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

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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 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 17th century, and of the 18th century in particular. Dendrochronological data confirmed this general tendency in the mentioned period.

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 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 Introduction

The increase of 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 droughts frequency and intensity 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 recent decades. On the other hand, some authors document that this change for the entire globe is not as clear as is presented in some abovementioned 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) 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. 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 have been observed in recent decades. Moreover, climatic models project that this tendency probably will be more common and clear in the future world. IPCC (2013) report concludes 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. 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 21st 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 of droughts chronology for the 16th to mid-19th 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 rom the south-west towards the center part of the country and, in some cases, to the north-east of Poland. Another study suggest that in the future some of the highest probability of drought occurrence can be in the central part with the lowets 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 more detailed manner than was done by the 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.

2 Data

2.1. Documentary data

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-15th century, which is why the mid-15th 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. Below we describe the types of historical sources used to reconstruct droughts in Poland.

Records of droughts in the Polish territory are most often found in narrative sources – chronicles, yearbooks, memoirs, diaries, travel accounts. The information included in these sources has a varying degree of accuracy. Often only one account concerning drought appeared, such as, for example, "magna siccitas". In many of the records, however, more detailed descriptions of the course of droughts and accompanying phenomena were given. In the ancient sources droughts were described above all when their manifestations were very clear and when they had an impact on economic and social life. Another group of sources used by us are daily records that have the character of meteorological observations. Sometimes, they were prepared by scholars such as professors of the Jagiellonian University Marcin Biem (ca. 1470–1540) and Michał of Wiślica (1499–1575), who conducted such observations in Kraków from 1499 to 1531 and from 1534 to 1551 (Limanówka, 2001), or townsmen with scientific ambitions such as Gottfried Reyger (1704–1788), who began his observations in Gdańsk in 1721 as a 17-year-old and continued them later, among others as a member of the *Naturforschende Gesellschaft* in Gdańsk until 1786 (Filipiak et al., 2019). Sometimes daily observations were conducted by amateurs, the best example of which are the records of the Polish nobleman from the eastern territories of the Polish–Lithuanian Commonwealth, Jan Antoni Chrapowicki, which were conducted for the years 1656–1685 (Nowosad et al., 2007). Sources of this kind are nonetheless relatively rare.

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

In addition to the above mentioned historical sources collected during the queries in Polish, Lithuanian, Ukrainian and German archives, the authors used several published collections (of varied quality) of historical sources concerning the climate research in the period from the 10th century to the end of the 18th for Poland, Europe Central or selected regions of Central Europe. They include: the period from the 10th century to the end of the 16th (Girguś et al., 1965); the Middle Ages (Malewicz, 1980); 1450–1586 (Walawender, 1935); the years 1648–1696 (Namaczyńska, 1937); and 1772–1848 (Szewczuk, 1939). In the last 20 years, two databases containing over ten thousand weather records were made available in universities in Toruń and Wrocław as part of cooperation between climatologists and historians. They have been used many times to study Poland's climate in historical times (Wójcik et al., 2000; Przybylak et al., 2001, 2004, 2005, 2010; Przybylak, 2011, 2016); they have also contributed to widening the scope of this research.

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

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

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

2.2. Dendrochronological data

We used 22 chronologies (17 oak chronologies, 5 pine chronologies and 1 fir chronology) from different locations in Poland to detect pointer years (Table 1, Fig. 1). Table 1 presents a list of them, including also time coverage and sources. As results from this Table, the longest chronology available to us covers the years 996–1986 and was constructed for western Pomerania (Site 5). For Upper Silesia (Sites 16 and 18) and Lesser Poland (Sites 21 and 22), the pointer years were detected by Opała and Mendecki (2014) and Opała (2015) for Upper Silesia, and by Szychowska-Krąpiec (2010) for Lesser Poland (Table 1, Fig. 1).

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

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	https://www.ncdc.noaa.gov/ (Ważny, 1990)
Site 2	Gdańsk	1762–1986	45	0.887	0.192	Oak	https://www.ncdc.noaa.gov/ (Ważny, 1990)
Site 3	Wolin	1554–1987	23	0.877	0.318	Oak	https://www.ncdc.noaa.gov/ (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	https://www.ncdc.noaa.gov/ (Ważny, 1990)
Region II (Masuria-Podlasie Province)							
Site 6	Gołdap	1871–1987	22	0.941	0.472	Oak	https://www.ncdc.noaa.gov/ (Ważny, 1990)
Site 7	Suwałki	1861–1987	19	0.872	0.303	Oak	https://www.ncdc.noaa.gov/ (Ważny, 1990)
Site 8	Hajnówka	1720–1985	19	0.851	0.314	Oak	https://www.ncdc.noaa.gov/ (Ważny, 1990)
Region III (Greater Poland-Pomerania Province)							
Site 9	Poznań	1836–1987	17	0.904	0.385	Oak	https://www.ncdc.noaa.gov/ (Ważny, 1990)
Site 10	Zielona Góra	1774–1987	19	0.876	0.330	Oak	https://www.ncdc.noaa.gov/ (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	https://www.ncdc.noaa.gov/ (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	https://www.ncdc.noaa.gov/ (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	https://www.ncdc.noaa.gov/ (Ważny, 1990)
Site 20	Kosobudy	1782 – 1989	22	0.937	0.448	Oak	https://www.ncdc.noaa.gov/ (Ważny, 1990)
Site 21	Lesser Poland	1109 – 2004	238	No data	No data	Pine	Szychowska-Krąpiec, 2010
Site 22	Lesser Poland	1109 – 2006	560	No data	No data	Fir	Szychowska-Krąpiec, 2010

