the fields.</del></p>	<p>Muz. Nar. w Krakowie rps. MNKr. 169, p. 82</p>
1683	<p><del>Im Jahre 1683 entstand durch die grosse Dürre und den Misswachs eine starke Theuerung und ein fast gänzlicher Mangel an Getreyde.</del></p>	<p><del>In 1683, due to the great drought and poor growth [of grain], high prices and almost complete lack of grain prevailed.</del></p>	<p>Pisański, Beschreibung der Stadt Johannisburg, p. 96</p>
1684	<p><del>[...] folgte auf Johanni [24.06.] eine grosse anhaltende Hitze darauf; davon das Erdreich dermassen dürrre wurde, dass das Sommer Getreyde, Flachs, und Grass, gantz zurücker geblieben, das Winter Korn an vielen Orten überreiffte, ehe es sich gehöriger massen in die</del></p>	<p><del>The great long-lasting drought arrived on the St. John's Day [24.06.]; the ground became dry, the crops became dry; flax and barley grew very poorly before the proper ear of grain had come out, which caused very high prices [...]</del></p>	<p>Gomoleke, p. 54</p>

	<i>Ahren kaum angesetzt, daher Theurung entstanden [...]</i>		
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Table 4

Year	Description	Translation	Source
1456	<i>Fuitque anno eodem precipue circa partes nostras, ubi plures sunt agri sabulosi et argillosi, post festa paschalia siccitas magna et usque ad messem continuata. Messis autem tante humiditatis et instabilitatis,</i>	And that year there was an exceptionally great drought in our area, where there are numerous sandy and loamy soils; it occurred after the Easter holidays and lasted until the harvest. In the harvest period it [the weather] was so wet and unstable [...]	Catalogus abbatum Saganensium, in: Scriptorum rerum Silesiacarum, vol. I, p. 340
<del>1472</del>	<del><i>Dieser Sommer, von Pfingsten bis auf aller Heiligen, war ganz trocken und warm [...]</i></del>	<del><i>That summer from Whitsunday to the All Saints Day it was quite dry and warm [...]</i></del>	<del>Pol, vol. 2, p. 89</del>
1532	<i>Ein dürrer Sommer. Es regnete in sieben Wochen nicht. Das Getreide und die Weide verdorrete auf den Hügeln ganz aus. In etlichen Dörfern war kein gar Wasser. Auf dem Lande konnte man nicht mahlen. Zu 10. 12. 18. Meilen musste man zur Mühle führen. Die Olau trocknete und dorrete auch aus, und hatte kein Wasser bis auf Bartholomei [24.08].</i>	Dry summer. It did not rain for seven weeks. The grain and grass on the hillsides dried up. In some places there was almost no water. In the countryside, it was impossible to grind grain. One needed to go 10, 12, 18 miles to reach mills. The Oława River dried up [Silesia, auth. suppl.] and there was no water in it until the Saint Bartholomew's Day [August 24].	Pol, vol. 3, p. 72

1585	<i>Mensis hic [March] fuit serenissimus usque ad miraculum et siccus</i>	That month [March] the weather was fine and it was dry	Reszka, p. 91
1637	<i>Przy przeważającej w tym miesiącu suszy ogień zniszczył wiele miast i wsi, widać słabnące plony [...]</i>	With the drought that prevailed that month, fire destroyed many cities and villages, we could see the yields failing [...].	Radziwiłł Albrycht Stanisław, Pamiętnik o dziejach w Polsce, vol. 2 1637–1646, A. Przyboś, R. Żelewski (eds), Warszawa, 1980
1665	<i>Der Sommer des Jahres 1665 wird als ungemein heiss angegehen, und soll es die ganzen Hundstage [10.07.–20.08.] hindurch auch nicht einmal geregnet haben.</i>	The summer of 1665 was incredibly hot; not even once did it rain – so called “Dog Days”.	Wernicke, Gesch. Thorns., vol. 2, p. 321

Table 5

Year	Description	Translation	Source
1461	<i>Eodem anno fuit estas calidissima et fluvius Odere valde modicus, similiter et alii fluvii.</i>	That year the summer was the hottest and the water level of the Odra River fell, as did other rivers.	Sigismundi Rosiczii chronica, p. 78.
1531	<i>Nazajutrz po bitwie pod Obertynem [22.08.] kometa nie dała się już tak świetnie widzieć iako przesley noey: która ieśli nie porażkę</i>	The following day, after the battle of Obertyn [22.08.], the comet did not let itself be seen so well as it had the previous night, which augured	Bielski, p. 311

	<del><i>Włoską, tedy suszę podobno znamieniowała; iakoż tego czasu była susza wielka.</i></del>	<del>the defeat of the Vlachs, or drought; And then the drought was really great.</del>	
1552	<i>Den 5 Junii [...] nach der Vesper und grosser Dürre kam ein gewünschter Regen, aber mit grossem Wetter</i>	On June 5 [...] after the evening and after a great drought, came the desired rain with a great storm.	Pol, vol. 3, p. 158.
1661	<i>Es folgte aber ein dürrer Sommer.</i>	However, a dry summer came.	Happelius, p. 148.

On page 19, chapter “2.3 Instrumental data” needs to be moved into “2. Data chapter”.

Answer: No. This is just an error. The numbering of the subchapter should be 3.3 and not 2.3 as it is in the original version. We corrected the numbering.

Instead there should be a clearly written paragraph about the detection of the climate-growth relationships of all tree-ring width chronologies, for which period and for what climate variables. Why not use the SPI data for the analysis of the climate response of the trees which would simplify the entire study a lot and at the same time, prove your hypotheses (p.18, l.9)?

Answer: SPI was not taken into account because this parameter results directly from precipitation data.

- Description of the methods lacks detailed and important information. For example, on p. 18, l. 14 “climate monthly precipitation and temperature” were used to evaluate the climate growth relationship. However, only results for precipitation are shown in Fig. 2 and information of the period over which the correlation was done is missing.

Answer: additional information were added in the new Table 6. The information about temperature was also updated (see text below and Table 6).

*For each site the climate growth relationships were tested against monthly precipitation and temperature data starting from 1951 and covers maximum time span depending on the length of the chronology (Table 6). Because the time span was too short (for example for Site 2 when chronology covers the years 1951-1986) for some extended analysis going back to previous months, the common period from previous October to current September was taken into account.*

Table 6. Climate growth relationships for analysed sites. Only the highest correlation coefficients are presented – with level of significance  $p < 0.05$ .

Site number	Site name	Analyzed period	Highest Pearson correlation coefficient	Months with highest correlation coefficient	Meteorological station	Species	Source
Region I (Baltic Province)							
Site 1	Koszalin	1951–1987	0.378	Sum of precipitation from May to June	Koszalin	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 2	Gdańsk	1951–1986	0.296 (not significant)	Sum of precipitation from June to July	Gdańsk	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 3	Wolin	1951–1987	0.565	Sum of precipitation from June to August	Świnoujście	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 4	Gdańsk	1175–1396	No climate data	No climate data	No climate data	Oak	Dąbrowski HP, unpublished
Site 5	western Pomerania	1951–1986	0.456	Sum of precipitation from June to July	Koszalin	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Region II (Masuria-Podlasie Province)							
Site 6	Goldap	1951–1987	0.589	Temperature current May	Suwałki	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 7	Suwałki	1951–1987	0.50	Sum of precipitation from June to July	Suwałki	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 8	Hajnówka	1951–1985	0.285	Sum of precipitation from July to August	Białystok	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Region III (Greater Poland-Pomerania Province)							
Site 9	Poznań	1951–1987	0.485	Sum of precipitation from May to July	Poznań	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 10	Zielona Góra	1951–1987	-0.322	Temperature, previous December	Gorzów Wielkopolski	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 11	Toruń	1951–2015	0.334 -0.334	Sum of precipitation from May to June, temperature in June	Toruń	Oak	Puchałka et al., 2016 (updated)
Site 12	Tuchola	1249–1490	No climate data	No climate data	No climate data	Pine	Dąbrowski HP, unpublished
Site 13	Kuyavia-Pomerania	1951–2015	0.443	Sum of precipitation from May to July	Toruń	Pine	Koprowski et al., 2012
Site 14	Chojnice	1100–1468	No climate data	No climate data	No climate data	Oak	Dąbrowski HP, unpublished
Region IV (Masovia-Podlasie Province)							

Site 15	Warszawa	1951–1985	-0.316	Temperature, previous December	Warszawa	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Region V (Silesia Province)							
Site 16	Upper Silesia	1886–1984	>0.4 Precipitation data not presented due to lower statistical significance	Temperature of February and March for pine	Opole, Wrocław, Katowice and Racibórz	Pine and oak	Opala and Mendecki, 2014
Site 17	Wrocław	1951–1987	0.376	Sum of precipitation from May to June,	Wrocław	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 18	Upper Silesia	1568–2010	Only pointer years were analysed			Pine	Opala, 2015
Region VI (Lesser Poland Province)							
Site 19	Kraków	1915–1986	0.324 (not significant)	Temperature in February	Kraków	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 20	Kosobudy	1951–1989	0.314 -0.323	Sum of precipitation from May to July, temperature in June	Lublin and Radawiec	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 21	Lesser Poland	1881–1999	>0.4	Temperature in March	Kraków	Pine	Szychowska-Krąpiec, 2010
Site 22	Lesser Poland	1881–1999	>0.4	Temperature in February	Kraków	Fir	Szychowska-Krąpiec, 2010

- Methodology for the evaluation of the climate-growth relationship is not sufficient. Firstly, it is not clear if the age trend from the individual tree-ring width series is removed and what method was applied. Secondly, it is questionable if daily precipitation data need to be used given 1) that this led the authors to a generalization which might be not true (p.19, l.4) and 2) the description and mention of the droughts in the documentary data are not on daily resolution either. Moreover, I would like to see a comprehensive climate-growth analysis of all tree-ring width chronologies with information of species, Pearson correlation coefficients, period of correlation etc., at least in a Table. This is very important since a publication by Przybylak et al. 2005 used a tree-ring width chronology from pine (*Pinus sylvestris*) to reconstruct mean January – April air temperature for Poland.

Answer: we added the passage describing detrending methods used by us, see text below

*De-trending of the chronology was done with the dplR software (Bunn 2008) using the smoothing spline option, which reflects trends in the chronology better than other options. The “n-year spline” was fixed at two thirds the wavelength of n years (Cook et al. 1990). The residual version of the chronology was built by pre-whitening, performed by fitting an autoregressive model to the data with AIC model selection (Bunn 2008).*

Daily data shows more precisely the period of the year which influences tree growth. We used this analysis to prove assumptions about the effect of drought on trees creating narrow rings. For the rest of the comments please see the text below and Table 6.

*For each site the climate growth relationships were tested against monthly precipitation and temperature data starting from 1951 and covers maximum time span depending on the length of the chronology (Table 6). Because the time span was too short (for example for Site 2 when chronology covers the years 1951-1986) for some extended analysis going back to previous months, the common period from previous October to current September was taken into account.*

- Please avoid repetitions, e.g., on p.19, l.7-11: the two sentences are the same.

Answer: Repeated parts were deleted

- P.19, l.11-16: please rephrase and clarify this entire paragraph since it is not clear what was done and why.

Answer: Paragraph was updated to the following version:

*The optimal window of days was revealed to be from May 6 to August 3 for pine with maximal correlation coefficient 0.435, and from April 21 to July 19 for oak with maximal correlation coefficient 0.305.*

## **Anonymous Referee #2**

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This article contains a useful review, and assessment, of the occurrence and severity of drought in Poland during the past five centuries using both instrumental data (from the 18th century), historical documentary data and tree-ring width data. As past drought, or hydroclimate in general, in Poland is an under-researched topic, the manuscript is clearly worth publication after revision. The manuscript is in need of some polishing and English language editing but can otherwise, in my opinion, be published.

The entire text was corrected by a native speaker.

That said, I would still recommend the authors to consider a few things:

1) Streamline part of the text, including the Abstract and the Introduction, as especially the Abstract is too long and too detailed.

Answer: was corrected, the first Reviewer also gave the same remarks. For text see reply to the first Reviewer.

Moreover, part of the Introduction does not really well capture the state-of-the-art knowledge of hydroclimatic changes with global warming and the selection of references in the introduction is a bit biased.

Answer: We have introduced some changes to the *Introduction* Section according to the Reviewer's suggestion (for details, please see the text in the reply to the first Reviewer). We hope that now the Introduction presents the real state and is not biased.

2) The translation of narrow tree-rings to dry years/growing seasons are a bit problematic as the response between tree-growth and hydroclimate is non-linear, and not stable over time, and low temperatures may also produce narrow rings. My concern here is mainly that some of the narrow rings during the

climax of the Little Ice Age c. 1570–1710, as well as during some other shorter time intervals, may in some cases be a result of very cold springs and summers. The authors could probably systematically compare the narrow rings with climate information in the documentary sources to rule this possibility out. It is a bit unclear in the present version of the manuscript if this has been done or not. Regarding the non-linear relationship between tree growth and climate, see the discussion and references given in: <https://iopscience.iop.org/article/10.1088/1748-9326/ab2c7e>

Answer: We are aware of these limitations. Pointer years confirmed the information from historical sources and show that drought can also affect the trees.

3) I would recommend the authors to better include, and cite, the recent scholarship in historical climatology. A good starting point, with ample references, could be the articles in The Palgrave Handbook of Climate History, ed. S White et al (London: Palgrave Macmillan).

Answer: Thank you for this recommendation. According to the Reviewer's suggestion the mentioned publication, which is important for general knowledge about drought occurrence in the world and their environmental and societal consequences, was cited. There is a myriad of publications dealing with the issue of droughts, thus the authors tried to cite the most important of them. To our knowledge the most important publication items dealing with the history of drought occurrence in Poland and central Europe in the last millennium are included in the paper.

Minor comments:

Page 2 (in general): The evidence for increasing droughts in recent decades is weaker, and more controversial, than evident from what the authors write. To a large extent, the results are dependent on which drought metrics is used.

Answer: The remarks of the reviewer were taken into account, the text has been changed and we hope that we have fulfilled the reviewer's expectation, see the Introduction chapter in the reply to the first Reviewer.

It is also questionable, except in some particular regions, if there is any empirical evidence for longer breaks between episodes of precipitation.

Answer: But we wrote (see lines 5-8) that this statement concerns only "... some regions".

The present reviewer has in the past six years worked considerably with hydroclimate and not found support for this in the literature.

Answer: we added one more reference showing the small changes in drought occurrence and the sentence that the issue still needs more research. See again the Introduction chapter in the reply to the first Reviewer.

Page 2, line 5: "The increase in degree of" is a strange formulation here.

Answer: was corrected to: The increase in rate ~~in degree~~ of global warming.

Page 2, line 16: Cite also: Greve P et al 2014 Global assessment of trends in wetting and drying over land Nat. Geosci. 7 716–21

Answer: citation was added.

Page 3, lines 30–33: I guess the authors provide these examples to show that hydroclimate reconstructions also can be obtained for rather cold regions of Europe? It should be made clearer here.



Answer: The text was changed to: *Also in other countries lying near Poland, such as Finland (Helama and Lindholm, 2003), Sweden (Seftigen et al., 2013) and Czech Republic (Dobrovolný et al., 2015) the relationships are significant enough to reconstruct drought.*

Page 12, lines 12–14: It should be better pointed out that some statements about rivers that had dried out certain summers likely are not reliable or that they, at least, are overstatements.

Answer: It seems to us that the information that the reviewer suggest to include in this passage is, in reality, present in the original text, see text below:

*Sometimes, and probably in an exaggerated way, sources reported the drying up of smaller rivers.*

For this reason, this kind of information was treated by us very carefully.

Section 2.2 and section 3.2: This must be placed in a better dendro research context. In particular, the non-linear relationships between temperature and hydroclimate and tree-growth need to be discussed. I also note that the correlation between the tree-ring records and precipitation is very weak. It is far weaker than in tree-ring chronologies explicitly developed for reconstructing hydroclimate. I think it is important, and fair to the reader, to point out that many of the included tree-ring chronologies have not been developed with that purpose explicitly in mind.

Answer: After the taking into account only narrow rings and precipitation in selected period from daily data the correlation coefficient is 0.79 ( $p < 0.05$ ) for pine, and 0.65 ( $p < 0.05$ ) for oak.

Page 23, lines 7–10: This part can be shortened as it is not very clear what is meant with that drought has not been “very frequent”.

Answer: the passage was shortened according to the Reviewer’s suggestion, see below the present version:

*Records on drought for historical reconstruction of climate can be found in many different historical sources from Poland. Their number has significantly increased since the mid-15<sup>th</sup> century, which is why the mid-15<sup>th</sup> century was adopted as the initial chronological boundary for the reconstruction of the number and intensity of droughts in the Polish territory using documentary evidence.*

Page 25, lines 15–16: This is an interesting and potentially important part. Could it also be that there were fewer droughts in the first half of the 17th century in Poland because it also was the coldest part of the Little Ice Age with less evapotranspiration due to lower temperatures?

Answer: According to the reconstruction made by Przybylak et al. (2005) this period had the same winter and summer temperatures as the neighbouring historical periods. Therefore we rather prefer to leave the text as it is.

Page 26, line 31: Very strange formulation. Please, consider revision.

Answer: Text was changed to: *More chronologies in the last 300 years result from existing living trees.*

Section 3.2 and Fig. 7: The low number of dry pointer years in the medieval times is certainly a result of fewer records. This should be pointed out as dry years in the region actually seem to have been more frequent back in medieval times. See, most recently: Scharnweber, T., Heußner, K.-U., Smiljanic, M., Heinrich, I., van der MaatenTheunissen, M., van der Maaten, E., Struwe, T., Buras, A., Wilmking, M., 2019. Removing the no-analogue bias in modern accelerated tree growth leads to stronger medieval drought. *Sci. Rep.* 9, 2509. <https://doi.org/10.1038/s41598-019-39040-5>.

Answer: We agree with the Reviewer's opinion and therefore the following text was added:

*However the small number of pointer years from 996 to 1200 may be related to the low number of samples. This period is called the "medieval climate anomaly" and reconstruction for northern-central Europe revealed considerably drier conditions for these years (Scharnweber et al., 2019).*

Page 33: Try to make changes in drought trends over time clearer to the reader. As it is written now, it is a bit hard to follow this.

Answer: According to the Reviewer's suggestions some changes (see text below) were introduced to the text. We hope that now the passage is more clear for readers.

*In winter, extreme droughts do not show any significant changes over time, but it should be emphasised here that they were slightly more frequent in 1951–2000 than in 1851–1900. In spring, moderate droughts prevailed still in the period 1851–1950 (usually 4–6 cases), with a greater frequency in the earlier 50-year period. Both severe and extreme droughts were most frequent (usually 1–3 cases) in both 1851–1900 and, in particular, 1951–2000 (Fig. 10). In summer, there is a clear change in the time pattern of drought occurrence: drought frequency rises in the 20<sup>th</sup> century (except severe droughts), and in the case of moderate droughts particularly in its second half. ~~The contrast in drought~~ The frequency of extreme droughts is evidently higher in ~~between~~ the 20<sup>th</sup> century compared to the pre-1900 period. ~~is very clear, primarily in the case of extreme droughts.~~ In autumn, moderate droughts do not show great changes in the last two centuries, while severe and extreme droughts were most frequent in ~~the first and second halves of the 20<sup>th</sup> century, respectively~~ (Fig. 10).*

Page 44, lines 18–21: The formulation is unclear and a bit hard to follow.

Answer: the text was rewritten and its final state is:

*On the basis of the research presented in this paper, we conclude that severe and extreme droughts of greater importance (indexes -2, -3, respectively) were in fact slightly less frequent, while their occurrence was increasing slightly in the period from the 15<sup>th</sup> to the 18<sup>th</sup> century, as previously stated*

Page 45, line 7: "T" is missing in "This".

Answer: was corrected

Page 45, line 22: Insects rather than vermin.