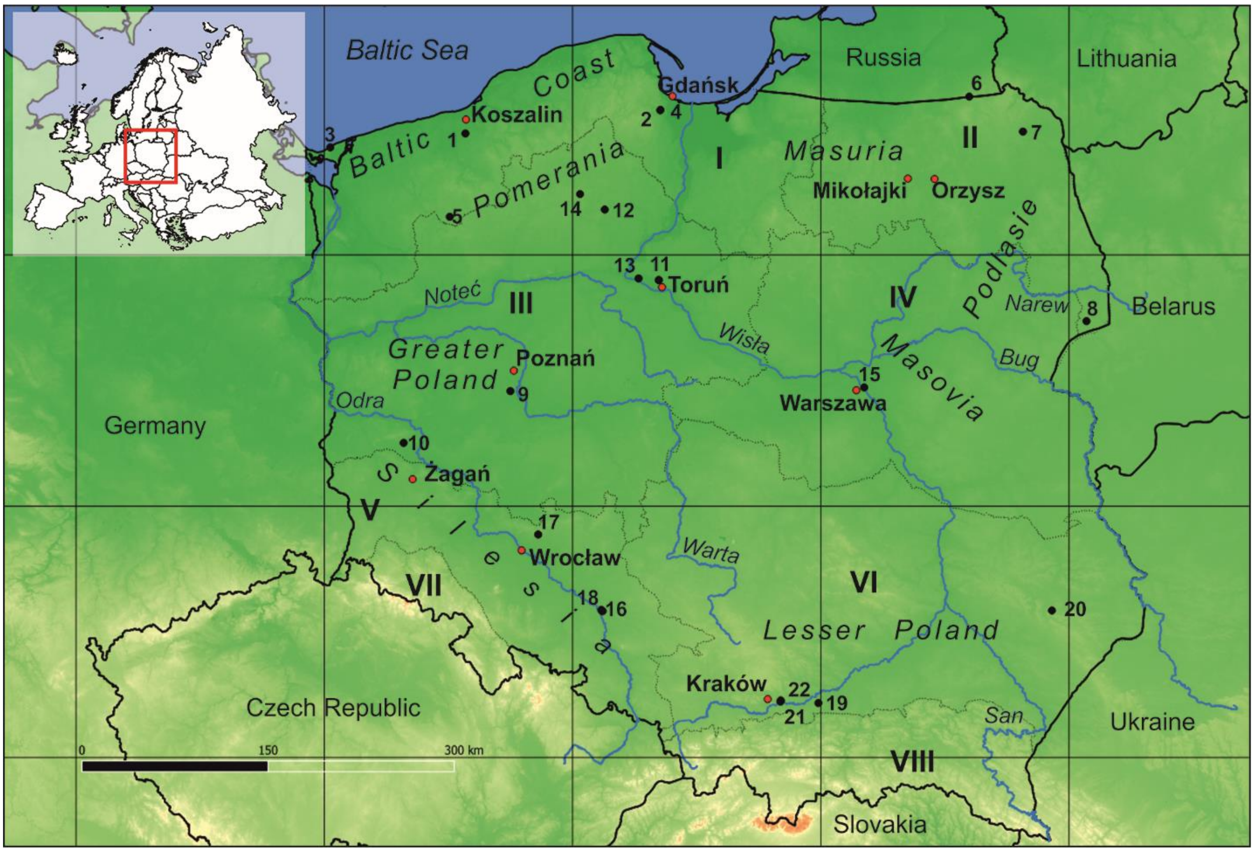

Fig. 1. Location of dendrochronological sites and natural-forest regions (black dots and black dotted lines, respectively, for more details see Table 1) as well as meteorological series (red dots) and geographical regions (for more details see Table 2) used in the study.