Answer: was corrected

# Droughts in the area of Poland in recent centuries **in the light of multi-proxy data**

Rajmund Przybylak<sup>1</sup> ORCID: 0000-0003-4101-6116, Piotr Oliński<sup>2</sup> ORCID: 0000-0003-1428-0800, Marcin Koprowski<sup>3</sup> ORCID: 0000-0002-0583-4165, Janusz Filipiak<sup>4</sup> ORCID: 0000-0002-4491-3886, Aleksandra Pospieszynska<sup>1</sup> ORCID: 0000-0003-2532-7168, Waldemar Chorążyczewski<sup>2</sup> ORCID: 0000-0002-0063-0032, Radosław Puchałka<sup>3</sup> ORCID: 0000-0002-4764-0705, and Henryk P. Dąbrowski<sup>5</sup> ORCID:0000-0002-8846-5042

<sup>1</sup> Department of Meteorology and Climatology, Faculty of Earth Sciences, Nicolaus Copernicus University, Toruń, Poland

<sup>2</sup> Department of Medieval History, Institute of History and Archival Sciences, Faculty of History, Nicolaus Copernicus University in Toruń, Poland

<sup>3</sup> Department of Ecology and Biogeography, Faculty of Biology and Environmental Protection, Nicolaus Copernicus University, Toruń, Poland

<sup>4</sup> Department of Meteorology and Climatology, Institute of Geography, Faculty of Oceanography and Geography, University of Gdansk, Poland

<sup>5</sup> Dendroarchaeological Laboratory, Archaeological Museum in Biskupin, Biskupin, Poland

*Correspondence to:* R. Przybylak ([rp11@umk.pl](mailto:rp11@umk.pl))

**Abstract:** The history of drought occurrence in Poland in the last millennium is poorly known. To improve this knowledge we have conducted a comprehensive analysis using both proxy data (documentary and dendrochronological) and instrumental measurements of precipitation. The paper presents the main features of droughts in Poland in recent centuries, including their frequency of occurrence, coverage, duration and intensity. The reconstructions of droughts based on all the mentioned sources of data covered the period 996–2015. Examples of megadroughts were also chosen using documentary evidence, and some of them were described.

Various documentary sources have been used to identify droughts in the area of Poland in period 1451–1800 and to estimate their intensity, spatial coverage and duration. Twenty-two local chronologies of trees (pine, oak, and fir) from Poland were taken into account for detecting negative pointer years (exceptionally narrow rings). The longest chronology covers the years 996–1986 and was constructed for eastern Pomerania. The delimitation of droughts based on instrumental data (eight long-term precipitation series) was conducted using two independent approaches (Standard Precipitation Index (SPI) calculated for 1-, 3-, and 24-month time scales, and new method proposed by authors). For delimitation of droughts (dry months), the criteria used were those proposed by McKee and modified for the climate conditions of Poland by Łabędzki.

More than one hundred droughts were found in documentary sources in period 1451-1800, including 17 megadroughts. A greater-than-average number of droughts was observed in the second halves of the 17<sup>th</sup> century, and of the 18<sup>th</sup> century in particular. Dendrochronological data confirmed this general tendency in the mentioned period. The clearly greatest number of negative pointer years occurred in the 18<sup>th</sup> century and then in the period 1451–1500. In the period 996–2015, a total of 758 negative pointer years were recorded.

Analysis of SPI (including its lowest values, i.e. droughts) showed that the long-term frequency of droughts in Poland has been stable in the last two or three centuries. Extreme and severe droughts were most frequent in the coastal part of Poland and in Silesia. Most droughts had a duration of two months (about 60–70%), or 3–4 months (10–20%). Frequencies of droughts with a duration of 5 and more months were lower than 10%. The longest droughts had a duration of 7–8 months. The frequency of droughts of all categories in Poland in the instrumental period 1722–2015 was greatest in winter, while in documentary evidence (1451-1800) droughts in this season are rarely mentioned.

The occurrence of negative pointer years (a good proxy for droughts) was compared with droughts delimited based on documentary and instrumental data. A good correspondence was found between the timing of occurrence of droughts identified using all three kinds of data (sources).

1

## 2 **1 Introduction**

3 The increase of rate in degree of global warming that has been observed in recent decades also  
4 influences characteristic changes in the occurrence and intensity of precipitation (IPCC, 2013).  
5 Although precipitation totals are slightly greater from year to year in some regions, frequency of  
6 precipitation is getting lower, while its intensity is increasing. As a result, breaks between  
7 precipitation episodes are getting longer and longer, which significantly favours the occurrence of  
8 droughts. The majority of statistical analyses presenting results of droughts frequency and intensity  
9 conducted—averaged for the entire world (Dai and Trenberth, 1998; Dai et al., 2004; Dai, 2011a,  
10 b, 2013; IPCC, 2013) and its different regions (see, e.g., Held et al., 2005; Alexander et al., 2006;  
11 Bartholy and Pongracz, 2007; Łabędzki, 2007; Brázdil et al., 2009; Seneviratne et al., 2012; NAS,  
12 2013; Miles et al., 2015; Osuch et al., 2016; Bąk and Kubiak-Wójcicka, 2017; Brázdil et al. 2018)  
13 usually confirm their rising tendencies, in particular in more frequency and intensity of droughts  
14 recent decades. On the other hand, However, some authors document that this change for the entire  
15 globe is not as big clear as is presented in some the abovementioned publications and depends  
16 among others on the drought metrics used (Sheffield et al., 2012; Greve et al., 2014 and references  
17 therein). For example, Sheffield et al. (2012) They argue that overestimation of the rate of change  
18 of global droughts is related to the shortcomings (simplifications) of the Palmer Drought Severity  
19 Index (PDSI) used for this purpose. Sheffield et al., 2012 They write: “The simplicity of the PDSI,  
20 which is calculated from a simple water-balance model forced by monthly precipitation and  
21 temperature data, makes it an attractive tool in large-scale drought assessments, but may give  
22 biased results in the context of climate change.” Thus, the reliable estimate of global tendencies in  
23 the occurrence and intensity of droughts still needs more research. Nevertheless, a greater or lesser  
24 increase in frequency of droughts in many regions global scale have been observed in recent  
25 decades. Moreover, climatic models project that this tendency probably will be more common and  
26 clear in the future world. also be seen in the entire 21<sup>st</sup> century. IPCC (2013) report concludes It is  
27 very likely that droughts will be not only more frequent, but also more intense in many regions,  
28 but particularly in areas with dry conditions in today’s climate (IPCC, 2013). For this reason, the  
29 study of drought occurrence and its intensity is very important, in particular when its manifold  
30 negative socio-economic consequences are taken into account. Many aspects dealing with drought  
31 (definition; kinds – meteorological, agricultural, hydrological, socio-economic; quantitative ways  
32 of measurement; socio-economic consequences; etc.) were described recently in many  
33 publications (e.g. Wilhite and Glantz, 1985; Tate and Gustard, 2000; Herweijer et al., 2007; Mishra  
34 and Singh, 2010; Dai 2011a; Brázdil et al., 2013, 2018; IPCC, 2014; Fragoso et al., 2018; White  
35 et al., 2018) and therefore a brief overview is omitted here.

1 To estimate how unprecedented is the scale of climate drying in recent decades, a longer  
2 perspective is needed. Therefore, in recent decades quite a lot of drought reconstructions  
3 encompassing almost the entire millennium, or the shorter historical, pre-industrial period, were  
4 constructed for different greater or smaller regions (e.g. Inglot, 1968; Piervitali and Colacino,  
5 2001; Cook et al., 2004, 2010, 2015; Herweijer et al., 2007; Pfister et al., 2006; Brewer et al.,  
6 2007; Domínguez-Castro et al., 2008, 2010; Woodhouse et al., 2010; Brázdil et al., 2013, 2016,  
7 2018 (see references herein); Dobrovolný et al., 2015; Fragoso et al., 2018; Hanel et al., 2018).

8 What is the state of knowledge about droughts occurrence and intensity in Poland – the area  
9 that is the object of our studies in the paper? It must be said that for the instrumental period, and  
10 in particular for the period after World War II, the knowledge is good. Papers have been published  
11 analysing: 1) classification of drought types and the development of drought indices (Bąk and  
12 Łabędzki, 2002; Łabędzki, 2007; Łabędzki and Kanecka-Geszke, 2009; Tokarczyk, 2013;  
13 Łabędzki and Bąk, 2014); 2) tendencies in drought occurrence and intensity (Farat et al., 1998;  
14 Magier et al., 2000; Łabędzki, 2007; Kalbarczyk, 2010; Bartczak et al., 2014; Radzka, 2015;  
15 Wypych et al., 2015; Bąk and Kubiak-Wójcicka, 2017); 3) monitoring of drought conditions  
16 (Łabędzki, 2006; Doroszewski et al., 2008, 2012; Tokarczyk and Szalińska, 2013; IMGW, 2014;  
17 ITP, 2014; Łabędzki and Bąk, 2014); and 4) drought hazard assessment for periods when  
18 observations are available (Łabędzki, 2009; Tokarczyk and Szalińska, 2014). In recent years the  
19 influence of future climate change on the occurrence of droughts in Poland in the 21<sup>st</sup> century has  
20 also been addressed (Liszewska et al., 2012; Osuch et al., 2012, 2016). On the other hand, little is  
21 known about drought occurrence in the pre-instrumental and early instrumental periods in Poland.  
22 Generally, only one ~~attempt~~ team of researchers under the direction of professor Stefan Inglot of  
23 ~~Wrocław University was focusing on this issue, in the 1960s. As a result, a first attempted~~  
24 ~~chronology~~ of droughts **chronology** for the 16<sup>th</sup> to mid-19<sup>th</sup> century was proposed based on  
25 documentary evidence (Inglot, 1968).

26 Drought is the one of the most stressful factors for trees (Vitas, 2001; Allen et al., 2010; Sohar  
27 et al., 2013). The measurement of tree ring widths is one of the ways to study the effect of climate  
28 parameters on trees (Zielski et al., 2010). Some factors such as frost or summer drought may have  
29 an immediate effect on ring width, whereas other factors, such as winter drought, may have a  
30 delayed effect on ring widths. This delayed effect occurs because the meristematic tissues are  
31 dormant during the winter months in temperate and cold climates. The effect of different factors  
32 is seen as variations in ring size and structure, which change systematically, or vary slowly  
33 throughout the life of the tree (Fritts, 1976). The effect of drought on tree rings is observed as  
34 narrow rings (Koprowski et al., 2012; Opała, 2015). The relationships are significant enough to  
35 reconstruct drought **in temperate climate also in cold regions like** Finland (Helama and Lindholm,  
36 2003), Sweden (Seftigen et al., 2013) and Czech Republic (Dobrovolný et al., 2015). Therefore,

1 we have assumed that information derived from tree rings can complement the existing knowledge  
2 about past droughts in Poland. According to studies by Somorowska (2016) the effect of drought  
3 extends from rom the south-west towards the center part of the country and, in some cases, to the  
4 north-east of Poland. Another study suggest that in the future some of the highest probability of  
5 drought occurrence can be in the central part with the lowets probability in south-eastern Poland  
6 (Diakowska et al., 2018).

7 Although in the last three decades many climate reconstructions for the last millennium have  
8 been conducted for Poland (see Przybylak et al., 2005 or Przybylak, 2016 for a review), droughts  
9 were not analysed. Therefore, to fill this important gap we decided to investigate them in more  
10 **detailed manner** than was done by the Inglot’s team. Moreover, for this purpose we used more  
11 sorts of proxy data (not only documentary but also dendrochronological). The reconstructions of  
12 droughts based on all the mentioned sources of data covered the period 996–2015. Thus, the main  
13 aim of the paper is to present the main features of drought occurrence, duration and intensity in  
14 the area of Poland in this period. Section 2 describes all the kinds of data used and their quality.  
15 Section 3 addresses the methods used in this study, including drought indices. Section 4 presents  
16 the results of three reconstructions of droughts derived from 1) documentary, 2) instrumental, and  
17 3) dendrochronological data. Examples of megadroughts are also analysed here. The results  
18 obtained are discussed in Section 5, and main conclusions in the last section.

19

## 20 **2 Data**

21

### 22 **2.1. Documentary data**

23

24 Records on drought **for historical reconstruction of climate** can be found in many different  
25 historical sources from Poland. Their number has significantly increased since the mid-15<sup>th</sup>  
26 century, which is why the mid-15<sup>th</sup> century was adopted as the initial chronological boundary for  
27 the reconstruction of the number and intensity of droughts in the Polish territory using  
28 documentary evidence. Below we describe the types of historical sources used to reconstruct  
29 droughts in Poland.

30 Records of droughts in the Polish territory are most often found in narrative sources –  
31 chronicles, yearbooks, memoirs, diaries, travel accounts. The information included in these  
32 sources has a varying degree of accuracy. Often only one account concerning drought appeared,  
33 such as, for example, “magna siccitas”. In many of the records, however, more detailed  
34 descriptions of the course of droughts and accompanying phenomena were given. In the ancient  
35 sources droughts were described above all when their manifestations were very clear and when  
36 they had an impact on economic and social life. Another group of sources used by us are daily

1 records that have the character of meteorological observations. Sometimes, they were prepared by  
2 scholars such as professors of the Jagiellonian University Marcin Biem (ca. 1470–1540) and  
3 Michał of Wiślica (1499–1575), who conducted such observations in Kraków from 1499 to 1531  
4 and from 1534 to 1551 (Limanówka, 2001), or townsmen with scientific ambitions such as  
5 Gottfried Reyger (1704–1788), who began his observations in Gdańsk in 1721 as a 17-year-old  
6 and continued them later, among others as a member of the *Naturforschende Gesellschaft* in  
7 Gdańsk until 1786 (Filipiak et al., 2019). Sometimes daily observations were conducted by  
8 amateurs, the best example of which are the records of the Polish nobleman from the eastern  
9 territories of the Polish–Lithuanian Commonwealth, Jan Antoni Chrapowicki, which were  
10 conducted for the years 1656–1685 (Nowosad et al., 2007). Sources of this kind are nonetheless  
11 relatively rare.

12 The correspondence, the manuscript press (“written newspapers”) and printed press were  
13 also used in the reconstruction of droughts. In the case of written newspapers, these are often  
14 records similar to those that appear in chronicles. They were drawn up on a regular basis, which  
15 increases their credibility. They provided news from the region, as well as information coming  
16 from other countries, e.g. from Lviv, from which a newswriter in 1698 wrote: “w tych krajach  
17 chaniebnie [! – emphasis added] susze wielkie, dla których na zimę bardzo mało siano, bo nie  
18 podobna lemiem ukroić ziemię” (ang. *in these countries shamefully there are great droughts,*  
19 *for which reason we sowed very little for the winter, because you cannot cut the land with the*  
20 *ploughshare*”) (Maliszewski, 2018). Other sources that turned out to be useful for the  
21 implementation of our project were official files (e.g. protocols from meetings of the regional  
22 dietines **and the Parliament (Sejm)**, treasury registers, inspection reports) documenting activities  
23 undertaken, e.g. in connection with droughts and fires. They reported requests for financial support  
24 in connection with drought, tax exemption requests, etc. In economic files one can find  
25 explanations for low harvests, which occurred for example due to drought. There are a few sources  
26 concerning religious behaviours in which, for example, the organisation of prayers asking for rain  
27 or describing the end of a drought were described. When such accounts appeared, it can be  
28 assumed that the drought must have been severe for people and the environment.

29 In addition to the above mentioned historical sources collected during the queries in Polish,  
30 Lithuanian, Ukrainian and German archives, the authors used several published collections (of  
31 varied quality) of historical sources concerning the climate research in the period from the 10<sup>th</sup>  
32 century to the end of the 18<sup>th</sup> for Poland, Europe Central or selected regions of Central Europe.  
33 They include: the period from the 10<sup>th</sup> century to the end of the 16<sup>th</sup> (Girguś et al., 1965); the  
34 Middle Ages (Malewicz, 1980); 1450–1586 (Walawender, 1935); the years 1648–1696  
35 (Namaczyńska, 1937); and 1772–1848 (Szewczuk, 1939). In the last 20 years, two databases  
36 containing over ten thousand weather records were made available in universities in Toruń and



1 Wrocław as part of cooperation between climatologists and historians. They have been used many  
2 times to study Poland's climate in historical times (Wójcik et al., 2000; Przybylak et al., 2001,  
3 2004, 2005, 2010; Przybylak, 2011, 2016); they have also contributed to widening the scope of  
4 this research.

5 To sum up, for the purpose of this research over 200 accounts referring directly to droughts  
6 and prolonged shortages of rainfall were used, along with a few hundred more descriptions from  
7 everyday weather observations, the use and critical elaboration of which allowed periods of  
8 drought to be indicated. The state of the preservation of sources for particular periods and for  
9 individual regions is uneven. Most of them describe droughts in Silesia, Pomerania and Lesser  
10 Poland. A large number of entries refers to droughts affecting the whole territory of Poland. In the  
11 case of Silesia, the distribution of sources is fairly even for the whole period; in the case of other  
12 regions their number increases with successive ages. The only exception is the first half of the 17<sup>th</sup>  
13 century, in which the number of preserved records is definitely smaller. To some extent, this was  
14 affected by the losses in the state of preserved sources that occurred during the Swedish invasion  
15 on Polish territories in 1655-1660. Many sources from the first half of the 17<sup>th</sup> century were then  
16 destroyed as a result of military actions.

17 The accuracy scale of the collected information is variable. Some accounts provide quite  
18 precise information concerning the duration of the drought, even to the accuracy of one day, while  
19 others are definitely more general – they only indicate the existence of a drought in a given year.  
20 It very often occurs that one drought is described in several, or sometimes even several dozen,  
21 independent sources, which confirms its high intensity.

22 To assess the credibility of individual records, it was necessary to conduct a critical source  
23 analysis, in which it turned out that sometimes even short accounts provided very important and  
24 reliable information, while other records with a similar structure proved to be wrong due to the  
25 fact that, e.g., the year of the occurrence of the drought was changed (e.g. by one year) when the  
26 information was being copied from another, earlier source. The sources containing daily records,  
27 as in the case of the memoirs of A. Chrapowicki or G. Reyger required a different treatment. It  
28 was possible to count the days with precipitation and without precipitation along with a very  
29 precise indication of the duration of the droughts.

30

31

## 32 **2.2. Dendrochronological data**

33

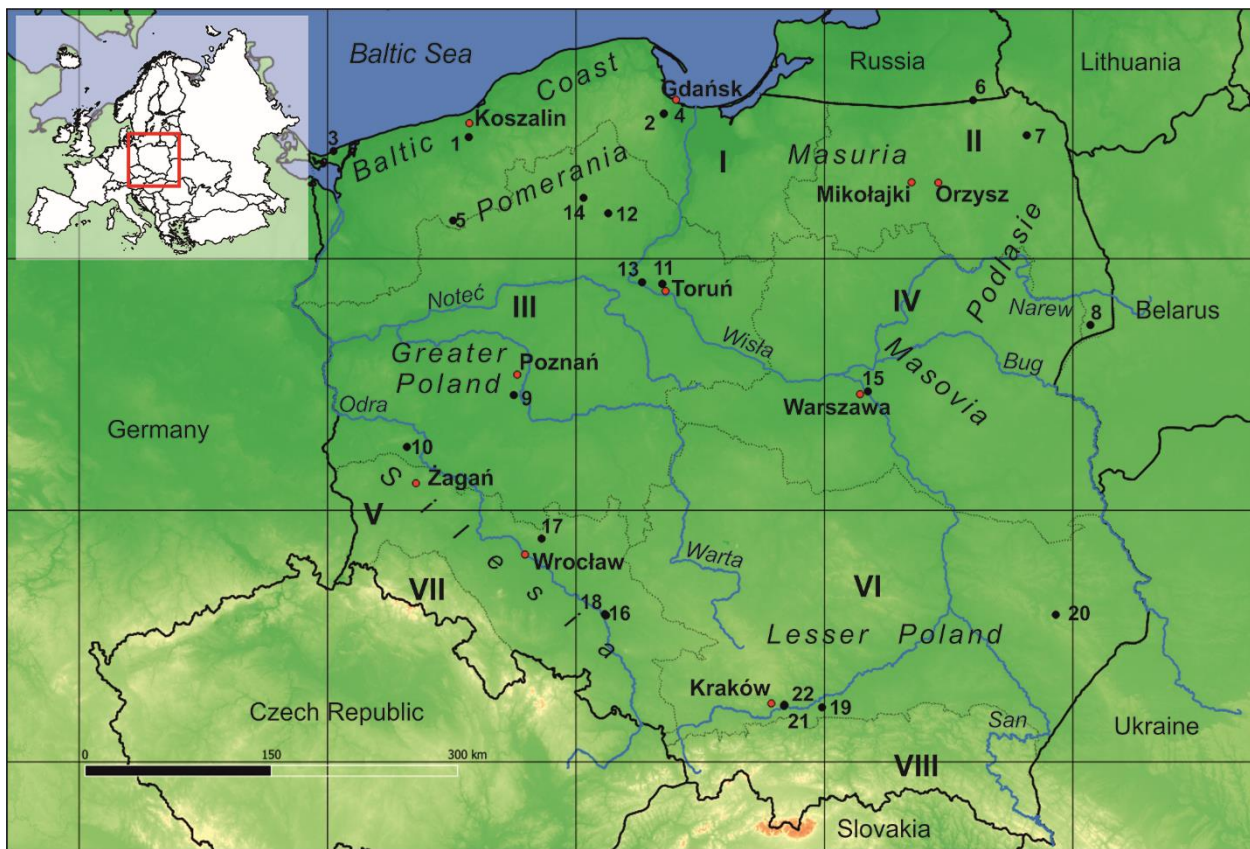
34 We used 22 chronologies (17 oak chronologies, 5 pine chronologies and 1 fir chronology) from  
35 different locations in Poland to detect pointer years (Table 1, Fig. 1). Table 1 presents a list of  
36 them, including also time coverage and sources. As results from this Table, the longest

1 chronology available to us covers the years 996–1986 and was constructed for ~~easter~~-western  
 2 Pomerania (Site 5). For Upper Silesia (Sites 16 and 18) and Lesser Poland (Sites 21 and 22), the  
 3 pointer years were detected by Opała and Mendecki (2014) and Opała (2015) for Upper Silesia,  
 4 and by Szychowska-Krąpiec (2010) for Lesser Poland (Table 1, Fig. 1).