2.3. Instrumental data

2.3.1. Isolated series

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

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

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

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

2.3.2. Long-term continuous series

The series from Wrocław (formerly Breslau) that commenced in 1791 (Bryś and Bryś, 2010) is the longest continuous Polish precipitation series. For the purpose of the present paper we prolonged this series until 1781 based on precipitation measurements in Żagań (formerly Sagan) within the Mannheim network of stations established for Europe and North America by the Palatine Meteorological Society in 1780 (Przybylak et al., 2014). The cited authors proved that there exist high correlations between the precipitation series from both places. Source data from Żagań were taken from the publication *Ephemerides Societatis Meteorologicae Palatinae, 1783–1795*. In addition, we must say that the Wrocław series is the only continuous series to have begun before 1800 in the area currently belonging to Poland. The best known long-term climatological series in Poland is the one from Kraków that commenced in 1792. The work on completing the collections of the Kraków series continue till the present day, the effect of which are reconstructions of monthly values of precipitation sums since 1863 (Twardosz, 2005, 2007). As for other Polish cities, Lorenc (2000) performed a homogenisation of series of monthly precipitation totals of Warszawa (Warsaw) since 1813. Miętus (2002) reconstructed atmospheric precipitation sums from Koszalin (formerly Köslin) since 1848. In another paper, Kożuchowski and Miętus (1996) presented series of precipitation totals in Szczecin (formerly Stettin) since 1848. In 2011 a reconstruction was performed of the precipitation series from Gdańsk in 1880–2008 (further extended to 1851) (Filipiak, 2011). During the CLIMPOL project (Climate of northern Poland during the last 1000 years: Constraining the future with the past) Filipiak reconstructed the series of monthly precipitation totals since 1891 for Lake Żabińskie in NE Poland (54°07' N; 21°59' E) (Larocque-Tobler et al., 2015). Further, the series of Orzysz (formerly Arys) and Mikołajki (formerly Nikolaiken), also in NE Poland, were collected for the years 1830–1904 and since 1889, respectively. As both stations are located very close to one another (approximately 20 km) these two series have very much in common. The correlation coefficient calculated for the overlapping periods 1889–1904 and 1981–2015 exceeds 0.85. Thus we decided to combine both series: data from Orzysz covers the period between 1830 and 1890, the later data comes from Mikołajki. A couple of series, e.g. Poznań (formerly Posen), Toruń (formerly Thorn), Racibórz (formerly Ratibor, Silesia), Śnieżka (formerly Schneekoppe, Sudety Mountains), began around the middle of the 19th century and are available in yearbooks that were initially released by the Royal Prussian Meteorological Institute (Königlich Preussischen Meteorologischen Institut), then since 1918 by the Polish National Meteorological and Hydrological Service (PIM until 1945, further PIHM and finally, after 1972 IMGW). The complete list of instrumental series employed in the current research and their sources are presented in Table 2.

Table 2. List of sites, their locations and periods covered by series of monthly precipitation totals 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.	*Ephemerides Societatis Meteorologicae Palatinae, 1783–1795* 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.	Kożuchowski (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

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

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

3. Methods

3.1. Documentary data

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

Extreme droughts (index -3) constituted periods of no rainfall or very scarce rainfall that were long-lasting – they lasted at least one season (2–3 months and more). The principle was adopted that extreme droughts should be recorded in sources from two regions or more; even in view of the absence of sources this allows us to assume that these were droughts of an exceptional nature, having been noted by many writers. Such an extreme drought of 1473 was described, among others, in the "Annals" by Jan Długosz and, for example, in the local chronicle of Wrocław by Nicolaus Pol. When the source information indicated an extreme drought, but at the same time there appeared information, for example, about the high level of water or floods, which may have indicated heavier precipitation especially in the summer season, it was concluded that no extreme drought had taken place. In agricultural terms, extreme droughts contributed to much earlier cereal harvests; they often seriously threatened the growth and size of yield, as was mentioned in the sources. Descriptions of extreme droughts usually contain several permanent elements: severe water shortages, fires, the destruction of crops; sometimes there also appeared records about the fact that people did not remember a similar drought having occurred in their lifetime. These droughts caused water reservoirs – ponds and lakes – to dry up completely. Sometimes, and probably in an exaggerated way, sources reported the drying up of smaller rivers.

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

Table 3. Examples of descriptions of extreme droughts (megadroughts) in 15th–17th-century sources

Year	Description	Translation	Source
1473	[...] *caumata et penuriam aquarum, adeo ut perennes aquae verterentur in aridam, et flumina Poloniae principalia ubique fuerunt permeabilia, 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 vernales exterminatae siccitate.*	[...] 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.	Długosz, vol. 12, p. 336
1540	[...] *fuit in aestate horrenda siccitas adeo, ut silices, montes et valles quasi igne flagrarent, duravit haec siccitas usque ad hyemem.*	[...] 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
1590	*Ist ein sehr heisser truckener Sommer gewesen, also, dass auch die Landflüsse, als der Bober, Queiss, Katzbach,*	The summer was so hot [and] dry that regional rivers like the Bóbr, the Kwisa, the Kaczawa, the Widawa, the Oława, the	Pol, vol. 4, p. 156

	Weida, Olau, Lohe, und andere mehr gänzlich ausgetrucknet. Die Oder ist auch so klein worden, dass man sie an allen Orten durchwatten können.	Ślęża [Silesia, auth. suppl.] and many others dried up completely. The Odra also became very shallow, so you could cross it anywhere.	
	38 Wochen regnete es nicht. Die Flüsse trockneten aus.	It did not rain for 38 weeks. The rivers dried up.	Reinhold, 1846, p. 143
	Zacken und andere Flüsse trockneten völlig aus	The Kamienna and other rivers dried up completely.	Bergemann, ~~J.G.~~ , 1830a, p. 84
	Der Bober trocknete infolge starker Hitze ganz aus.	The Bóbr dried up completely due to severe drought.	Bergemann, ~~J.G.~~ 1830b, vol. 3, p. 85
1676	*Tego roku straszne Panowały Susze, że zboża wypalało w polach.*	That year a terrible drought took place so that crops burnt in the fields.	Muz. Nar. w Krakowie rps. MNKr. 169, p. 82
1684	[...] *folgete auf Johanni [24.06.] eine grosse anhaltende Hitze darauf; davon das Erdreich dermassen dürre wurde, dass das Sommer-Getreyde, Flachs, und Grass, gantz zurücke geblieben, das Winter-Korn an vielen Orten überreiffte, ehe es sich gehöriger massen in die Ahren kaum angesetzet, dahero Theurung entstanden* [...]	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 […]	Gomolcke, p. 32-33