5  
 6 Table 1. Basic characteristic of the chronologies used for pointer year analysis. Location  
 7 of natural-forest regions (Zielony and Kliczkowska, 2010) and sites is shown in Fig. 1.  
 8 EPS- expressed population signal, rbar.tot- the mean of all correlations between different  
 9 cores  
 10

Site number	Site name	Time span	Number of samples	EPS	rbar.tot	Species	Source
<b>Region I (Baltic Province)</b>							
Site 1	Koszalin	1782 – 1987	22	0.899	0.339	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 2	Gdańsk	1762 – 1986	45	0.887	0.192	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 3	Wolin	1554 – 1987	23	0.877	0.318	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 4	Gdańsk	1175 – 1396	13	0.579	0.388	Oak	Dąbrowski HP, unpublished
Site 5	western Pomerania	996–1986	205	0.907	0.250	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
<b>Region II (Masuria-Podlasie Province)</b>							
Site 6	Gołdap	1871 – 1987	22	0.941	0.472	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 7	Suwałki	1861 – 1987	19	0.872	0.303	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 8	Hajnówka	1720 – 1985	19	0.851	0.314	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
<b>Region III (Greater Poland-Pomerania Province)</b>							
Site 9	Poznań	1836 – 1987	17	0.904	0.385	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 10	Zielona Góra	1774 – 1987	19	0.876	0.330	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 11	Toruń	1714 – 2015	48	0.886	0.335	Oak	Puchałka et al., 2016 (updated)

Site 12	Tuchola	1249 – 1490	7	0.054	0.347	Pine	Dąbrowski HP, unpublished
Site 13	Kuyavia-Pomerania	1169 – 2015	247	0.816	0.195	Pine	Koprowski et al., 2012
Site 14	Chojnice	1100 – 1468	21	0.688	0.327	Oak	Dąbrowski HP, unpublished
Region IV (Masovia-Podlasie Province)							
Site 15	Warszawa	1690 – 1985	19	0.850	0.291	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Region V (Silesia Province)							
Site 16	Upper Silesia	1770 – 2010	80	0.880 (average)	correlation 0.530	Pine and oak	Opała and Mendecki, 2014
Site 17	Wrocław	1727 – 1987	22	0.870	0.327	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 18	Upper Silesia	1568 – 2010	178	0.850	correlation 0.510	Pine	Opała, 2015
Region VI (Lesser Poland Province)							
Site 19	Kraków	1792 – 1986	29	0.906	0.361	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 20	Kosobudzy	1782 – 1989	22	0.937	0.448	Oak	<a href="https://www.ncdc.noaa.gov/">https://www.ncdc.noaa.gov/</a> (Ważny, 1990)
Site 21	Lesser Poland	1109 – 2004	238	No data	No data	Pine	Szychowska-Krapiec, 2010
Site 22	Lesser Poland	1109 – 2006	560	No data	No data	Fir	Szychowska-Krapiec, 2010



1

2 Fig. 1. Location of dendrochronological sites and natural-forest regions (black dots and black  
 3 dotted lines, respectively, for more details see Table 1) as well as meteorological series (red dots)  
 4 and geographical regions (for more details see Table 2) used in the study.

5

6

7

### 2.3. Instrumental data

8

#### 2.3.1. Isolated series

9 The number of known precipitation series and whose beginnings date back to earlier than the 20<sup>th</sup>  
 10 century is very limited. There are only a dozen of those begun before 1800. Efforts to organise  
 11 meteorological measurements in Poland were made relatively early in comparison to other  
 12 European countries. The country's complicated history (e.g. many wars and changes of borders)  
 13 has resulted in the loss of the majority of sources collected in the archives, in many cases  
 14 irretrievably. However, actions to restore the long measurement series based on the discovered  
 15 collections have been taken for a few selected locations.

16 The oldest surviving results of instrumental precipitation series in Poland come from  
 17 Gdańsk and are dated to the first half of the 18<sup>th</sup> century. In January 1739, Michael Christoph  
 18 Hanov, a mathematician and physician, started daily observations of weather phenomena and  
 19 measurements of a dozen meteorological elements, including precipitation. The results of his  
 20 efforts were published in the newspaper *Danziger Erfahrungen* on a weekly basis. Hanov  
 21 presented the complete series in his manuscript *Wetter Beobachtungen in Danzig 1739–1773*.

1 Hanov's instrumental series was accompanied by the notes from a weather chronicle  
2 authored by Gottfried Reyger. He started systematic observations of the weather in Gdańsk in  
3 December 1721 and carried them out until the mid-1786. The results of observations were used  
4 mainly to study how climate affects the development of plants. Reyger published the outcomes of  
5 his studies in *Die Beschaffenheit der Witterung in Danzig vom Jahr 1722 bis 1769 beobachtet*  
6 *nach ihren Veränderungen und Ursachen erwogen* (Reyger, 1770) and in *Die Beschaffenheit der*  
7 *Witterung in Danzig. Zweyter Theil vom Jahr 1770 bis 1786, nebst Zustätzen zur Danziger Flora*  
8 (Reyger, 1788).

9 Reyger usually presented remarks on general weather conditions supplemented by some  
10 additional data. Months were usually described in a qualitative, even aggregate, manner. His notes  
11 were very detailed and even the weather of the particular days or weeks was very often  
12 characterised. Reyger paid special attention to particularly important weather and climate  
13 phenomena (heavy rain, floods, droughts, and heat and cold waves). His notes after 1783 (Hanov's  
14 death) were more accurate. Despite the lack of measured values of precipitation, detailed data on  
15 the monthly number of rainfall and snowfall were presented (for more details including the  
16 reconstruction of the air temperature and precipitation series since 1721 see Filipiak et al., 2019).  
17 Some sources suggest an even earlier date for the beginning of Reyger's instrumental observations  
18 (Hellmann, 1883, after Rojecki, 1965). Besides the short description in the mentioned literature no  
19 other proof of such activity is available.

20

### 21 **2.3.2. Long-term continuous series**

22 The series from Wrocław (formerly Breslau) that commenced in 1791 (Bryś and Bryś, 2010) is  
23 the longest continuous Polish precipitation series. For the purpose of the present paper we  
24 prolonged this series until 1781 based on precipitation measurements in Żagań (formerly Sagan)  
25 within the Mannheim network of stations established for Europe and North America by the  
26 Palatine Meteorological Society in 1780 (Przybylak et al., 2014). The cited authors proved that  
27 there exist high correlations between the precipitation series from both places. Source data from  
28 Żagań were taken from the publication *Ephemerides Societatis Meteorologicae Palatinae, 1783–*  
29 *1795*. In addition, we must say that the Wrocław series is the only continuous series to have begun  
30 before 1800 in the area currently belonging to Poland. The best known long-term climatological  
31 series in Poland is the one from Kraków that commenced in 1792. The work on completing the  
32 collections of the Kraków series continue till the present day, the effect of which are  
33 reconstructions of monthly values of precipitation sums since 1863 (Twardosz, 2005, 2007). As  
34 for other Polish cities, Lorenc (2000) performed a homogenisation of series of monthly  
35 precipitation totals of Warszawa (Warsaw) since 1813. Miętus (2002) reconstructed atmospheric

1 precipitation sums from Koszalin (formerly Köslin) since 1848. In another paper, Kożuchowski  
2 and Miętus (1996) presented series of precipitation totals in Szczecin (formerly Stettin) since 1848.  
3 In 2011 a reconstruction was performed of the precipitation series from Gdańsk in 1880–2008  
4 (further extended to 1851) (Filipiak, 2011). During the CLIMPOL project (Climate of northern  
5 Poland during the last 1000 years: Constraining the future with the past) Filipiak reconstructed the  
6 series of monthly precipitation totals since 1891 for Lake Żabińskie in NE Poland (54°07' N;  
7 21°59' E) (Larocque-Tobler et al., 2015). Further, the series of Orzysz (formerly Arys) and  
8 Mikołajki (formerly Nikolaiken), also in NE Poland, were collected for the years 1830–1904 and  
9 since 1889, respectively. As both stations are located very close to one another (approximately 20  
10 km) these two series have very much in common. The correlation coefficient calculated for the  
11 overlapping periods 1889–1904 and 1981–2015 exceeds 0.85. Thus we decided to combine both  
12 series: data from Orzysz covers the period between 1830 and 1890, the later data comes from  
13 Mikołajki. A couple of series, e.g. Poznań (formerly Posen), Toruń (formerly Thorn), Racibórz  
14 (formerly Ratibor, **Silesia**), Śnieżka (formerly Schneekoppe, **Sudety Mountains**), began around the  
15 middle of the 19<sup>th</sup> century and are available in yearbooks that were initially released by the Royal  
16 Prussian Meteorological Institute (Königlich Preussischen Meteorologischen Institut), then since  
17 1918 by the Polish National Meteorological and Hydrological Service (PIM until 1945, further  
18 PIHM and finally, after 1972 IMGW). The complete list of instrumental series employed in the  
19 current research and their sources are presented in Table 2.

20 Table 2. List of sites, their locations and periods covered by series of monthly precipitation totals  
21 used in the paper

No.	Station	Geographical region	Observation period	Location (φ, λ, h)	Sources of data
Isolated series					
1a	Gdańsk *	1	1722–1786	54°20'N 18°40'E 13 m a.s.l.	Reyger (1770, 1788) and Filipiak et al. (2019) for the periods 1722–1738 and 1773–1786; Hanov (1773) for the period 1739–1773
Long-term continuous series					
1b	Gdańsk	1	1851–2015	54°20'N 18°40'E 13 m a.s.l.	Filipiak (2010 modified 2018) for the whole period
2	Koszalin	1	1851–2015	54°12'N 16°11'E 46 m a.s.l.	Reichsamt für Wetterdienst (1939) for the period 1851–1930 corrected by Miętus (2002); Miętus (2002) for the period 1931–1990; Central Database of Historical Data of IMGW-PIB (Polish National Meteorological and Hydrological Service) for years 1991–2015

3a	Orzysz	2	1830–1890	53°48'N 21°56'E 122 m a.s.l.	Dove (1851) for the period 1830–1850; Reichsamt für Wetterdienst (1939) for the years 1851–1904
3b	Mikołajki	2	1891–2015	53°48'N 21°34'E 116 m a.s.l.	Central Database of Historical Data of IMGW-PIB for the whole period
4	Toruń	3	1871–2015	53°01'N 18°36'E 60 m a.s.l.	Pospieszyńska and Przybylak (2013) for the period 1871–2010; Central Database of Historical Data of IMGW-PIB for years 2011–2015
5	Poznań	3	1848–2015	52°25'N 16°56'E 66 m a.s.l.	Dove (1851) for the period 1848–1850; Central Database of Historical Data of IMGW-PIB for the years 1851–2015
6	Warszawa	4	1813–2015	52°13'N 21°01'E 97 m a.s.l.	Lorenc (2000, 2007) for the years 1813–1999; Central Database of Historical Data of IMGW-PIB for the years 2000–2015
7a	Żagań	5	1781–1790	51°37'N 15°19'E 102 m a.s.l.	<i>Ephemerides Societatis Meteorologicae Palatinae, 1783–1795</i> for the whole period
7b	Wrocław	5	1791–2015	51°07'N 17°05'E 120 m a.s.l.	Bryś and Bryś (2010) for the years 1791–2000; Central Database of Historical Data of IMGW-PIB for the years 2001–2015
8	Kraków	6	1876–2015	50°04'N 19°58'E 216 m a.s.l.	Koźuchowski (1985) for the period 1876–1900, Twardosz (2007) for the years 1901–2000, Central Database of Historical Data of IMGW-PIB for the years 2001–2015

1

2 Key: geographical regions: 1 – Baltic Coast – Pomerania, 2 – Masuria – Podlasie, 3 – Great  
3 Poland, 4 – Masovia, 5 – Silesia, 6 – Lesser Poland

4 \*the series for periods 1722–1738 and 1773–1786 were reconstructed based on Reyger's weather  
5 chronicle

6

### 7 3. Methods

#### 8 3.1. Documentary data

9 The collected historical sources informing about droughts were evaluated according to a three-  
10 level scale, taking into account, first of all, signalled manifestations and consequences of the  
11 drought and its duration. The droughts were divided into “extreme”, “severe” and “moderate”.

12 Extreme droughts (**index** -3) constituted periods of no rainfall or very scarce rainfall that  
13 were long-lasting – they lasted at least one season (2–3 months and more). The principle was  
14 adopted that extreme droughts should be recorded in sources from two regions or more; even in

1 view of the absence of sources this allows us to assume that these were droughts of an exceptional  
 2 nature, having been noted by many writers. Such an extreme drought of 1473 was described,  
 3 among others, in the “Annals” by Jan Długosz and, for example, in the local chronicle of Wrocław  
 4 by Nicolaus Pol. **When the source information indicated an extreme drought, but at the same time**  
 5 **there appeared information, for example, about the high level of water or floods, which may have**  
 6 **indicated heavier precipitation especially in the summer season, it was concluded that no extreme**  
 7 **drought had taken place.** In agricultural terms, extreme droughts contributed to much earlier cereal  
 8 harvests; they often seriously threatened the growth and size of yield, as was mentioned in the  
 9 sources. Descriptions of extreme droughts usually contain several permanent elements: severe  
 10 water shortages, fires, the destruction of crops; sometimes there also appeared records about the  
 11 fact that people did not remember a similar drought having occurred in their lifetime. These  
 12 droughts caused water reservoirs – ponds and lakes – to dry up completely. Sometimes, and  
 13 probably in an exaggerated way, sources reported the drying up of smaller rivers.

14 During extreme droughts, there were frequent records of persistent very low water levels  
 15 in the largest rivers – the Odra and the **Wisła** ~~Vistula~~ (Table 3). The result was a lack of water for  
 16 people and animals, halting the work of water mills in whole provinces. The consequences of  
 17 drought were underlined – particularly a lack of food and high prices. Numerous fires broke out  
 18 in cities, villages and forests. The sources used such phrases as “*estas ferventissima et siccitas*  
 19 *inaudita*” [very hot and incredible summer drought], “*sidere solari plus solito effervescente et*  
 20 *nullas dante pluvias*” [extraordinary sun heat and continuous drought], “*unaufhörlich trockene*  
 21 *Witterung*” [unbelievably dry weather], “*alle Bäche vertrockneten*” [all streams dried up] and the  
 22 like, underlining the extreme nature of the drought. Superlative adjectives were very often used.

23

24 Table 3. Examples of descriptions of extreme droughts in 15<sup>th</sup>–17<sup>th</sup>-century sources

Year	Description	Translation	Source
1463	<i>[...] fuit magnus calor et arditas, ita quod sylvae, nemora et montana incenderentur, ex voragine ignis pro magna parte absumptae</i>	<i>[...] there were such great heat and drought that forests, groves and mountain vegetation burned, and were largely destroyed by the fire</i>	Rocznik wrocławski dawny, MPH, vol. 3, p. 686
1473	<i>[...] caumata et penuriam aquarum, adeo ut perennes aquae verterentur in aridam, et flumina Poloniae principalia ubique fuerunt permeabilia,</i>	<i>[...] hot weather and a lack of water, to such an extent that the places where there had always been water dried up everywhere, and the main</i>	Długosz, vol. 12, p. 336



	<i>insignis. [...] Fumabant in universis Poloniae regionibus silvae, borrae, arbusta, saltus, irremediabili igne, nec ante rescindi flamma poterat, donec ignis etiam radicem arborum voraret, ex quo ubique fragor ruentium saltuum audiebatur. Apum quoque et alveariorum arbores plurimae deletae, segetes vernaes exterminatae siccitate.</i>	Polish rivers could be crossed everywhere. [...] Forests, woods, thickets and forested hills burnt with fire; there was no way to put it out, and it was impossible to extinguish the flame before the fire even devoured the root of the trees; from here you could hear the clatter of collapsing thickets. Very numerous bee and beekeeping trees were destroyed, and many spring crops were destroyed due to drought.	
1540	<i>[...] fuit in aestate horrenda siccitas adeo, ut silices, montes et valles quasi igne flagrarent, duravit haec siccitas usque ad hyemem.</i>	[...] in the summer there was such a terrible drought that the rocks, mountains and valleys were burned down with fire; this drought lasted until winter	Archivum vetus et novum ecclesiae archipresbyteralis Heilsbergensis, in: MHW, vol. 8, p. 597
<del>1561</del>	<del><i>Im Julio und Augusto war es sehr dürre und dürre Winde, dass das Wasser sehr austrocknete. Die Oder war klein, dass es keinem Mann gedachte. Viel Brunnen trockneten aus.</i></del>	<del>In July and August there were dry and very dry winds, so that the water completely dried out. The Odra became shallow as it had never been before. Many wells dried up.</del>	<del>Pol, vol. 4, p. 17</del>
<del>1575</del>	<del><i>At in Polonia inaudita fere siccitas vere, aestate, autumno et hyeme denique aestivalium segetum, quas arefecerat, penuriam fecit, amnium vero undas adeo minuit, ut iis passim fere privaretur ipsaque Vistula</i></del>	<del>However, in Poland, a truly unbelievable drought, in summer, autumn and winter, along with spring crops that had dried up, caused poverty[:] the level of the water in rivers had fallen so much that</del>	<del>Orzelski, in: SRP, vol. 22, p. 360</del>

	<del><i>infra Dobrinum multis locis vadabilis fieret, unde nec sal e Russia per Sanum in Vistulam permeari potuit.</i></del>	<del>everywhere the rivers almost disappeared, while the Wisła Vistula in many areas below Dobrzyń became quite shallow, and it was not possible to transport any salt from Ruthenia through the San to the Wisła Vistula.</del>	
1590	<i>Ist ein sehr heisser truckener Sommer gewesen, also, dass auch die Landflüsse, als der Bober, Queiss, Katzbach, Weida, Olau, Lohe, und andere mehr gänzlich ausgetrocknet. Die Oder ist auch so klein worden, dass man sie an allen Orten durchwatten können.</i>  <i>38 Wochen regnete es nicht. Die Flüsse trockneten aus.</i>  <i>Zacken und andere Flüsse trockneten völlig aus</i>  <i>Der Bober trocknete infolge starker Hitze ganz aus.</i>	The summer was so hot [and] dry that <del>national</del> regional rivers like the Bóbr, the Kwisa, the Kaczawa, the Widawa, the Oława, the Ślęza [Silesia, auth. suppl.] and many others dried up completely. The Odra also became very shallow, so you could cross it anywhere.  It did not rain for 38 weeks. The rivers dried up.  The Kamienna and other rivers dried up completely.  The Bóbr dried up completely due to severe drought.	Pol, vol. 4, p. 156  Reinhold, 1846, p. 143  Bergemann, J.G., 1830a, p. 84  Bergemann, J.G. 1830b, vol. 3, p. 85
1653	<del><i>In Monath Maii fiel ein dürres Wetter ein, und dauerte biss Ende August. Die alle Bäche vertrockneten, auch Flachs und Gerste verdorrete.</i></del>	<del>In the month of May the dry weather began and lasted until the end of August. All streams dried up, as did flax and barley.</del>	<del>Gomoleke, p. 53</del>
1676	<del><i>Tego roku straszne Panowały Susze, że zboża wypalało w polach.</i></del>	<del>That year a terrible drought took place so that crops burnt in the fields.</del>	<del>Muz. Nar. w Krakowie rps. MNKr. 169, p. 82</del>

1683	<i>Im Jahre 1683 entstand durch die grosse Dürre und den Misswachs eine starke Theuerung und ein fast gänzlicher Mangel an Getreyde.</i>	In 1683, due to the great drought and poor growth [of grain], high prices and almost complete lack of grain prevailed.	Pisański, Beschreibung der Stadt Johannisburg, p. 96
1684	<i>[...] folgete auf Johanni [24.06.] eine grosse anhaltende Hitze darauf; davon das Erdreich dermassen dürre wurde, dass das Sommer-Getreyde, Flachs, und Grass, gantz zurüeke geblieben, das Winter-Korn an vielen Orten überreiffte, ehe es sich gehöriger massen in die Ahren kaum angesetzt, dahero Theurung entstanden [...]</i>	The great long-lasting drought arrived on the St. John's Day [24.06.]; the ground became dry, the crops became dry; flax and barley grew very poorly before the proper ear of grain had come out, which caused very high prices [...]	Gomoleke, p. 54

1

2 Severe (~~strong~~) droughts that lasted almost the whole season but no longer (up to about 2–3  
3 months) were marked with the -2 index. When they fell in the spring period of plant growth, they  
4 influenced the quality of the harvest. It was frequently reported that crops had dried up in fields  
5 on hillslopes especially exposed to the sun and with less humid soils than in the valleys. Those  
6 droughts made it difficult for people and animals to obtain water; sometimes they prevented the  
7 work of some mills on the rivers, but they did not paralyse grain milling in the entire province.  
8 Droughts were incidentally related to forests and meadows. Efforts were made to focus on those  
9 descriptions in which at least two of the phenomena described above appeared. There was no  
10 requirement to describe such droughts in more sources. Examples of descriptions of severe  
11 droughts in different historical sources are presented in Table 4.

12

13 Table 4. Examples of descriptions of severe droughts in 15<sup>th</sup>–17<sup>th</sup>-century sources

Year	Description	Translation	Source
1456	<i>Fuitque anno eodem precipue circa partes nostras, ubi plures sunt agri sabulosi et argillosi, post festa paschalia siccitas</i>	And that year there was an exceptionally great drought in our area, where there are numerous sandy and loamy	Catalogus abbatum Saganensium, in: Scriptorum rerum

	<i>magna et usque ad messem continuata. Messis autem tante humiditatis et instabilitatis,</i>	soils; it occurred after the Easter holidays and lasted until the harvest. In the harvest period it [the weather] was so wet and unstable [...]	Silesiacarum, vol. I, p. 340
1472	<del><i>Dieser Sommer, von Pfingsten bis auf aller Heiligen, war ganz trocken und warm [...]</i></del>	<del><i>That summer from Whitsunday to the All Saints Day it was quite dry and warm [...]</i></del>	<del><i>Pol, vol. 2, p. 89</i></del>
1532	<i>Ein dürrer Sommer. Es regnete in sieben Wochen nicht. Das Getreide und die Weide verdorrete auf den Hügeln ganz aus. In etlichen Dörfern war kein gar Wasser. Auf dem Lande konnte man nicht mahlen. Zu 10. 12. 18. Meilen musste man zur Mühle führen. Die Olau trocknete und dorrete auch aus, und hatte kein Wasser bis auf Bartholomei [24.08].</i>	Dry summer. It did not rain for seven weeks. The grain and grass on the hillsides dried up. In some places there was almost no water. In the countryside, it was impossible to grind grain. One needed to go 10, 12, 18 miles to reach mills. The Oława River dried up [Silesia, auth. suppl.] and there was no water in it until the Saint Bartholomew's Day [August 24].	Pol, vol. 3, p. 72
1585	<del><i>Mensis hic [March] fuit serenissimus usque ad miraculum et siccus</i></del>	<del><i>That month [March] the weather was fine and it was dry</i></del>	<del><i>Reszka, p. 91</i></del>
1637	<del><i>Przy przeważającej w tym miesiącu suszy ogień zniszczył liczne miasta i wsie, widać słabnące plony [...]</i></del>	<del><i>With the drought that prevailed that month, fire destroyed many cities and villages, we could see the yields failing [...]</i></del>	<del><i>Radziwiłł Albrycht Stanisław, Pamiętnik o dziejach w Polsce, vol. 2 1637–1646, A. Przyboś, R. Żelewski (eds), Warszawa, 1980</i></del>

1665	<i>Der Sommer des Jahres 1665 wird als ungemein heiss angegehen, und soll es die ganzen Hundstage [10.07.–20.08.] hindurch auch nicht einmal geregnet haben.</i>	The summer of 1665 was incredibly hot; not even once did it rain – so called “Dog Days”.	Wernicke, Gesch. Thorns., vol. 2, p. 321
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1

2 Moderate droughts – marked with the -1 index – were ones whose appearance was noticeable by  
3 people; however, they lasted for a relatively short period of time and affected crops to a limited  
4 extent. This group also includes records that seem incidental, are not confirmed in other sources,  
5 or may indicate a small range of drought, yet they were significant enough to be recorded in the  
6 sources (Table 5). There is no record of consequences (including economic ones). In the  
7 description of the drought, a superlative adjective is not used. There appear such expressions as  
8 “*dürerer Sommer*” [dry summer]. In other sources, in reference to the same period of time, there  
9 may be records that indicate, for example, rain instead of drought.

10 Table 5. Descriptions of moderate droughts in 15<sup>th</sup>–17<sup>th</sup>-century sources

Year	Description	Translation	Source
1461	<i>Eodem anno fuit estas calidissima et fluvius Odere valde modicus, similiter et alii fluvii.</i>	That year the summer was the hottest and the water level of the Odra River fell, as did other rivers.	Sigismundi Rosiczii chronica, p. 78.
<del>1531</del>	<del><i>Nazajutrz po bitwie pod Obertynem [22.08.] kometa nie dała się już tak świetnie widzieć iako przesley nocy: która ieśli nie porażkę Wołoską, tedy suszą podobno znamieniowała; iakoż tego czasu była susza wielka.</i></del>	<del>The following day, after the battle of Obertyn [22.08.], the comet did not let itself be seen so well as it had the previous night, which augured the defeat of the Vlachs, or drought; And then the drought was really great.</del>	<del>Bielski, p. 311</del>
1552	<i>Den 5 Junii [...] nach der Vesper und grosser Dürre kam ein gewünschter Regen, aber mit grossem Wetter</i>	On June 5 [...] after the evening and after a great drought, came the desired rain with a great storm.	Pol, vol. 3, p. 158.
1661	<i>Es folgte aber ein dürerer Sommer.</i>	However, a dry summer came.	Happelius, p. 148.

1

2 Therefore, relatively long periods of fifty years were adopted to assess long-term (secular)  
3 frequencies. It should also be added that most probably in the oldest sources from the 15<sup>th</sup>–17<sup>th</sup>  
4 centuries, primarily droughts of considerable intensity were recorded (i.e. droughts referred to by  
5 us as severe and extreme), while those of a smaller scale (moderate) were omitted. This is due to  
6 the nature of the sources at the time and the relatively modest number of such records. Therefore,  
7 it can be assumed that droughts of -1, and probably in some part also droughts of -2 may be  
8 underestimated from the perspective of historical sources. The sources for the 18<sup>th</sup> century are  
9 definitely more precise. In the 18<sup>th</sup> century, the duration of the drought as well as its territorial  
10 range can often be very precisely determined, though not always.

11

### 12 **3.2 Dendrochronological data**

13

14 We hypothesised that narrow tree rings are linked with drought. The limited access to water during  
15 the vegetation season leads to a water deficit in trees and as a consequence the cambium activity  
16 decreases and produces fewer cells, which is positively correlated with tree-ring widths (Liang et  
17 al., 2013). De-trending of the chronology was done with the dplR software (Bunn 2008) using the  
18 smoothing spline option, which reflects trends in the chronology better than other options. The  
19 “n-year spline” was fixed at 2/3 the wavelength of n years (Cook et al. 1990). The residual version  
20 of the chronology was built by pre-whitening, performed by fitting an autoregressive model to the  
21 data with AIC model selection (Bunn 2008). At first the relationships between tree growth and  
22 precipitation was checked. We analysed the effect of climate monthly precipitation and  
23 temperature on tree-ring widths using the treeclim package (Zang and Biondi, 2015). Analysis of  
24 climate growth relationships for monthly data for Toruń revealed that precipitation during the  
25 vegetation season plays a significant role for both pine and oak. For example a significant positive  
26 correlation was observed for June and July for pine, while for oak a positive correlation was  
27 observed for the previous August and current June and a negative correlation for August (Fig. 2).  
28 For each site the climate growth relationships were tested against monthly precipitation and  
29 temperature data starting from 1951 and covers maximum time span depending on the length of  
30 the chronology (Table 6). Because the time span was too short (for example for Site 2 when  
31 chronology covers the years 1951-1986) for some extended analysis going back to previous  
32 months, the common period from previous October to current September was taken into account.  
33 The sum of monthly precipitation was also included, the months were selected dependably on the  
34 significant correlation of the single months and period selected by daily data analysis.

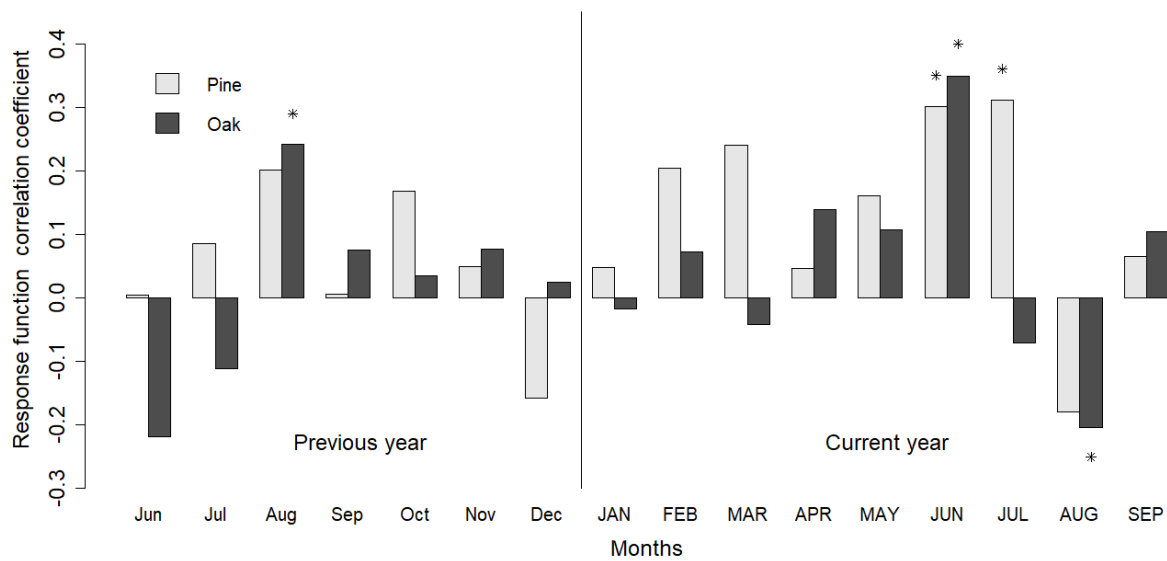
35 Table 6. Climate growth relationships for analysed sites. Only highest correlation  
36 coefficient are presented with level of significance,  $p < 0.05$ .

Site number	Analysed period	Highest Pearson correlation coefficient	Months with highest correlation coefficient	Meteorological station
<b>Region I (Baltic Province)</b>				
Site 1	1951–1987	0.378	Sum of precipitation from May to June	Koszalin
Site 2	1951–1986	0.296 (not significant)	Sum of precipitation from June to July	Gdańsk
Site 3	1951–1987	0.565	Sum of precipitation from June to August	Świnoujście
Site 4	1175–1396	No climate data	No climate data	No climate data
Site 5	1951–1986	0.456	Sum of precipitation from June to July	Koszalin
<b>Region II (Masuria-Podlasie Province)</b>				
Site 6	1951–1987	0.589	Temperature current May	Suwałki
Site 7	1951–1987	0.50	Sum of precipitation from June to July	Suwałki
Site 8	1951–1985	0.285	Sum of precipitation from July to August	Białystok
<b>Region III (Greater Poland-Pomerania Province)</b>				
Site 9	1951–1987	0.485	Sum of precipitation from May to July	Poznan
Site 10	1951–1987	-0.322	Temperature, previous December	Gorzów Wielkopolski
Site 11	1951–2015	0.334 -0.334	Sum of precipitation from May to June, temperature in June	Toruń
Site 12	1249–1490	No climate data	No climate data	No climate data
Site 13	1951–2015	0.443	Sum of precipitation from May to July	Toruń
Site 14	1100–1468	No climate data	No climate data	No climate data
<b>Region IV (Masovia-Podlasie Province)</b>				
Site 15	1951–1985	-0.316	Temperature, previous December	Warszawa
<b>Region V (Silesia Province)</b>				
Site 16	1886–1984	>0.4 Precipitation data onot presented due	Temperature of February and March for pine	Opole, Wrocław, Katowice and Racibórz

		to lower statistical significance		
Site 17	1951–1987	0.376	Sum of precipitation from May to June	Wrocław
Site 18	1568–2010	Only pointer years were analysed		
Region VI (Lesser Poland Province)				
Site 19	1915–1986	0.324 (not significant)	Temperature in February	Kraków
Site 20	1951–1989	0.314 -0.323	Sum of precipitation from May to July, temperature in June	Lublin i Radawiec
Site 21	1881-1999	>0.4	Temperature in March	Kraków
Site 22	1881-1999	>0.4	Temperature in February	Kraków

1

2



3

4 Fig. 2. Climate growth relationships between tree rings in pine (grey bars) and oak (black bars)  
5 and monthly totals of precipitation. Key: Asterisks indicate statistically significant correlation  
6 coefficients at the level of 0.05. Climate data were taken from Toruń Meteorological Station.

7

8 Next we used daily data for Toruń and tree-ring chronologies of pine and oak representing Region  
9 III. Daily data shows more precisely the period of the year which influences tree growth.  
10 According to previous findings, the climate growth relationships are comparable at different sites  
11 in Poland (Zielski et al., 2010), so we used the relationships between daily data and Site 11 and 13  
12 as a model for the rest of our study sites. The reason for this generalisation was also the limited



1 access to daily data. A period of 90 days with the 1-year lag for the years 1947–2015 was used to  
2 find the significant relationships between the daily precipitation data and indexes of tree rings. For  
3 this purpose we used the dendroTools package (Jevšenak and Levanič, 2018). The optimal window  
4 of days was revealed to be from May 6 to August 3 for pine with maximal correlation coefficient  
5 0.435, and from April 21 to July 19 for oak with maximal correlation coefficient 0.305. ~~Study of  
6 climate-growth relationships with daily precipitation data from 1947 to 2015 for a 90-day optimal  
7 window width revealed optimal selection from May 6 to August 3 for pine, and from April 21 to  
8 July 19 for oak.~~ The sums of daily precipitation for these periods were summed and correlated  
9 with indexed growth in years of growth reduction (narrow rings) and growth recovery (wide rings).  
10 The correlation coefficient is 0.79 ( $p < 0.05$ ) for pine, and 0.65 ( $p < 0.05$ ) for oak. Next, the same  
11 summed daily precipitations for the selected periods were correlated with the remaining tree ring  
12 indexes (after exclusion of wide and narrow ring indexes). The correlation coefficient is 0.40 for  
13 pine and 0.16 for oak.

14 To determine the pointer years we used the dplR package (Bunn, 2008). The minimum  
15 absolute relative radial growth variation, above which the growth change from year  $t-1$  to  $t$  is  
16 considered significant, was 10. Any year in which more than 95% of trees per site displayed  
17 significant relative radial growth variations above 10 was qualified as “extreme reduction”; “great  
18 reduction” was determined as between 85–95% of trees; and “moderate reduction” was between  
19 75% and 85%.

20

### 21 **2.3 Instrumental data**

22 As results from Table 2, for the analysis of droughts in the instrumental period, eight long-term  
23 series of monthly totals of precipitation have been used. All these precipitation series were checked  
24 for completeness. The few data gaps in the analysed series were completed using homogenised  
25 precipitation series from the nearest stations. For this purpose, a simple method of constant  
26 quotients was utilised (Pruchnicki, 1987). However, due to the lack of available reference series,  
27 such a procedure was not used to fill data for the period 1880–1884 for Orzysz. Homogenisation  
28 of all the used precipitation series was checked using the AnClim software (Štěpánek et al., 2009).

29 On the basis of the completed series of atmospheric precipitation, the possibility of  
30 obtaining a synthetic precipitation index for the whole country was tested. A similar method was  
31 adopted in Brázdil et al. (2007) to determine drought indices in the Czech Republic for the period  
32 1881–2006. In Poland, Kożuchowski (1985) presented a 100-year series of average areal annual  
33 atmospheric precipitation for 1881–1980 (his Table 3) calculated from data from 12  
34 meteorological stations using precipitation regression equations relative to altitude above sea level.  
35 Miętus (1996), in turn, presented mean areal precipitation for the Coast area. For the analysis, we  
36 took 30-year moving correlation coefficients ( $r$ ) for monthly totals of precipitation counted for the

1 period 1901–2000. All correlation coefficients were statistically significant ( $p < 0.05$ ) with values  
 2 varying from 0.46 to 0.71 (see Table 6, upper part). Only the Kraków series had a significantly  
 3 lower value of  $r$  (the highest value of 0.33 described the relationship between Kraków and  
 4 Wrocław). For annual precipitation totals in the period 1951–2000, Kożuchowski and Żmudzka  
 5 (2003) obtained only slightly higher values of correlation coefficients, varying from 0.6 to 0.8.  
 6 Unsatisfactory results of  $r$ , particularly related to the series for Kraków, suggested that we should  
 7 not construct monthly precipitation series for **the entire** Poland. It seems that the number of long-  
 8 term precipitation series is probably relatively too small for a country of such area (312,679 km<sup>2</sup>).  
 9 Further analysis was thus carried out on regions delimited by a landscape criterion, though this  
 10 excludes mountains, whose atmospheric precipitation is spatially and temporally far more variable  
 11 (Kożuchowski, 1985).

12

13 Table 7. Correlation coefficients between monthly totals of atmospheric precipitation  
 14 (upper part of table) and SPI1 (lower part of table) in area of Poland calculated based on data from  
 15 the period 1901–2000

Station	Toruń	Koszalin	Gdańsk	Orzysz-Mikołajki	Poznań	Warszawa	Żagań-Wrocław	Kraków
Toruń	<del>0.00</del>	<i>0.56</i>	<i>0.67</i>	<i>0.62</i>	<i>0.69</i>	<i>0.62</i>	<i>0.61</i>	<i>0.29</i>
Koszalin	<i>0.56</i>	<del>0.00</del>	<i>0.71</i>	<i>0.55</i>	<i>0.55</i>	<i>0.52</i>	<i>0.46</i>	<i>0.20</i>
Gdańsk	<i>0.62</i>	<i>0.69</i>	<del>0.00</del>	<i>0.66</i>	<i>0.58</i>	<i>0.61</i>	<i>0.55</i>	<i>0.26</i>
Orzysz-Mikołajki	<i>0.55</i>	<i>0.53</i>	<i>0.60</i>	<del>0.00</del>	<i>0.55</i>	<i>0.71</i>	<i>0.54</i>	<i>0.31</i>
Poznań	<i>0.66</i>	<i>0.57</i>	<i>0.55</i>	<i>0.49</i>	<del>0.00</del>	<i>0.58</i>	<i>0.68</i>	<i>0.25</i>
Warszawa	<i>0.58</i>	<i>0.48</i>	<i>0.52</i>	<i>0.63</i>	<i>0.53</i>	<del>0.00</del>	<i>0.61</i>	<i>0.28</i>
Żagań-Wrocław	<i>0.56</i>	<i>0.44</i>	<i>0.47</i>	<i>0.45</i>	<i>0.64</i>	<i>0.53</i>	<del>0.00</del>	<i>0.33</i>
Kraków	0.00	-0.03	-0.03	-0.03	-0.03	-0.02	0.00	<del>0.00</del>

*values statistically significant at the level of  $p < 0.05$  are shown in italic*

16

17 The aim of analysis of instrumental series was to calculate the number, length and category  
 18 of droughts in the area of Poland since 1722, i.e. for almost 300 years. The Standardised  
 19 Precipitation Index (SPI, McKee et al., 1993) was calculated from monthly precipitation totals to  
 20 explore the occurrence of droughts in the analysed locations (Table 2). This index is one of the  
 21 simplest methods used to identify meteorological droughts, since it uses only monthly totals of  
 22 precipitation and is therefore widely used in the literature. Osuch et al. (2015) state that the SPI is  
 23 used for both research and operational purposes in over 60 countries. The SPI index is also most  
 24 popularly used in Poland (e.g. Łabędzki, 2007; Kalbarczyk, 2010; Bąk et al., 2012; Bartczak et al.,  
 25 2014; Osuch et al., 2015, 2016; Bąk and Kubiak-Wójcicka, 2017). What is more, the SPI is used  
 26 also by two institutes mentioned in Section 1 (IMGW-PIB, and the Institute of Technology and  
 27 Life Sciences [ITP]) and also by the Institute of Soil Science and Plant Cultivation, which is  
 28 responsible for agricultural drought monitoring in Poland (for more details see Łabędzki and Bąk,  
 29 2014). Hence our decision to also use this index in our work.