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

Table 4. Examples of descriptions of severe droughts in 15th–17th-century sources

Year	Description	Translation	Source
1456	*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,*	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: Scriptores rerum Silesiacarum, vol. I, p. 340
1532	*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].*	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
1665	*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.*	The summer of 1665 was incredibly hot; not even once did it rain – so called "Dog Days".	Wernicke, Gesch. Thorns., vol. 2, p. 321

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

Table 5. Descriptions of moderate droughts in 15th–17th-century sources

Year	Description	Translation	Source
1461	*Eodem anno fuit estas calidissima et fluvius Odere valde modicus, similiter et alii fluvii.*	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.
1552	*Den 5 Junii* [...] *nach der Vesper und grosser Dürre kam ein gewünschter Regen, aber mit grossem Wetter*	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	*Es folgte aber ein dürrer Sommer.*	However, a dry summer came.	Happelius, p. 148.

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

3.2 Dendrochronological data

We hypothesised that narrow tree rings are linked with drought. The limited access to water during the vegetation season leads to a water deficit in trees and as a consequence the cambium activity decreases and produces fewer cells, which is positively correlated with tree-ring widths (Liang et al., 2013). 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 2/3 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). At first the relationships between tree growth and precipitation was checked. We analysed the effect of climate monthly precipitation and temperature on tree-ring widths using the treeclim package (Zang and Biondi, 2015). Analysis of climate growth relationships for monthly data for Toruń revealed that precipitation during the vegetation season plays a significant role for both pine and oak. For example a significant positive correlation was observed for June and July for pine, while for oak a positive correlation was observed for the previous August and current June and a negative correlation for August (Fig. 2). 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. The sum of monthly precipitation was also included, the months were selected dependably on the significant correlation of the single months and period selected by daily data analysis.

Table 6. Climate growth realtionships for analysed sites. Only highest correlation 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
Region I (Baltic Province)				
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
Region II (Masuria-Podlasie Province)				

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
Region III (Greater Poland-Pomerania Province)				
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
Region IV (Masovia-Podlasie Province)				
Site 15	1951–1985	-0.316	Temperature, previous December	Warszawa
Region V (Silesia Province)				
Site 16	1886–1984	>0.4 Precipitation data onot presented due to lower statistical significance	Temperature of Fabruary and March for pine	Opole, Wrocław, Katowice and Racibórz
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

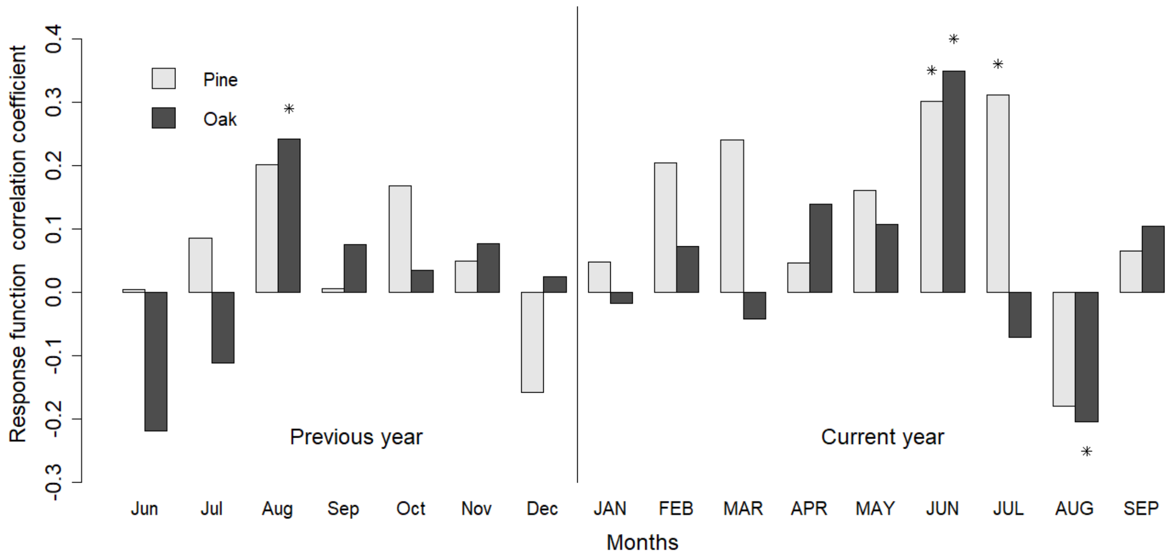

Fig. 2. Climate growth relationships between tree rings in pine (grey bars) and oak (black bars) and monthly totals of precipitation. Key: Asterisks indicate statistically significant correlation coefficients at the level of 0.05. Climate data were taken from Toruń Meteorological Station.

Next we used daily data for Toruń and tree-ring chronologies of pine and oak representing Region III. Daily data shows more precisely the period of the year which influences tree growth. According to previous findings, the climate growth relationships are comparable at different sites in Poland (Zielski et al., 2010), so we used the relationships between daily data and Site 11 and 13 as a model for the rest of our study sites. The reason for this generalisation was also the limited access to daily data. A period of 90 days with the 1-year lag for the years 1947–2015 was used to find the significant relationships between the daily precipitation data and indexes of tree rings. For this purpose we used the dendroTools package (Jevšenak and Levanič, 2018). 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. The sums of daily precipitation for these periods were summed and correlated with indexed growth in years of growth reduction (narrow rings) and growth recovery (wide rings). The correlation coefficient is 0.79 ($p<0.05$) for pine, and 0.65 ($p<0.05$) for oak. Next, the same summed daily precipitations for the selected periods were correlated with the remaining tree ring indexes (after exclusion of wide and narrow ring indexes). The correlation coefficient is 0.40 for pine and 0.16 for oak.

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

2.3 Instrumental data

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

On the basis of the completed series of atmospheric precipitation, the possibility of obtaining a synthetic precipitation index for the whole country was tested. A similar method was adopted in Brázdil et al. (2007) to determine drought indices in the Czech Republic for the period 1881–2006. In Poland, Kożuchowski (1985) presented a 100-year series of average areal annual atmospheric precipitation for 1881–1980 (his Table 3) calculated from data from 12 meteorological stations using precipitation regression equations relative to altitude above sea level. Miętus (1996), in turn, presented mean areal precipitation for the Coast area. For the analysis, we took 30-year moving correlation coefficients (*r*) for monthly totals of precipitation counted for the period 1901–2000. All correlation coefficients were statistically significant ($p<0.05$) with values varying from 0.46 to 0.71 (see Table 6, upper part). Only the Kraków series had a significantly lower value of *r* (the highest value of 0.33 described the relationship between Kraków and Wrocław). For annual precipitation totals in the period 1951–2000, Kożuchowski and Żmudzka (2003) obtained only slightly higher values of correlation coefficients, varying from 0.6 to 0.8. Unsatisfactory results of *r*, particularly related to the series for Kraków, suggested that we should not construct monthly precipitation series for the entire Poland. It seems that the number of long-term precipitation series is probably relatively too small for a country of such area (312,679 km^2). Further analysis was thus carried out on regions delimited by a landscape criterion, though this excludes mountains, whose atmospheric precipitation is spatially and temporally far more variable (Kożuchowski, 1985).

Table 7~~6~~. Correlation coefficients between monthly totals of atmospheric precipitation (upper part of table) and SPI1 (lower part of table) in area of Poland calculated based on data from the period 1901–2000

Station	Toruń	Koszalin	Gdańsk	Orzysz-Mikołajki	Poznań	Warszawa	Żagań-Wrocław	Kraków
Toruń		*0.56*	*0.67*	*0.62*	*0.69*	*0.62*	*0.61*	*0.29*

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

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

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

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

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

Drought is a widely occurring phenomenon, but its frequency is extremely limited within particular long-term periods. For this reason, it was decided to group numbers of droughts into longer periods. For a fuller comparison of drought occurrence identified on the basis of dendrochronological data (narrow rings), we used instrumental data to calculate the number and duration of droughts within ten-year periods, starting from the slightly shorter period 1722–1730, through full decades, to the five-year period 2011–2015. Next, we also summed the number of droughts by 50-year period, also determining seasons in this case, just as we did when analysing the documentary data.

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

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

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

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

where:

$N_{i,100}$ – the number of droughts for a timescale i in 100 years

N_i – the number of months with droughts for a timescale i in the n-year set

i – timescale (1, 3, 24, months)

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

4. Results

The climatic conditions of Poland have been characterized many times by different authors such as Paszyński and Niedźwiedź 1991; Woś 1999 and Lorenc 2005. For many years The Polish National Meteorological and Hydrological Service IMGW-PIB has presenting the fruits of their monitoring (www.klimat.pogodynka.pl), allowing analyses and assessments to be made.

The climate of Poland is in general temperate. Due to its location in the central part of the continent and being considerably affected by oceanic features in the western part of the country and a pronounced continental impact in the east, the area of Poland is diverse in terms of climatic conditions. An important geographic feature of Poland is the latitudinal course of its natural landscape types – from its sea coast in the north to its lakelands, lowlands, uplands and mountains located southward.

The mean annual air temperature in particular regions of the country varies between almost 7°C to nearly 10°C (as for the period 1981-2010) with lowest temperatures in January (from -

3.5°C to 0.5°C) and highest temperatures in July (from 16.5°C to 19.5°C) (IMGW 2020). The whole country is experiencing a systematic considerable increase in air temperature with rates of increase of 0.3°C every 10 years occurring since the second half of the 20th century. The largest increases have taken place in northern and western parts of Poland. In 2019, mean annual air temperature reached 10°C, translating into the warmest year in Poland since the beginning of instrumental measurements of air temperature. Annual precipitation ranges from 450mm in the central belt to 700 mm in the uplands and 1500-1700 mm in the highest mountain ranges in southern Poland (IMGW 2020). February is the driest month in Poland and July is the month when the highest monthly precipitation totals occur. During the last number of decades symptoms of the systematic drying of climate in Poland can be observed. Westerly and south-westerly winds predominate and only in northern, coastal parts of the country is there a considerable amount of north-westerly winds.