1 The program SPI Generator (National Drought Mitigation Center, University of Nebraska),  
2 was used to perform this analysis. SPI was initially calculated for 1-, 3- 6-, 12- and 24-month time  
3 scales. Further analysis was, however, done using SPI calculated only for 1-, 3- and 24-month time  
4 scales. All of them represent meteorological droughts, from short-term to long-term, respectively.  
5 The last two (SPI3 and SPI24) can also be used as a good proxy for agricultural and hydrological  
6 droughts, respectively. For climate conditions in Poland it was shown that there exists a strong  
7 spatial relationship of SPI values (Table 6, lower part). Significant empirical relations were also  
8 found between SPI and pure agricultural and hydrological indices. Łabędzki et al. (2008) found  
9 high correlation coefficients ( $|r|>0.7$ ) between SPI and some agricultural indices such as: crop  
10 drought index (CDI), water deficit (N) and relative duration of soil moisture deficit ( $t_{def}$ ). On the  
11 other hand, a much weaker relation ( $r<0.5$ ) was found between SPI24 and hydrological droughts  
12 estimated based on SWI-24 (24-month standardised water level index) for the ~~Wisła~~ ~~Vistula~~ river  
13 in Toruń by Bąk and Kubiak-Wójcicka (2017). According to them, this relation was reduced by  
14 the influence of external factors (the hydropower plant in Włocławek **located in middle part of the**  
15 **river**, major groundwater basin), and climate factors appearing in the upper and middle parts of  
16 the river basin.

17 To identify droughts (dry months), the criterion proposed by McKee (1993) and modified  
18 for Polish climate conditions by Łabędzki (2007) was used. Droughts were divided into three  
19 categories based on SPI values: moderate droughts (-0.50 to -1.49), severe (-1.50 to -1.99), and  
20 extreme ( $\leq -2.00$ ). Methods that identify multi-month droughts using the SPI calculated for  
21 different, rigidly defined numbers of consecutive months (3, 6, 12 or 24) simplify analysis,  
22 especially in terms of drought duration and calculating the cumulative intensity of the whole  
23 phenomenon. Therefore, in this work, we have adopted the following criteria to identify droughts  
24 and determine their duration. Firstly, instances of an SPI1 value within any of the above ranges  
25 for only a single month were considered irrelevant. Secondly, a drought was considered to be at  
26 least two consecutive months during which the SPI1 value was  $\leq -0.50$ . Thus identified, a drought  
27 was determined both in terms of duration and by category. Thirdly, drought category was  
28 determined by the dry month of lowest SPI1 value. A drought was thus considered extreme if the  
29 SPI1 value for at least one of the drought months was  $\leq -2.00$ . If the SPI1 of the driest month within  
30 a particular instance of drought was between -1.50 and -1.99, the drought was determined to be  
31 severe. The remaining droughts were qualified as moderate. Number of droughts was determined  
32 for years and for climatological seasons. A drought's final month determined its season.

33 Drought is a widely occurring phenomenon, but its frequency is extremely limited within  
34 particular long-term periods. For this reason, it was decided to group numbers of droughts into  
35 longer periods. For a fuller comparison of drought occurrence identified on the basis of  
36 dendrochronological data (narrow rings), we used instrumental data to calculate the number and

1 duration of droughts within ten-year periods, starting from the slightly shorter period 1722–1730,  
2 through full decades, to the five-year period 2011–2015. Next, we also summed the number of  
3 droughts by 50-year period, also determining seasons in this case, just as we did when analysing  
4 the documentary data.

5 For the purpose of comparison of SPI1 values (meteorological droughts) against historical  
6 indices (-1, -2 and -3) the following assumptions were established: the -1 index was attributed to  
7 SPI1 values ranging from -0.50 to -1.49; -2 for the range -1.50 to -1.99; and -3 for SPI1 ≤ -2.00.  
8 Frequency of occurrence of meteorological droughts for the instrumental period was calculated  
9 for standard meteorological seasons (Dec–Feb, Mar–May, etc.) as well as for May–July. This  
10 allowed for comparison of the occurrence of droughts against their statistics available in  
11 documentary evidence (seasons) and dendrochronological data (May–July). The last period was  
12 added because for this time a significant influence of precipitation on tree-ring widths in Poland  
13 was found (see Sect. *Methods*). It was revealed that most of the growth reduction (negative pointer  
14 years) was related to the occurrence of drought. Thus, years with extreme, great and moderate tree  
15 growth reductions can roughly, and with a large probability, indicate the occurrence of extreme,  
16 severe and moderate droughts, respectively. In the case of documentary data such droughts were  
17 described using indices -3, -2 and -1.

18 As mentioned in Section 3.1, information about droughts in historical times is rather  
19 heavily underestimated, in particular in the case of moderate droughts, and therefore documentary  
20 identified droughts of categories -2 and -3 have frequently been used for the purpose of comparison  
21 against other sources. Such an approach also increases the probability that identified droughts  
22 occurred in large part of Poland. In addition, to be sure that they were caused only by climate, the  
23 assumption of their occurrence in minimum two geographical regions was usually also utilised.  
24 On the other hand, for comparison of droughts delimited using dendrochronological and  
25 instrumental data, all categories of them were used.

26 The number of months  $N_i$  in each class of drought intensity (moderate, severe and extreme)  
27 was computed for the 1- 3-, and 24-month timescales. Then the number of droughts per 100 years  
28 was calculated according to the following formula proposed by Łabędzki (2007):  
29

$$N_{i,100} = \frac{N_i}{i \cdot n} \cdot 100$$

31  
32 where:  
33  $N_{i,100}$  – the number of droughts for a timescale  $i$  in 100 years  
34  $N_i$  – the number of months with droughts for a timescale  $i$  in the  $n$ -year set  
35  $i$  – timescale (1, 3, 24, months)

1  $n$  – the number of years in the particular study data set

2

## 3 **4. Results**

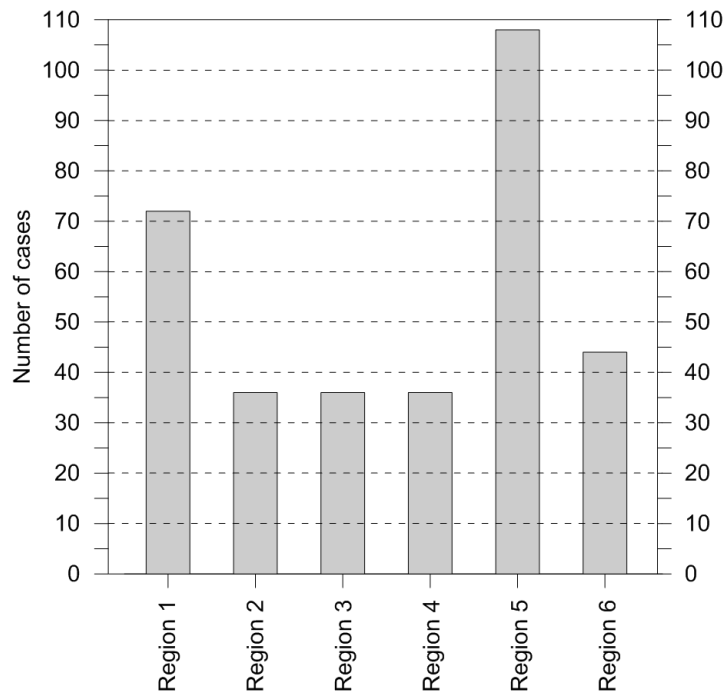
### 4 **4.1 Droughts in Poland based on documentary data**

5 It seems that droughts were not very frequent in Poland. In particular regions (including droughts  
6 presented in sources as nationwide, and therefore also noticeable in individual regions) in total  
7 from 33 to 71 droughts were recorded between 1451 and the end of the 18<sup>th</sup> century (Fig. 3). Most  
8 of those were recorded in Pomerania and Silesia, and the least in Greater Poland, Masuria and  
9 Mazovia (Figs 3 and 4). This is undoubtedly not a reflection of the frequency of droughts in  
10 individual regions, but a consequence of the sources preserved for each region. Without a shadow  
11 of doubt, the richest and most accurate sources come from two regions: Pomerania ( especially  
12 from big cities like Gdańsk, Toruń and Elbląg) and Silesia. It very often happens that one drought  
13 is described in many sources from the region; moreover, it is confirmed by records referring to the  
14 entire territory of Poland. A drought described in this way can be analysed more accurately. The  
15 sources from Greater Poland, Mazovia and Masuria are definitely poorer. Consequently, it is  
16 probable that the number of droughts in these regions was actually higher, and close to the number  
17 of droughts in Silesia or Pomerania.

18 Information that refers to the same year and comes from different regions confirms a larger  
19 territorial range of drought. This does not mean, however, that in cases where such information  
20 was preserved only for one of the regions, other areas were not affected by drought. This lack of  
21 reports may have resulted from the lack of appropriate sources, and not from the fact that there  
22 was no drought in a given region. These numbers undoubtedly depend on the surviving sources  
23 and reflect part of the actual state of affairs. In order to partially compensate for these source  
24 deficiencies, it was assumed that the records referring to drought in the whole country refer  
25 simultaneously to each of the six identified regions.

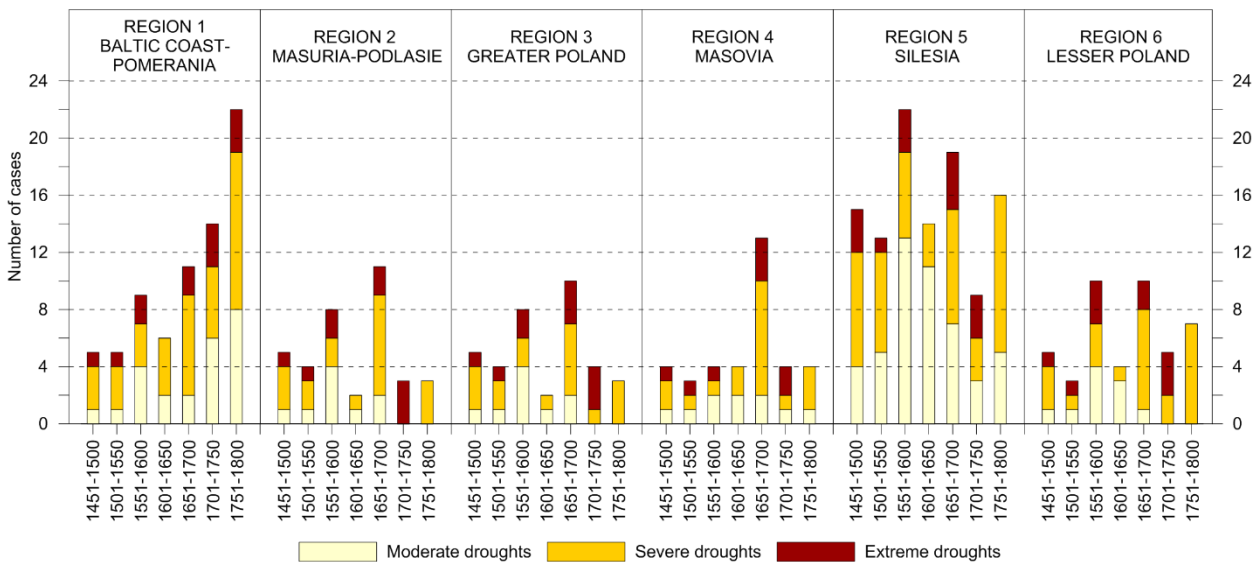
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27



1

2 Fig. 3. Number of years with droughts in six geographical regions of Poland (including information  
3 related to the whole country) 1451–1800. See Table 2 or Fig. 4 for names of regions.



4

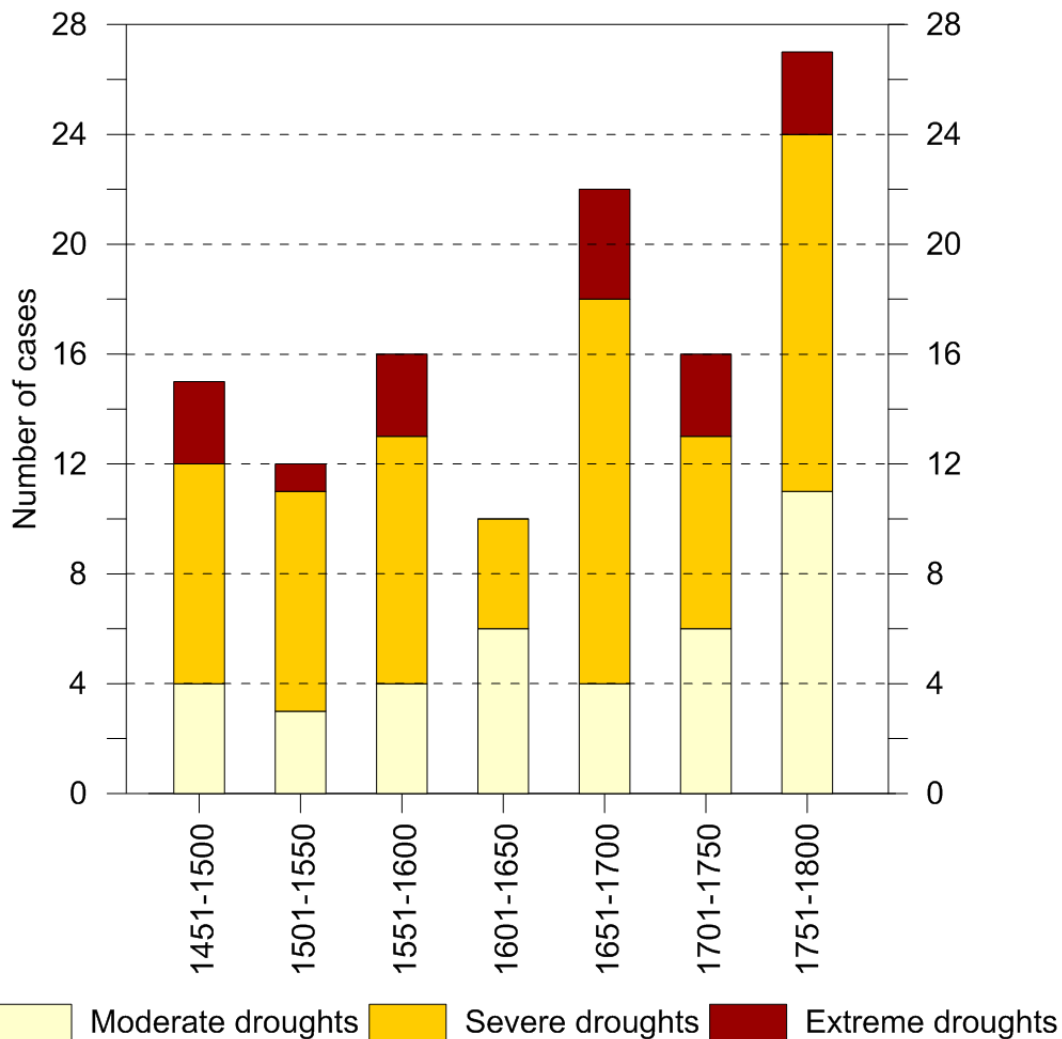
5 Fig. 4. Frequency of occurrence of three categories of droughts in six distinguished  
6 geographical regions in Poland in 50-year periods, 1451–1800

7

8 We also calculated the frequency of **all** droughts **occurring** ~~covering a large part of in~~  
9 Poland, ~~i.e. more than one region~~ (Fig. 5). In the chronological order in the periods of 50 years,  
10 the number of extreme droughts (-3) never exceeded five; in the first half of the 16<sup>th</sup> century only  
11 the drought of 1540 was recognised as such, while in the first half of the 17<sup>th</sup> century, extreme  
12 droughts were completely absent (Fig. 5). It seems that extreme droughts, whose total number in

1 the period 1451–1800 was 17, were regularly recorded in sources, and this information is quite  
2 reliable.

3



4

5 Fig. 5. Frequency of occurrence of three categories of droughts in large part of Poland in 50-year  
6 periods, 1451–1800

7 The number of severe droughts (-2) was usually between four and nine in particular periods  
8 of fifty years. Many more droughts belonging to this category were recorded in the second half of  
9 the 17<sup>th</sup> century and in the second half of the 18<sup>th</sup> century; their numbers were respectively 14 and  
10 13 (Fig. 5).

11 However, the total frequency of extreme (-3) and severe (-2) droughts amounted to 80 and  
12 ranged from 4 to 12 in particular fifty-year periods, except for the second half of the 17<sup>th</sup> century  
13 and the second half of the 18<sup>th</sup> century, when there occurred as many as 18 and 16 droughts,  
14 respectively (Fig. 5). The increase in the number of identified droughts in the second half of the  
15 17<sup>th</sup> century was certainly due to the availability of detailed weather records from the period 1656–  
16 1685 taken from the memoirs of Jan Antoni Chrapowicki (Nowosad et al., 2007). However, the

1 minimum number of droughts (only 4) took place in the first half of the 17<sup>th</sup> century (Fig. 5), for  
2 which, in turn, we recorded significant losses in the sources.

3 The number of moderate droughts (-1) varied in all 50-year periods from 3 to 6, except for  
4 the second half of the 18<sup>th</sup> century, when there were recorded as many as 11 droughts belonging  
5 to this category (Fig. 5). A larger number of such droughts starting from the beginning of the 18<sup>th</sup>  
6 century undoubtedly results from regional sources being more accurate. In this century, many  
7 historical sources were created; they now allow for a fairly accurate reconstruction of the weather  
8 **conditions**, including the appearance of smaller droughts and prolonged shortages of rainfall.

9 Spring (31) and summer (37) droughts prevailed among the recorded droughts. Also,  
10 droughts in spring–summer were often mentioned (22), but much less frequently in summer and  
11 autumn (4). Rare were droughts that occurred only in autumn (4). Winter droughts were reported  
12 only in three years. In the case of many reports mentioning “a drought occurring this year” it is  
13 difficult to decide what the time of its occurrence was.