4.1 Droughts in Poland based on documentary data

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

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

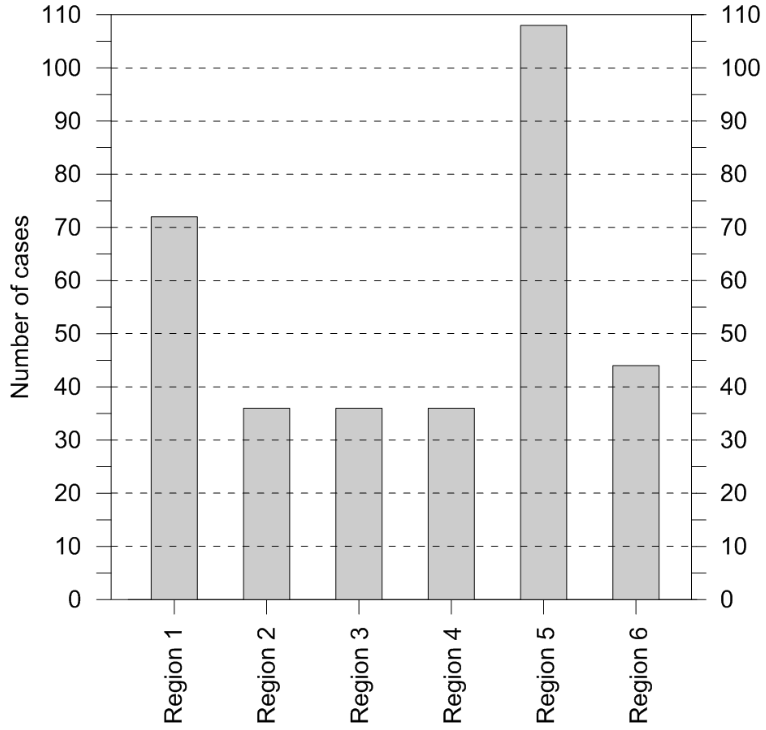

Fig. 3. Number of years with droughts in six geographical regions of Poland (including information related to the whole country) 1451–1800. See Table 2 or Fig. 4 for names of regions.

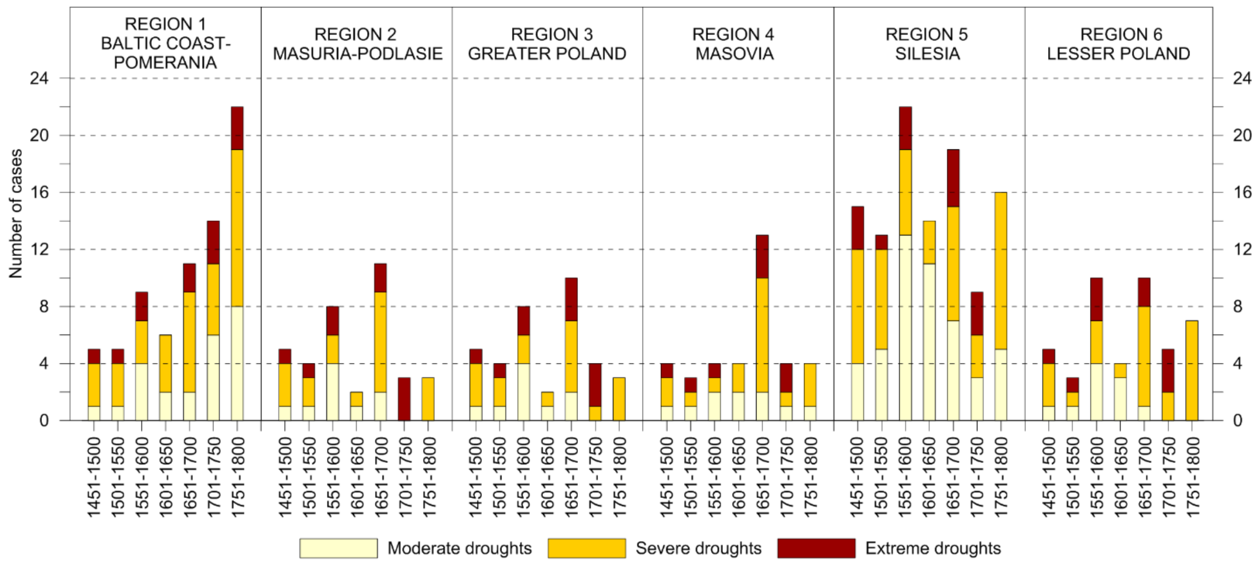

Fig. 4. Frequency of occurrence of three categories of droughts in six distinguished geographical regions in Poland in 50-year periods, 1451–1800

We also calculated the frequency of all droughts occurring (Fig. 5). In the chronological order in the periods of 50 years, the number of extreme droughts (-3) never exceeded five; in the first half of the 16th century only the drought of 1540 was recognised as such, while in the first half of the 17th century, extreme droughts were completely absent (Fig. 5). It seems that extreme droughts, whose total number in the period 1451–1800 was 17, were regularly recorded in sources, and this information is quite reliable.

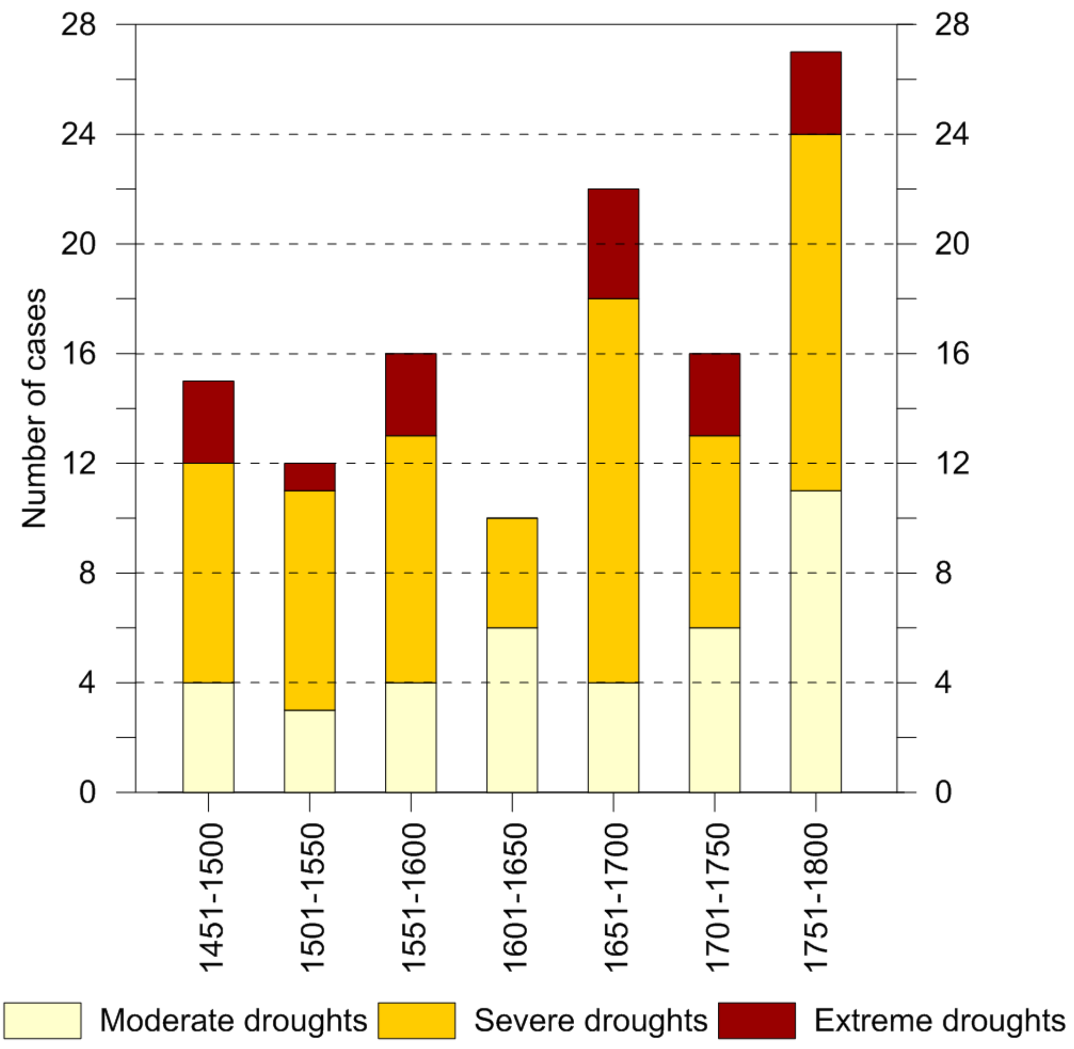

Fig. 5. Frequency of occurrence of three categories of droughts in Poland in 50-year periods, 1451–1800

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

However, the total frequency of extreme (-3) and severe (-2) droughts amounted to 80 and ranged from 4 to 12 in particular fifty-year periods, except for the second half of the 17th century and the second half of the 18th century, when there occurred as many as 18 and 16 droughts, respectively (Fig. 5). The increase in the number of identified droughts in the second half of the 17th century was certainly due to the availability of detailed weather records from the period 1656–1685 taken from the memoirs of Jan Antoni Chrapowicki (Nowosad et al., 2007). However, the minimum number of droughts (only 4) took place in the first half of the 17th century (Fig. 5), for which, in turn, we recorded significant losses in the sources.