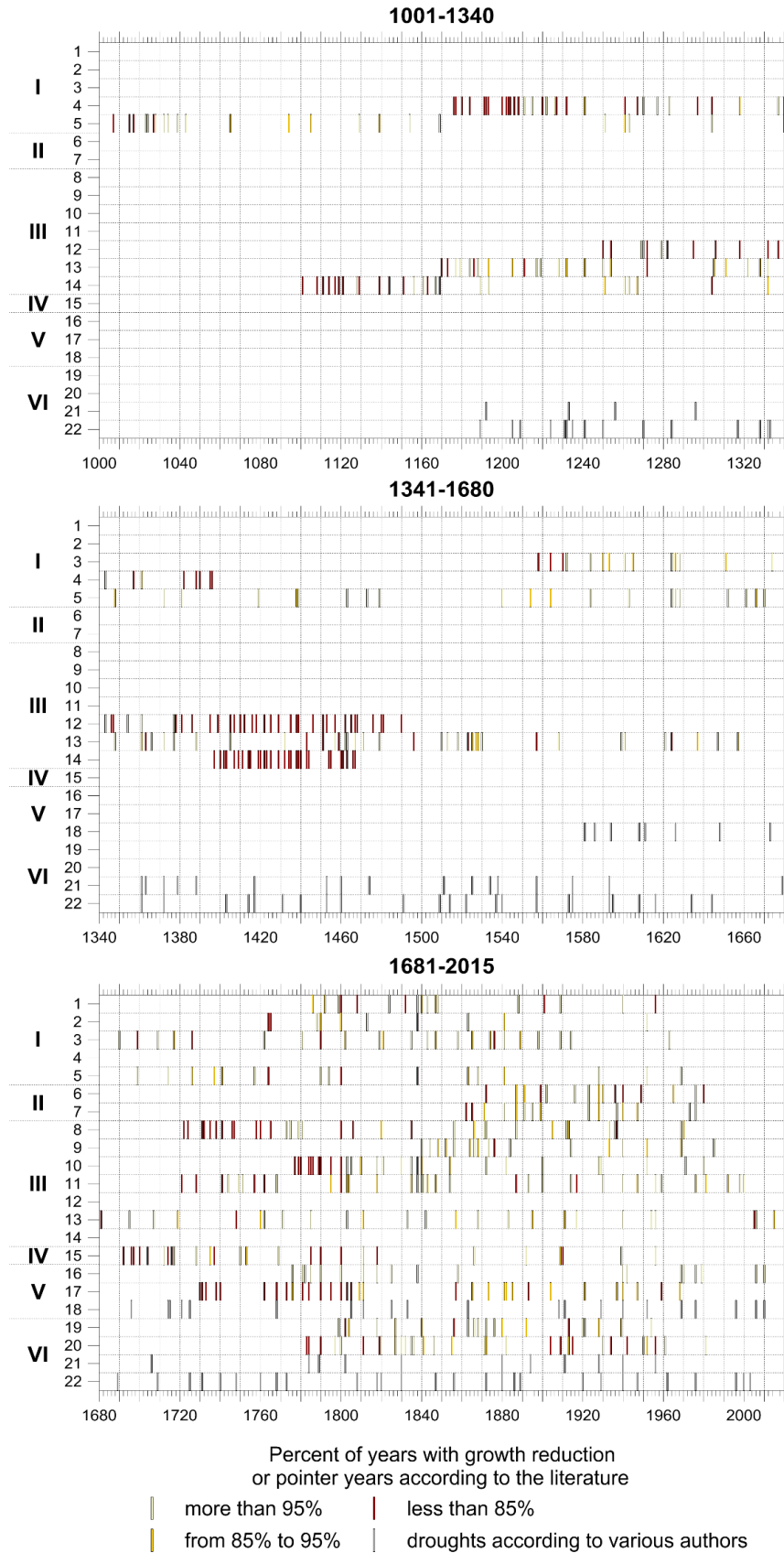
14 Nevertheless, the findings should be treated with some caution. The specificity of the  
15 chronicle’s narrative was that weather phenomena were recorded in the case of their extreme rare  
16 character, or because of their consequences for human existence. Droughts undoubtedly posed a  
17 serious threat to crops during periods of plant growth – above all in spring and summer. In the case  
18 of winters, the lack of snowfall could hardly be perceived as a manifestation of drought.

#### 19 20 **4.2 Droughts in Poland based on dendrochronological data**

21 Twenty-two local chronologies of trees (pine, oak, and fir) from Poland were taken into account  
22 for detecting negative pointer years, showing narrow rings. In a year in which we have narrow  
23 rings at more than 1 site, we count this pointer year as a “multiple observation” year, whereas, in  
24 a year with only one observation, at one site, we call it a year “without multiple observation”. In  
25 total, 758 pointer years with multiple observations were detected and 432 years without multiple  
26 observations. There are 237 multiple observation years of extreme reduction, 122 of great  
27 reduction, 252 of moderate reduction and 147 negative pointer years from the literature (Opała and  
28 Mendecki, 2014; Opała, 2015; Szychowska-Krapiec, 2010) (Fig. 6). **The number of pointer years**  
29 **in selected 50-year periods varies (Fig. 7). At least 30 pointer years were noted within the years**  
30 **1401–1450 and within each of the 50-year intervals from 1701 to 1950.** The evidently smallest  
31 number of negative pointer years occurred in the first 150 years (Fig. 7). In the years 996–1000,  
32 drought did not occur, and therefore this period was omitted in Figures 6 and 7. **However the small**  
33 **number of pointer years from 996 to 1200 may be related to the low number of samples. This**  
34 **period is called as medieval climate anomaly and reconstruction for northern-central Europe**  
35 **revealed considerably drier conditions for this years (Scharnweber et al., 2019).** The number of  
36 chronologies varies and depends on region. More chronologies in the last 300 years result from

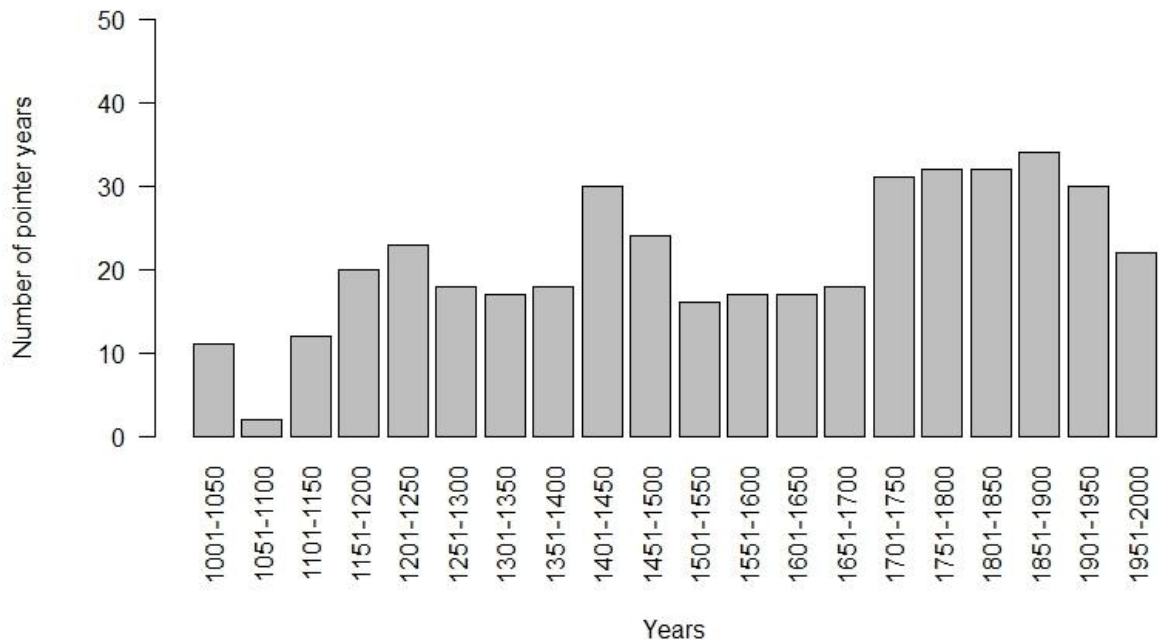


1 existing old trees. It also led to the detection of more pointer years. According to Neuwirth et al.  
 2 (2007) during extreme climatic conditions trees react in the same way, but during years of less  
 3 pronounced weather conditions regional differences in growth reactions increase. Narrow rings  
 4 observed in the same year in trees from different regions suggests extreme climatic conditions.



1

2 Fig. 6. Pointer years in Poland, 1001–2015



3

4

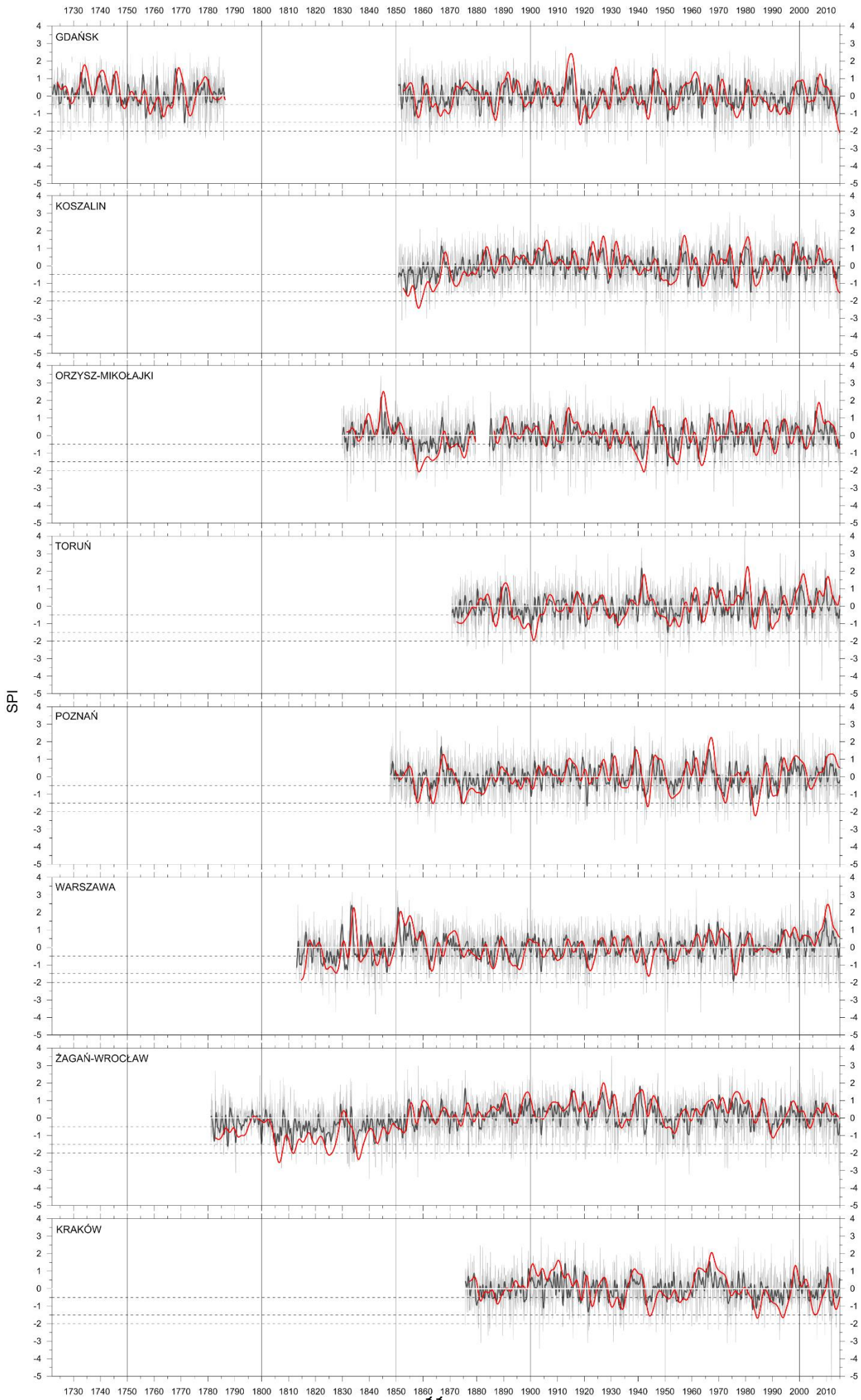
5 Fig. 7. Number of negative pointer years (without multiply observation – i.e. narrow  
6 rings in 1976 were observed on six samples but are treated as a one-pointer year) in  
7 Poland in 50-year periods, 1001–2000.

8

### 9 4.3 Droughts in Poland based on instrumental data

10 Instrumental observations of precipitation in Poland are among the longest-standing in the world  
 11 (Filipiak 2007). As results from Table 2, they are available since 1722. In Figure 8 we present the  
 12 SPI calculated for eight sites in Poland for 1-, 3-, and 24-month time scales. The values of SPI3  
 13 and SPI24 were filtered by 10-element and 30-element low-pass Gauss filters, respectively, in  
 14 order to more clearly distinguish long-term dry periods. The analysis of Figure 8 reveals that the  
 15 occurrence of droughts in different areas of Poland shows both similarities and discrepancies. It is  
 16 very clear that in northern and central Poland, a long-term (24 months' duration, red line) and  
 17 extreme drought occurred at the threshold of the 1850s/60s. Almost one hundred years later (at the  
 18 threshold of the 1940s/50s) such a strong drought was present across the entire area of Poland (Fig.  
 19 8). Except for Kraków, and also Gdańsk in the last few years, severe droughts have not been  
 20 observable at the turn of the 21<sup>st</sup> century. In Silesia, a very dry period occurred for almost the entire  
 21 first half of the 19<sup>th</sup> century, and then significantly less severe droughts occurred here only in the  
 22 1950s and 1990s. For the 18<sup>th</sup> century we have mainly information for Gdańsk. Figure 8 shows

1 that dry periods (moderate droughts) occurred here only at the threshold of the 1750s/60s and in  
2 the mid-1770s. The most extreme droughts in different parts of Poland occurred in different times.  
3 For example, in Gdańsk at the threshold of the 1910s/20s, in Koszalin and Orzysz-Mikołajki in  
4 the 1850s, in Toruń in the 1910s, in Poznań in the 1980s, and in Kraków in the 1980s and 1990s  
5 (Fig. 8).

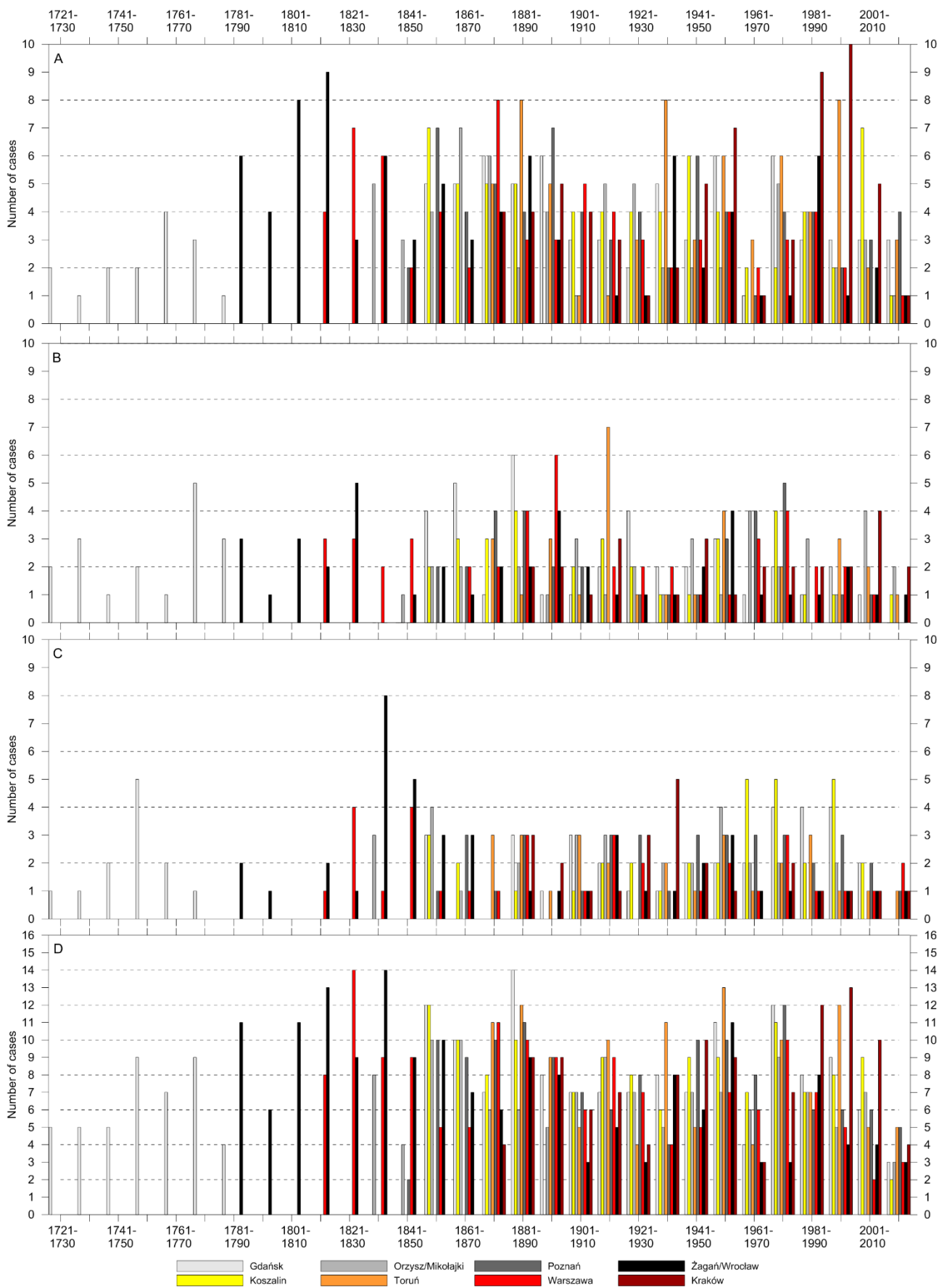


1 Fig. 8. Variability in SPI: 1-month (grey curve), 3-month (black curve) and 24-month (red curve)  
2 calculated from the Polish instrumental series listed in Table 2 (oriented from north to south) in  
3 the period 1722–2015. SPI-3 and SPI-24 were filtered by 10-element and 30-element low-pass  
4 Gauss filters, respectively. **Dashed lines indicate thresholds taken for distinguishing droughts**  
5 **categories (see Section *Methods*).**

6

7 Trend **coefficients** calculated for three types of SPI (SPI1, SPI3, and SPI24) are very small  
8 and not statistically significant in all study regions. This means that long-term frequency of  
9 droughts in Poland has been stable for the last two or three centuries.

10 The number of moderate, severe, extreme and all-category droughts (see Section *Methods*  
11 for definitions) in ten-year periods calculated from the Polish instrumental series ~~listed in Table 2~~  
12 (oriented from north to south) in the period 1722–2015 is presented in Figure 9. In the period  
13 1876–2015, for which complete series of SPI are available for all study sites, the number of all-  
14 category droughts (Fig. 9D) varies mainly in the ranges 3–4 and 8–12 per decade. Below the lower  
15 threshold of this range we must mention the occurrence of only two droughts in the decade 2001–  
16 2010 in Warszawa. On the other hand, this range of frequency was exceeded in only three decades.  
17 The greatest 10-year number of all-category droughts (14) in the study period was noted in Gdańsk  
18 in the decade 1881–1890. In another two decades (1951–1960 and 1991–2000) 13 droughts  
19 occurred in Toruń and Kraków, respectively (Fig. 9D). Two decades 1851–1860 and 1861–1870  
20 were very dry in Poland, in particular in its northern and western parts, and the number of droughts  
21 varied between 6 and 10 per decade. For pre-1850, the information about drought occurrence is  
22 significantly sparser, but it can be stated that in both areas for which data exist (Silesia and  
23 Masovia) the number of droughts in the first half of the 19<sup>th</sup> century (8–14 per decade) was higher  
24 than in the rest of the study period. The contrast is particularly great for Silesia (see also Fig. 8).  
25 **The number of droughts occurring in the 18<sup>th</sup> century varied from 4 to 8–9 per decade and was**  
26 **typical as in the rest of the study period (Fig. 9).**



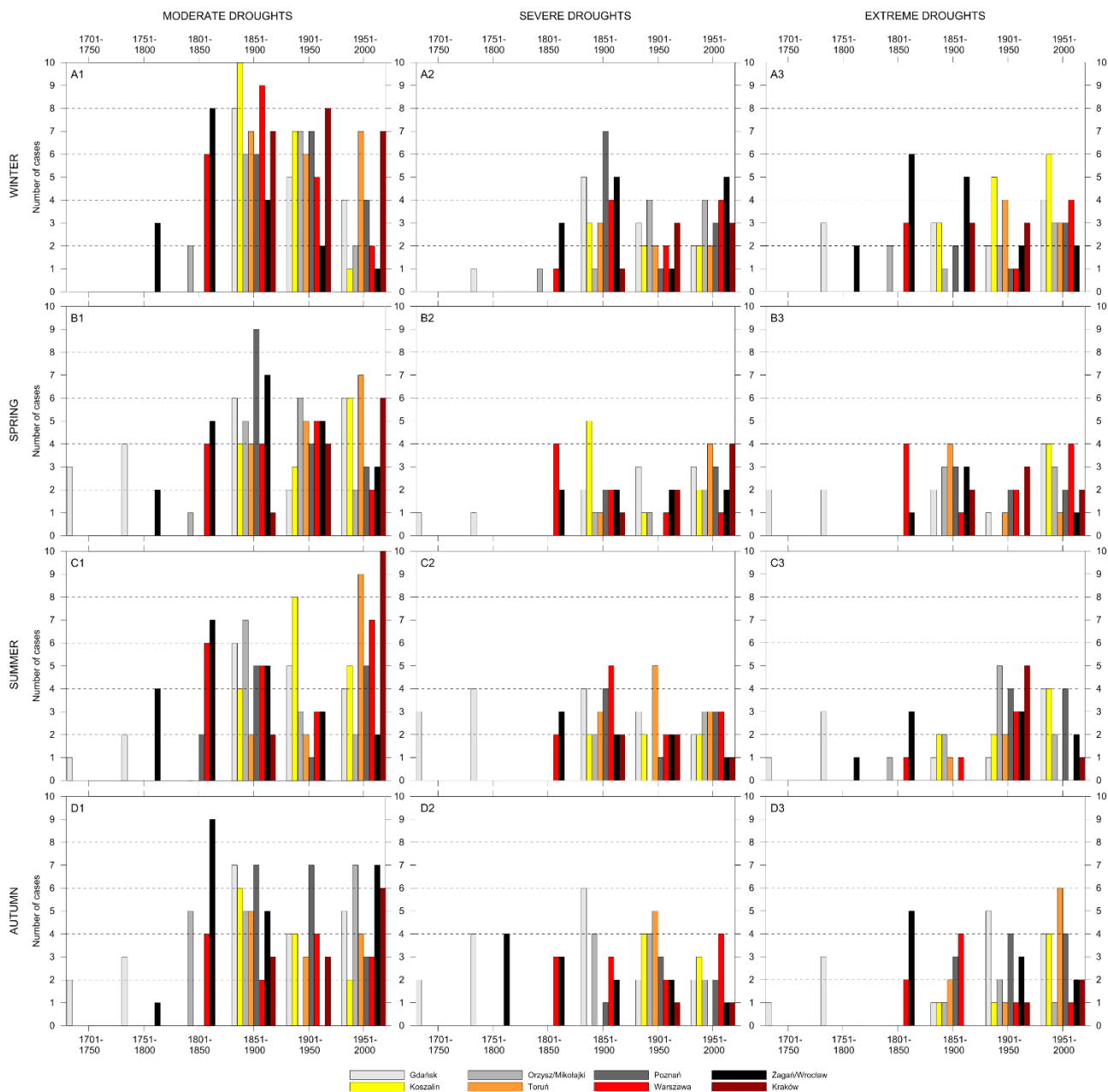
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Fig. 9. Decadal frequency of droughts in Poland in 1722–2015 identified using SPI1  
Key: A – moderate droughts, B – severe droughts, C – extreme droughts, D – all-category droughts

1 In line with expectations, moderate droughts evidently dominate, usually with a frequency  
2 of 2–8 per decade (Fig. 9A), then severe (Fig. 9b), and extreme (Fig. 9c) with typical frequencies  
3 not being much different, at 1–4 per decade and 1–3 per decade, respectively. In terms of these  
4 drought characteristics (Fig. 9), as with the characteristics described by SPI1, SPI3 and SPI24 (see  
5 Fig. 8), no long-term trends are observable in Poland for the last two or three centuries (Fig. 9).

6 For comparison against the number of droughts delimited using documentary evidence, 50-  
7 year frequencies of the three categories of droughts were calculated for climatological seasons  
8 (Fig. 10). It comes as little surprise that the frequency of all-category droughts was greatest in  
9 winter. Other seasons show more-or-less similar frequencies. In winter, droughts evidently  
10 dominated in the study period in the second half of the 19<sup>th</sup> century, this is particularly well seen  
11 in the case of severe droughts, and slightly less so for moderate droughts, which were also quite  
12 frequent in the first half of the 20<sup>th</sup> century. Extreme droughts in winter do not show any significant  
13 changes over time, but it should be emphasised here that they were slightly more frequent in 1951–  
14 2000 than in 1851–1900. In spring, moderate droughts prevailed still in the period 1851–1950  
15 (usually 4–6 cases), with a greater frequency in the first 50-year period. Both severe and extreme  
16 droughts were most frequent (usually 1–3 cases) in 1851–1900, and in particular in 1951–2000  
17 (Fig. 10). In summer there is a clear change in the time pattern of drought occurrence: drought  
18 frequency rises in the 20<sup>th</sup> century (except severe droughts), and in the case of moderate droughts  
19 particularly in its second half. The contrast in drought frequency of extreme droughts is evidently  
20 higher in between the 20<sup>th</sup> century compared to pre-1900 period. is very clear, primarily in the case  
21 of extreme droughts. In autumn, moderate droughts do not show great changes in the last two  
22 centuries, while severe and extreme droughts were most frequent in the first and second halves of  
23 the 20<sup>th</sup> century, respectively (Fig. 10).

24



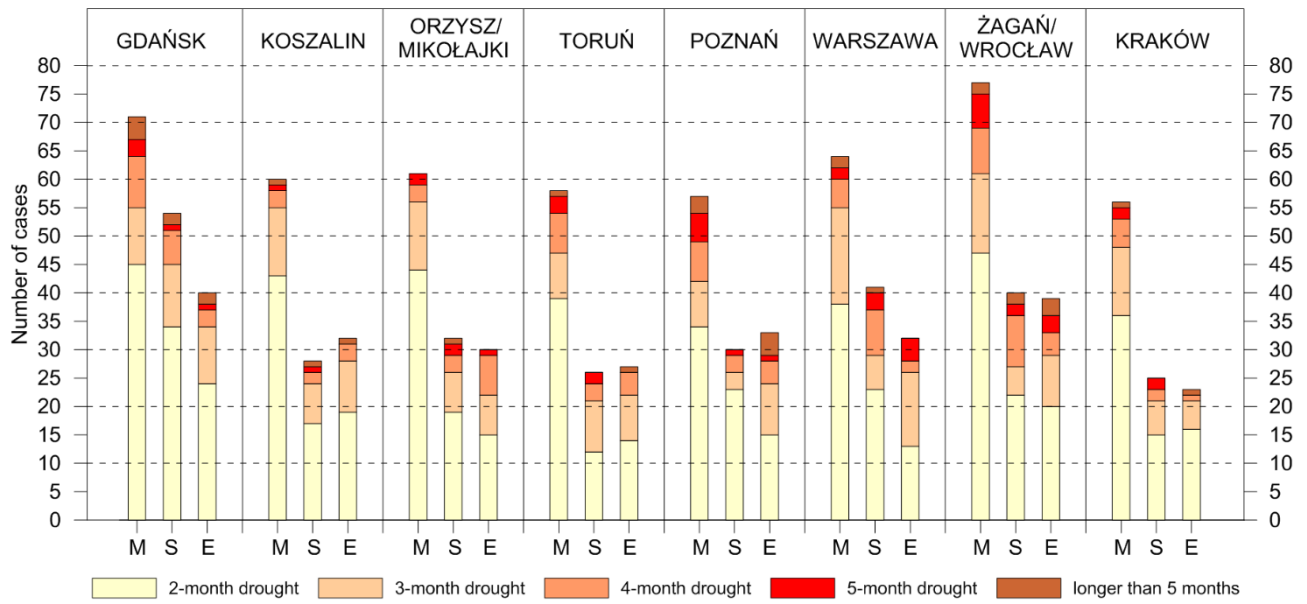
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Fig. 10. Seasonal 50-year frequency of droughts in Poland in 1722–2015 identified using SPI1

5 The frequencies of droughts per 100 years calculated for different their durations (2  
6 months, 3 months, etc.) are shown in Figure 11. The greatest number of all-category droughts  
7 occurred in Gdańsk (165) and in Żagań/Wrocław (155), while the smallest was in Kraków (104).  
8 In line with expectations, moderate droughts clearly dominate (55–75). The number of severe and  
9 extreme droughts is more-or-less comparable, most often ranging between 25 and 40. Both these  
10 two categories of droughts were most frequent in the coastal part of Poland, and least frequent in  
11 Lesser Poland (Fig. 11). Most droughts lasted two months (about 60–70%), and then 3–4 months  
12 (10–20%). The frequency of droughts of 5-or-more months was less than 10%. The longest  
13 droughts had durations of 7–8 months and occurred in Gdańsk from January to July of 1771, in  
14 Wrocław from March to September of 1805, in Poznań from May to November of 1874, in Toruń

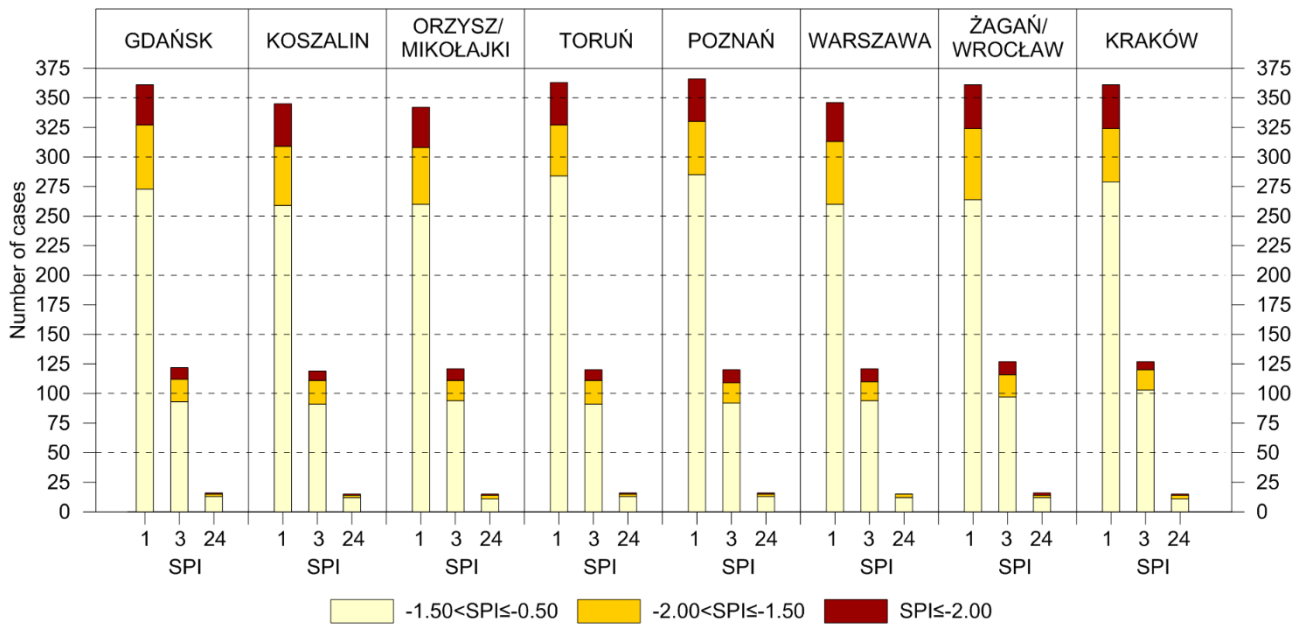


1 from March to September of 1900, and in Wrocław (again) from August 1953 to March of 1954  
 2 (8 months).  
 3



4  
 5  
 6 Fig. 11. Average frequency of three categories of droughts (M – moderate, S – severe, E –  
 7 extreme) in Poland per 100 years stratified by duration, 1722–2015  
 8

9 Łabędzki (2007) proposed a simple formula to calculate the frequency of occurrence of dry  
 10 months and droughts per 100 years based on SPI values (see methods). Using his formula we  
 11 calculated frequencies of dry months using SPI1, short-term droughts (SPI3) and long-term  
 12 droughts (SPI24), including three categories of them (see Fig. 12). Analysis of this figure shows  
 13 that the number of dry months in Poland usually ranges around 350 per 100 years (from 342 in  
 14 Orzysz/Mikołajki to 366 in Poznań). The number of short-term droughts (SPI3) for Poland as a  
 15 whole is comparable and usually ranges around 120 per 100 years (from 119 in Koszalin to 127 in  
 16 Wrocław and Kraków), while the frequency of long-term droughts (SPI24) is 15–16 per 100 years.  
 17 The short-term droughts distinguished here using SPI3 are most comparable to droughts delimited  
 18 using the method proposed in the paper. Ratios of frequencies between moderate, severe and  
 19 extreme droughts are generally similar in both methods (Figs 11 and 12), although in the Łabędzki  
 20 method there is a greater domination of moderate droughts over the other two categories. Severe  
 21 droughts are also clearly more numerous than extreme droughts (Fig. 12), which is not so clearly  
 22 visible in drought frequencies calculated using our method (Fig. 11).



2

3

4 Fig. 12. Frequencies of dry months (SPI1), short-term droughts (SPI3) and long-term droughts  
5 (SPI24) in Poland, including three intensity categories calculated using Łabędzki's formula

6

#### 7 4.4 Selected megadroughts in Poland from historical times

8

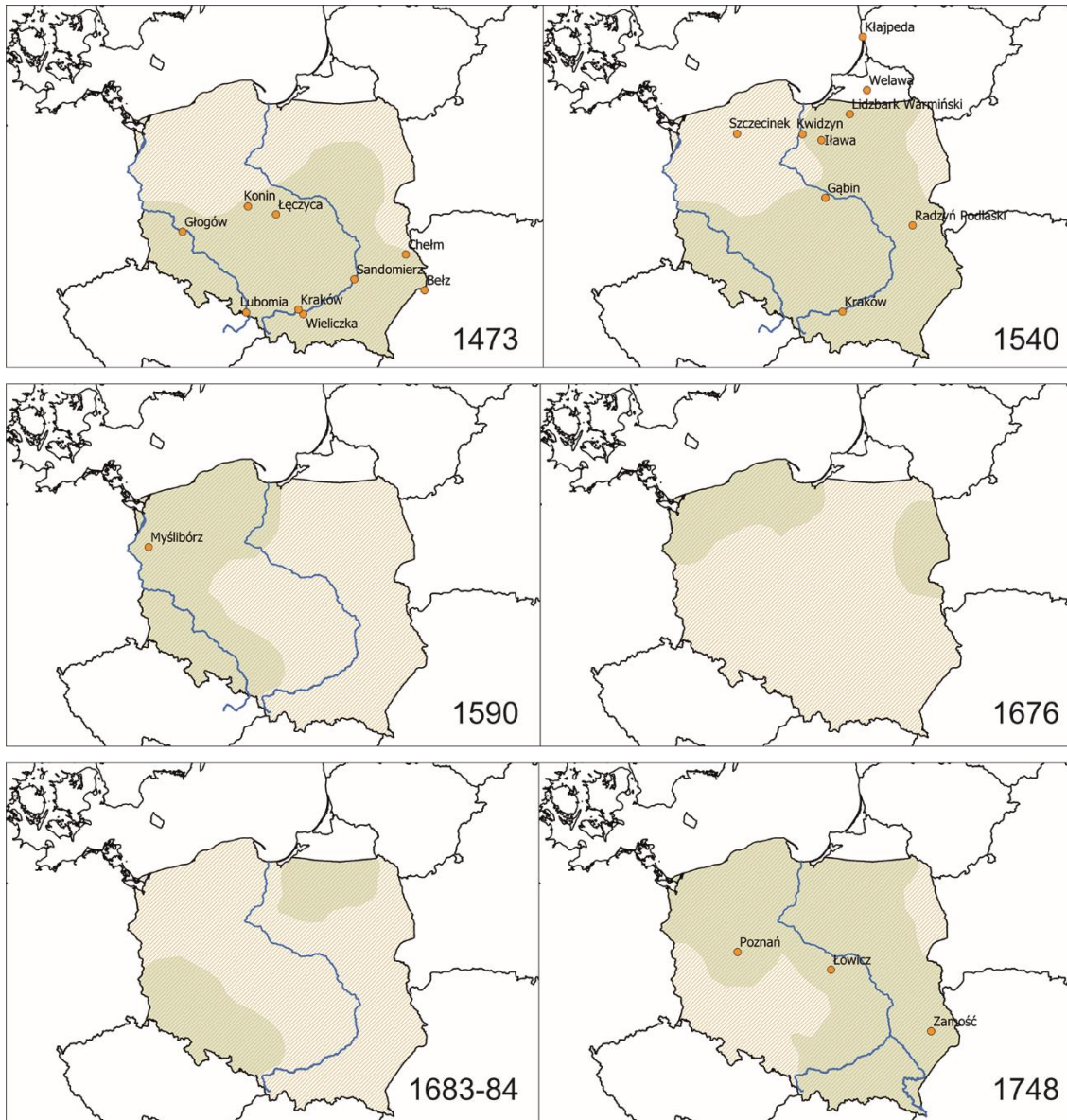
9 Based on detailed analysis of all documentary evidence gathered for the period 1451–1800 we  
10 distinguished 17 megadroughts (also referred to in the paper as “extreme droughts”, index -3) in  
11 Poland (see Fig. 5). Six of them – the most severe (Fig. 13) – have been chosen for more detailed  
12 presentation here. The main features of each megadrought are described (e.g. time of occurrence,  
13 duration, geographical area, consequences for nature, socio-economic impact).

14

##### 15 4.4.1 The year 1473

16 This drought affected the whole of Europe. In the case of Poland, it was quite well described by  
17 Jan Długosz in “Annales”, as Długosz himself observed its course. He wrote about extraordinary  
18 heat and a prolonged lack of rain. He emphasised the extremely low level of water in the **Wisła**  
19 ~~Vistula~~ River and many other rivers that could be easily waded across. Water reservoirs were  
20 completely dry. The lack of water was marked throughout the whole country. Fires were another  
21 commonplace phenomenon. There were forest fires. Długosz also mentioned economic  
22 consequences. Fires destroyed wild beehives in the forests. Drought destroyed the spring sowing.  
23 Animals got sick. Fires affected such cities as Kraków, Wieliczka, Konin, Bełz, Chełm, Lubomia,  
24 Łęczyca, Sandomierz and others (Długosz Ks.) (see Fig. 13). According to the Silesian chronicler

1 Peter Eschenloer, the drought lasted from 23 April to 11 November. This chronicler recorded an  
 2 extremely low level of water in the Odra River. Water mills could not operate. There was no water  
 3 in wells. Even wild animals were affected by the lack of water. Similar information was provided  
 4 by another Silesian chronicler, Nicolaus Pol. Meanwhile, the author of *Roczniki glogowskie*,  
 5 Kaspar Borgeni, reported that the drought lasted only 10 weeks. However, he provided many  
 6 detailed dates in his narrative about the harvest time and their quality; there was no rain from April  
 7 4 to September 22, so it should be considered that the drought lasted almost 6 months.



9 Fig. 13. The most severe megadroughts, with spatial coverage (dark colour). Location of  
 10 sites and rivers mentioned in Section 4.4 and Table 3 is shown.

11 4.4.2 The year 1540

12 This drought belongs to one of the best described droughts in old Europe. In Poland, however, the  
 13 year 1540 began with numerous floods in the winter (Poznań) and early spring (Żuławy and  
 14 Gdańsk). Heavy rainfalls also caused floods in Świecie **located on the Wisła River in its lower**

1 **part.** Polish sources are quite laconic, if unambiguous, about the drought of 1540, considering its  
2 scale. A parish priest from Lidzbark Warmiński wrote about a terrifying drought. The Silesian  
3 chronicler Nicolaus Pol wrote about the drying of many waters and the greening of the Odra River,  
4 probably as a result of the development of algae at high temperatures. It was reported that grass  
5 was drying out, cereal harvests were poor, cattle had to go many miles to watering places. The  
6 detailed observations of the Kraków professor Marcin Biem leave no doubt as to the lack of rainfall  
7 and the extreme nature of the drought in the vicinity of Kraków. The drought lasted until October.  
8 There were many fires, including in such cities as Kwidzyn, Welawa, Klaipeda in the Prussian  
9 state, Gąbin in Mazowsze, and Radzyń Podlaski (see Fig. 13). Fires were also reported in Iława  
10 and Szczecinek (Nowosad and Oliński, 2019).

11

#### 12 4.4.3 The year 1590

13 The winter of 1589/90 was quite harsh, and rivers froze. There must certainly have been spring  
14 thaws. In the literature, mention is made of there having been no rain for 38 weeks. In the vicinity  
15 of Myślibórz on 4 May there was a severe frost, followed by a strong heat. There were also heavy  
16 storms. The phenomena resulted in numerous fires. From the end of May there was an  
17 uninterrupted rainless heat that lasted for a very long time. The duration of the heat was determined  
18 to have lasted 38 weeks, which is probably a mistake. Rivers dried up, the river mills stopped  
19 working. Prices rose significantly (Reinhold, 1846, p. 143; Girguś et al., 1965, p. 182). The dry  
20 summer and the drying of many rivers were also mentioned in reference to Silesia and the  
21 Karkonosze Mountains (Bergemann, 1830a, b). The level of the ~~Vistula~~-**Wisła** River was also  
22 extremely low. The drought therefore affected all Polish areas and lasted continuously from the  
23 end of May to the end of autumn. Many of its manifestations (total lack of rainfall, drying of rivers,  
24 high temperatures, consequences for agriculture and nature) indicate its extreme character.

25

#### 26 4.4.4 The year 1676

27 The drought of 1676 was described independently in several sources. Spring is supposed to have  
28 abounded in storms that caused numerous fires. There was drought in the summer. In Pomerania  
29 (see Fig. 13) it rained only twice in the summer. The whole summer was dry and hot. The drought  
30 caused damage to crops in slightly higher areas. The harvest of **fruits** and vegetables was also poor  
31 due to the drought. In Podlasie, the beginning of January was exceptionally warm, although frosts  
32 arrived later. According to the records from Antoni Chrapowicki's diary, June and July were very  
33 dry months in Podlasie. Chrapowicki wrote that crops "burned out" in the fields. In August and  
34 September, Chrapowicki stayed in eastern Belarus, which is why his records concerning the late

1 summer and autumn cannot be taken into account (Diaryusz Życia JWJmci Pana Jan Antoni  
2 Chrapowicki). The research into the memoirs of Chrapowicki indicates that the precipitation in  
3 1676 was the slightest of all the years covered by his diary (1656–1684) (Przybylak and Marciniak,  
4 2010). In other sources, the high prices that prevailed in the country this year were also underlined  
5 (Namaczyńska, 1937).

6

#### 7 4.4.5 The years 1683–1684

8 It is known from **later** record that a great drought was recorded in Masuria in 1683. It caused a  
9 lack of crops and high prices. **In Poland** in 1684, after a harsh winter, a hot, dry summer came. The  
10 drought resulted in earlier, but thus weaker, harvests of winter grain and the destruction of spring  
11 crops. Water reservoirs dried up. There were not enough watering places for animals  
12 (Namaczyńska, 1937). According to Silesian sources, the drought came on 24 June **1684**; it  
13 destroyed grain and flax, and burned grass. Cattle died, for a lack of grass and water. Prices were  
14 very high (Gomolcke, 32–33, 54). From various sources it can be established that the drought  
15 began at the end of June and continued **until** ~~in July, August and~~ September **1684**.

16

#### 17 4.4.6 The year 1748

18 The winter was quite long. In Gdańsk, on 7 April, there was ice-floe on the Motława River. In the  
19 vicinity of Toruń the ice on the ~~Vistula~~ **Wisła** River did not start to melt until the beginning of  
20 April. Near Toruń, the ~~Vistula~~ **Wisła** river flooded adjacent territories. The water level began to  
21 fall at the beginning of May. Beautiful, dry weather came, and it started to arouse farmers' anxiety  
22 about the growth of plants. On 25 May, it rained in Toruń, but the **intensity of** precipitation was  
23 insignificant. The second half of May was considered to be extremely dry. In Gdańsk, heat and  
24 drought prevailed from 8 to 23 May. In Toruń, on 7 June an increase was recorded in the water  
25 level in the ~~Vistula~~ **Wisła** River, which may indicate more significant rainfalls in the south of  
26 Poland. In the vicinity of Toruń, rain fell after a long break, on 11 June, causing people to rejoice,  
27 but by 22 June dry weather was again recorded. In Gdańsk, in June, dry days prevailed, but they  
28 were interspersed with rainy days.

29 On 1 July, in Toruń, it was recorded that there had been light rains from time to time, but  
30 above all, a great drought had been felt. No fires had broken out in the vicinity yet, but they had  
31 in many places in Poland and Lithuania: fires were recorded in Poznań and Zamość (see Fig. 13).  
32 In Gdańsk, rainless weather prevailed throughout the first half of July, while in the second half  
33 there were only five days with rain. In mid-July, high prices resulting from the prolonged drought  
34 were reported. Transport on the ~~Vistula~~ **Wisła** River was extremely difficult due to the low water

1 level. Information about the drought also came from other European countries. In addition,  
2 locusts appeared in Hungary and Transylvania. In Toruń and Gdańsk, rain fell for a few days  
3 after the solar eclipse of 25 July. Similar rains fell at that time in Warszawa. At the beginning of  
4 August, however, the drought was reported again. In Toruń, rain fell on 5 August, then on 8  
5 August. At that time, the water level in the ~~Vistula~~ **Wisła** River also increased for a short time,  
6 but at the same time, there were reports of fires having destroyed Łowicz. In Toruń, the drought  
7 prevailed until the end of August and the first half of September. In Gdańsk, the whole month of  
8 August was very dry. Rain fell there in early September, but in the following days the drought  
9 returned and did not stop until mid-September. The autumn was very cold. The end of the drought  
10 was not seen in Toruń until mid-October, but complaints about the very low water level in the  
11 San River were still being reported (Reyger, Brauer).

12

## 13 **5 Discussion**

14

15 Every climate proxy has its own advantages, but also its weaknesses. Therefore, to increase the  
16 probability of correctly dating drought in Poland, we decided to use both documentary evidence  
17 and dendrochronological data for the period before the 19<sup>th</sup> century. A satisfactory number of data  
18 obtained from both kinds of proxies is available for period 1451–1800, allowing for reliable cross-  
19 checking of information about the occurrence and characteristics of droughts. For the most recent  
20 period (1801–2015), the usefulness of tree-ring data in describing dry spells (droughts) was  
21 checked by comparing it against droughts delimited for the area of Poland using SPI calculated for  
22 eight long-term series of monthly precipitation totals.

23 Tree rings in Poland can be a source of information about both hydroclimate phenomena,  
24 such as droughts, and air temperature (Büntgen et al., 2007, 2011; Koprowski et al., 2012; Opała  
25 and Mendecki, 2014; Opała, 2015; Pritzkow et al., 2016; Balanzategui et al., 2017). The key issue  
26 is to isolate which factor strongly influences tree-ring growth. Up till now, tree-ring widths in  
27 Poland have been used only for air temperature reconstructions (e.g. Przybylak et al., 2005;  
28 Szychowska-Krapiec, 2010; Niedźwiedz et al., 2015). In the present paper, this kind of proxy data  
29 is used for the first time to **identify drought occurrence** ~~identified droughts occurring~~ in the  
30 vegetation period. It was assumed that the combined information from historical and instrumental  
31 sources on the one hand, and dendrochronological sources on the other, would be crucial in  
32 identifying the strength of water shortage and the occurrence of droughts in Poland in recent  
33 centuries.

34 Extreme and severe drought occurrence in spring and summer, as identified by  
35 documentary data, corresponds closely with the occurrence of negative pointer years (droughts).  
36 In the period 1451–1800, 48 severe and extreme droughts **in the mentioned seasons** have been

1 determined to have occurred across all of Poland or in at least two geographical regions (see Fig.  
2 1). Dendrochronological data showed significantly smaller rings having formed during 52.1% of  
3 these. Dobrovolný et al. (2015) found very similar results for the Czech Republic based on a set  
4 of 3,194 oak-ring-width samples for the last 1,250 years (761–2010). Negative tree-ring-width  
5 extremes were confirmed in documentary sources in 53% of cases. Analysis of extreme and severe  
6 droughts that occurred in only one geographical region in Poland reveals a better correspondence  
7 between analysed proxies than those described earlier for the greater area of Poland (at least two  
8 regions). In this case negative pointer years in tree rings were noted in as many as 59.1% of  
9 detected droughts by historical sources.

10 Even better agreement between both kinds of proxy data was found when megadroughts  
11 identified by documentary evidence were taken into account. In four (1473, 1540, 1590 and 1748)  
12 of the six described here (see Section 4), clear signals in dendrochronological data were detected  
13 (negative pointer years). Using documentary sources, two megadroughts (1540 and 1590) were  
14 also qualified as very outstanding droughts in the Czech Republic (Brázdil et al., 2013). Of those,  
15 however, only the year 1590 had a negative tree-ring width index (TRW) (of -1.818), although this  
16 value was not very high (see Table S1 in Supplement in Dobrovolný et al., 2015). Brázdil et al.  
17 (2013) **using documentary evidence** also distinguished three other outstanding droughts in the  
18 Czech Lands (1616, 1718 and 1719). All of those also occurred in Poland, but their category using  
19 documentary evidence was estimated by us as -2 (severe). In all those years except 1718, negative  
20 pointer years were also found in one Polish region (see Fig. 6), while in the Czech Republic an  
21 extreme negative TRW index (-2.474) was found only for the year 1616 (see Table S1 in  
22 Supplement in Dobrovolný et al., 2015). Based on the published list of TRW indices for Czech  
23 Republic (oak chronology) by Dobrovolný et al. (2015) we found 33 extreme negative TRW  
24 indices in the period 1451–1800, which suggests favourable conditions for drought occurrence.  
25 We excluded the two last years (1790 and 1800), which were identified for Scots pine tree rings  
26 from Upper Silesia (Opała and Mendecki, 2014). For almost half of this set of years (48.5%), we  
27 confirmed the existence of strong negative pointer years **also** in Poland's tree dendrochronologies.  
28 Significantly better agreement (89%), between the occurrence of narrow rings in the Czech  
29 Republic on the one side, and Upper Silesia (Opała and Mendecki, 2014) and southern Poland  
30 (Opała, 2015) on the other, was found by Dobrovolný et al. (2015) for the overlapping period  
31 1770–1932. These quite good correspondence patterns between negative TRW in the Czech  
32 Republic and Poland (in particular its southern part), which are also very clear in analysis of  
33 drought occurrence and areal coverage (which are presented in the Old World Drought Atlas  
34 [OWDA, Cook et al., 2015]), are the result of large positive sea-level-pressure anomalies over the  
35 whole of central Europe (including Poland) in MAM and JJA during the occurrence of negative  
36 extremes in TRW (see Fig. 5 in Dobrovolný et al., 2015). Significantly weaker agreement (about

1 30%) was found between the timings of droughts in Poland delimited using documentary evidence  
2 and droughts reconstructed for the whole of Europe using tree rings (Cook et al., 2015). This is  
3 caused by the fact that Cook et al. (2015) used significantly fewer dendrochronologies from Poland  
4 (only four – and those mainly from northern Poland, see their Supplementary Materials) than we  
5 used in the present paper (22, see Table 1 for details).

6 The megadrought year of 1473 was detected in the Baltic Province on the basis of an oak  
7 chronology from Eastern Pomerania (Ważny, 1990). Narrow rings were observed in 80 percent of  
8 the samples for this year. The effect of the drought in 1473 can also be shifted and observed in  
9 southern Poland in 1474 (Szychowska-Krapiec, 2010). The drought in 1540 was observed in  
10 different parts of Europe; particularly strong evidence is available in documentary sources (Wetter  
11 et al., 2014; Pfister et al., 2015; Brázdil et al., 2016). Additionally, many dendrochronological data  
12 confirm the existence of strong droughts in much of Europe, in particular from France to Latvia,  
13 Belarus and Ukraine and from the southern Scandinavian Peninsula to northern parts of Italy  
14 (OWDA, Cook et al., 2015). Čufar et al. (2008) identified the existence of droughts in Slovenia in  
15 1540 based on tree rings. The scale and intensity of the 1540 megadrought in Europe described by  
16 Wetter et al. (2014) as “an unprecedented 11-month-long Megadrought” (more severe than the  
17 2003 drought in Western Europe and the 2010 drought in Russia) was, however, recently  
18 questioned by Büntgen et al. (2015), who analysed this year in light of 24,303 individual tree-ring-  
19 width measurement series. It is also worth adding here that in different parts of Europe the effect  
20 in tree rings was shifted and observed in 1541 (Büntgen et al., 2011). Analysis of our 22  
21 dendrochronologies reveals the occurrence of narrow rings in trees growing in the Baltic Province  
22 and in the Lesser Poland Province, and thus not in the whole of Poland as shown in the OWDA  
23 (Cook et al., 2015). In 1590, narrow rings were observed in the Baltic Province, but the decidedly  
24 strongest droughts in Europe in view of this proxy were those occurring in France and Germany  
25 (Cook et al., 2015). Narrow rings were also noted in most sites in central and eastern Europe, as  
26 well as in Scandinavia. The year 1748 seems to have a somewhat regional character; narrow rings  
27 were noted in the Greater Poland and Pomerania Province and in the Lesser Poland Province.  
28 There is no information about tree reaction for this drought in selected sites in central Europe  
29 (Büntgen et al., 2011). Looking at OWDA we see the occurrence of droughts in this year mainly  
30 in northern and western parts of Poland (although their severity is not so large). Evidently more  
31 severe droughts in this year in Europe were particularly observed in southern Germany, the whole  
32 of Austria and the western borders of the Czech Republic (Cook et al., 2015).

33 Both documentary evidence and dendrochronological data clearly indicate that in the  
34 period 1451–1800 the greatest frequency of droughts in Poland occurred in the 18<sup>th</sup> century, and  
35 particularly the second half (32 cases). Similar results are also seen in the Czech Republic (see  
36 Fig. 4a in Brázdil et al., 2013). The smallest number of droughts was noted in the 16<sup>th</sup> century



1 (about 35), and was different than in the Czech Lands, where the evidently smallest number  
2 occurred in the 17<sup>th</sup> century. In the study period, the total number of all-category droughts in  
3 Poland identified reached 148 and 156 – using documentary evidence and dendrochronological  
4 data, respectively. This means that both proxies reconstruct quite a similar frequency of drought  
5 occurrence in time scales from centuries to decades. The overall numbers of droughts identified  
6 using documentary evidence in Poland (present study) and the Czech Lands (Fig. 4a in Brázdil et  
7 al., 2013) in the overlapping period 1501–1800 were very similar and reached 132 and 126 cases,  
8 respectively.

9 All the dendrochronologies and long-term series of precipitation that we gathered and used  
10 for SPI calculation are available only for the common period 1876–1985. Therefore, for this  
11 period, statistics were calculated to compare the timings of dry periods (droughts) in Poland  
12 identified using both of these kinds of data. The agreement between droughts occurring at least in  
13 two geographical (SPII<sub>May–Jul</sub> delimited droughts) and two natural-forest regions (significant  
14 negative pointer years) was 25.5%. On the other hand, for a less strict criterion, i.e. the occurrence  
15 of droughts at least in one region, the agreement reached 50.9%. Thus, the latter number is close  
16 to the value of agreement of drought timings identified using documentary evidence and the  
17 occurrence of negative pointer years (59.1%).

18 Having those series for the abovementioned period, we also conducted a correlation  
19 analysis to investigate how spatially coherent the association is between climate (SPII<sub>May–Jul</sub>) and  
20 tree-ring widths in the area of Poland. Coefficients of Pearson's linear correlation were calculated  
21 for 1–2 dendrochronologies representing each natural-forest region, with SPII<sub>May–Jul</sub> values  
22 calculated for long-term series of precipitation taken from meteorological stations in the same  
23 region and closest to the area covered by the dendrochronologies. The closest relationships  
24 between climate and tree-ring growth were obtained for the Greater Poland and Pomerania  
25 Province and the Silesia Province, where the correlation coefficient  $r$  reached: 0.40 (site 9, Poznań  
26 in Table 1), 0.44 (site 11, Kuyavia-Pomerania) and 0.46 (site 17, Wrocław). Such good correlation  
27 ( $r=0.43$ ) was also found by Dobrovolný et al. (2015) for the Czech Republic between 18 variants  
28 of Czech oak chronology and March–June precipitation totals. In three other Polish provinces  
29 (Baltic Coast, Masuria and Masovia, see Fig. 1) correlation coefficients are still statistically  
30 significant, but are clearly smaller: 0.25 (site 3, Wolin in Table 1), 0.14 (site 1, Koszalin), 0.24  
31 (site 7, Suwałki), 0.13 (site 8, Hajnówka) and 0.21 (site 15, Warszawa). A similar correlation value  
32 (about 0.20) between tree-ring width and precipitation in June and July was found by Helama et  
33 al. (2014) for south-western Finland. On the other hand, a significantly better correlation (about  
34 0.4) was calculated by Seftigen et al. (2013) for south-eastern Sweden. The increased strength of  
35 correlation here was probably due to the selection of trees growing at xeric sites, where the radial  
36 growth was most likely limited by moisture availability. The climate–tree-ring-growth relationship

1 in Lesser Poland Province was not stated – the coefficient of correlation was equal to 0.0. The  
2 reasons for this different climate–tree-growth behaviour in this part of Poland in comparison to  
3 other studied regions are unknown.

4 From the perspective of available historical sources from the period 1451–1800, an  
5 increasing number of droughts was reported from the second half of the 16<sup>th</sup> century onwards,  
6 excluding the first half of the 17<sup>th</sup> century. The decrease in their occurrence in this period can be  
7 explained by large source deficiencies. They resulted from the destruction of many documents  
8 during the Swedish invasion on Polish territories in 1655-1660. The number of droughts in the  
9 first half of the 17<sup>th</sup> century is likely to have been higher. As information about moderate droughts  
10 is quite accidental, the sources certifying extreme and severe droughts seem more reliable and  
11 complete. According to our research, droughts occurred most frequently in the second half of the  
12 18<sup>th</sup> century. This rectifies the previously accepted data on drought in Poland ~~available in some-~~  
13 ~~in~~ geographic works (see e.g. Słota et al., 1992; Kaca et al., 1993; Łabędzki, 2006), which include  
14 ~~information~~ was established that in the 14<sup>th</sup> century there were 20 droughts in Poland, 25 in the  
15 15<sup>th</sup> century, 19 in the 16<sup>th</sup> century, 24 in the 17<sup>th</sup> century, and 22 in the 18<sup>th</sup> century. However,  
16 ~~these numbers~~ the data refer to the frequency of hot summer seasons distinguished by Sadowski  
17 (1991, Sadowski also assumed the year 1300, 1400, etc. to be the first year of a century). ~~In later~~  
18 ~~geographic works, their authors assumed that during hot summer seasons delimited by Sadowski~~  
19 ~~Sadowski's findings were accepted, assuming, however, that the hot summer seasons he had~~  
20 ~~identified were characterised by the occurrence of most occurred droughts and therefore such~~  
21 ~~information was included~~ Therefore, many subsequent Polish works mention only the number of  
22 droughts (see e.g. Słota et al., 1992; Kaca et al., 1993; Łabędzki, 2006). On the basis of the research  
23 presented in this paper above, we conclude that severe and extreme droughts of greater importance  
24 (indexes -2, -3, respectively) were in fact slightly less frequent, while their occurrence in the period  
25 from the 15<sup>th</sup> to the 18<sup>th</sup> century, as previously stated, was slightly increasing.

26

27

28 Summary and concluding remarks

29

30 The main results of the present paper can be summarised as follows:

- 31 1. More than one hundred droughts were found in documentary sources from the mid-15<sup>th</sup>  
32 century to the end of the 18<sup>th</sup> century, including 17 megadroughts. A greater-than-average  
33 number of droughts was observed in the second halves of the 17<sup>th</sup> and, particularly, the 18<sup>th</sup>  
34 century. Dendrochronological data confirmed this general tendency in the mentioned  
35 period. The clearly greatest number of negative pointer years occurred in the 18<sup>th</sup> century  
36 and then in the period 1451–1500.

- 1 2. Droughts in the period 1451–1800 occurred most frequently in the Baltic Coast–Pomerania  
2 and Silesia regions, while in the rest of the analysed regions their frequency was more-or-  
3 less similar. Generally similar results have been found for the period 1722–2015 based on  
4 instrumental data.
- 5 3. Analysis of SPI (including its lowest values – droughts) showed that the long-term  
6 frequency of droughts in Poland has been stable in the last two or three centuries.
- 7 4. Most droughts in the period 1722–2015 lasted for two months (about 60–70%), and the  
8 next most common duration was 3–4 months (10–20%). Frequencies of droughts of 5 or  
9 more months were below 10%. The longest droughts lasted for 7–8 months.
- 10 5. The frequency of all-category droughts in Poland in the period 1722–2015 was greatest in  
11 winter. This fact should be taken into account when droughts delimited using documentary  
12 evidence are analysed. In light of this information, droughts in spring and summer clearly  
13 dominated in Poland in the period 1451–1800, while in winter only three cases were  
14 mentioned.
- 15 6. Analysis of the occurrence of negative pointer years (a good proxy for droughts) showed a  
16 good correspondence with droughts delimited based on documentary and instrumental data  
17 in the periods 1451–1800 and 1722–2015, respectively.

18 Our study supports the usefulness of both kinds of proxy data as reliable tools for delimiting  
19 and characterising droughts for the pre-instrumental period in Poland. Information about droughts  
20 received from historical and dendrochronological data very often complete each other. In some  
21 cases where it is difficult to reliably categorise droughts based on historical sources, the occurrence  
22 of narrow rings in trees from different regions and their magnitude can significantly help in final  
23 and more reliable categorisation of this phenomenon. Such a possibility appears to be very  
24 important due to the fact that the historical data are based on subjective observations. On the other  
25 hand, the information received from old historical documents can be also useful for indicating  
26 reasons for the occurrence of the narrow rings noted in trees (droughts, insects ~~vermin~~, etc.). As  
27 long as historical buildings in Poland continue not to be extensively investigated for wood dating,  
28 and not all historical documents are analysed for the study of old weather conditions, the  
29 knowledge about droughts will be incomplete, and further work is thus needed.

30  
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32  
33

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