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

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

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

4.2 Droughts in Poland based on dendrochronological data

Twenty-two local chronologies of trees (pine, oak, and fir) from Poland were taken into account for detecting negative pointer years, showing narrow rings. In a year in which we have narrow rings at more than 1 site, we count this pointer year as a "multiple observation" year, whereas, in a year with only one observation, at one site, we call it a year "without multiple observation". In total, 758 pointer years with multiple observations were detected and 432 years without multiple observations. There are 237 multiple observation years of extreme reduction, 122 of great reduction, 252 of moderate reduction and 147 negative pointer years from the literature (Opała and Mendecki, 2014; Opała, 2015; Szychowska-Krąpiec, 2010) (Fig. 6). The number of pointer years in selected 50-year periods varies (Fig. 7). At least 30 pointer years were noted within the years 1401–1450 and within each of the 50-year intervals from 1701 to 1950. The evidently smallest number of negative pointer years occurred in the first 150 years (Fig. 7). In the years 996–1000, drought did not occur, and therefore this period was omitted in Figures 6 and 7. However the small number of pointer years from 996 to 1200 may be related to the low number of samples. This period is called as Medieval Climate Anomaly and reconstruction for northern-central Europe revealed considerably drier conditions for this years (Scharnweber et al., 2019). The number of chronologies varies and depends on region. More chronologies in the last 300 years result from existing old trees. It also led to the detection of more pointer years. According to Neuwirth et al. (2007) during extreme climatic conditions trees react in the same way, but during years of less pronounced weather conditions regional differences in growth reactions increase. Narrow rings observed in the same year in trees from different regions suggests extreme climatic conditions.

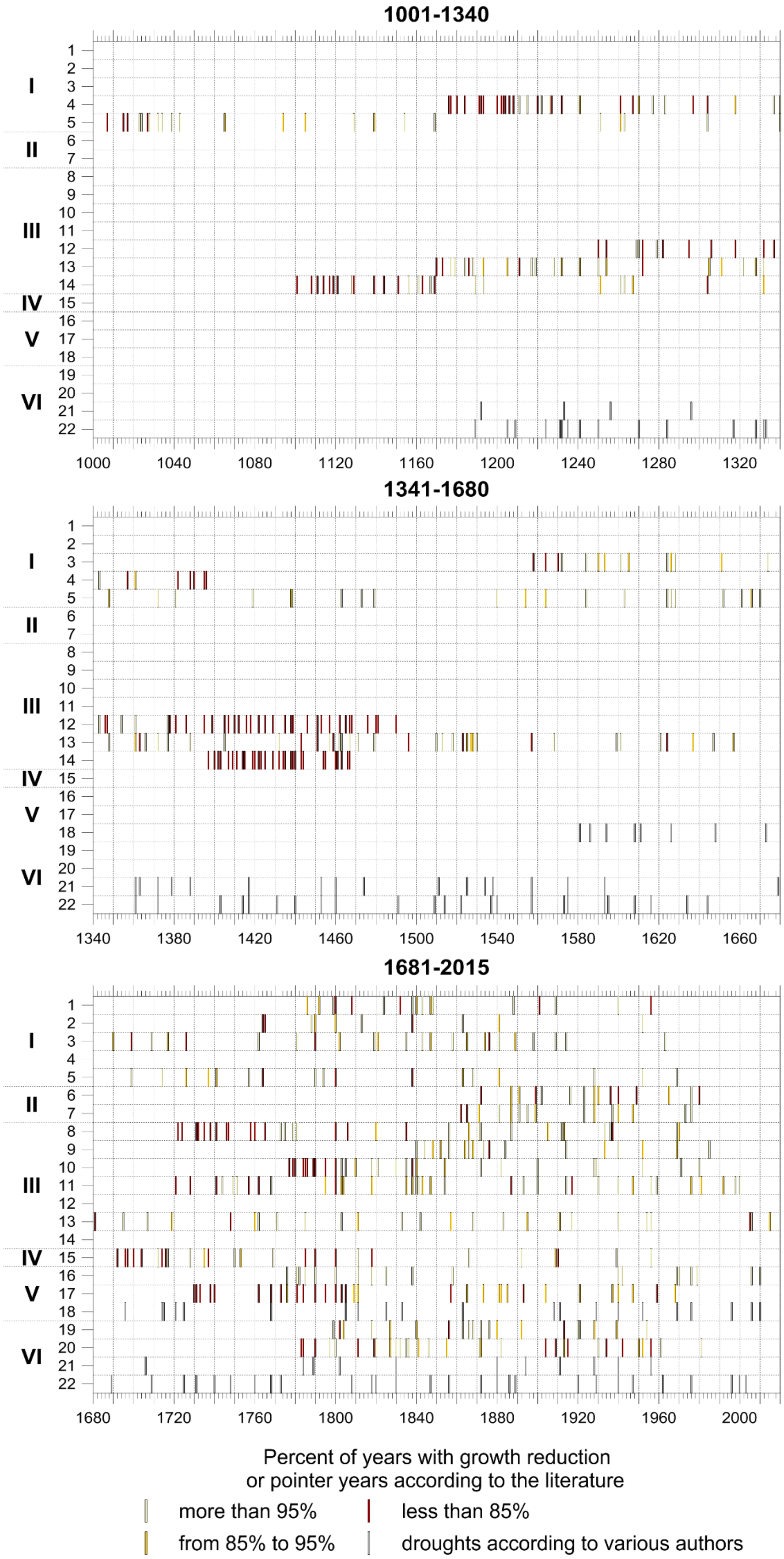

Fig. 6. Pointer years in Poland, 1001–2015

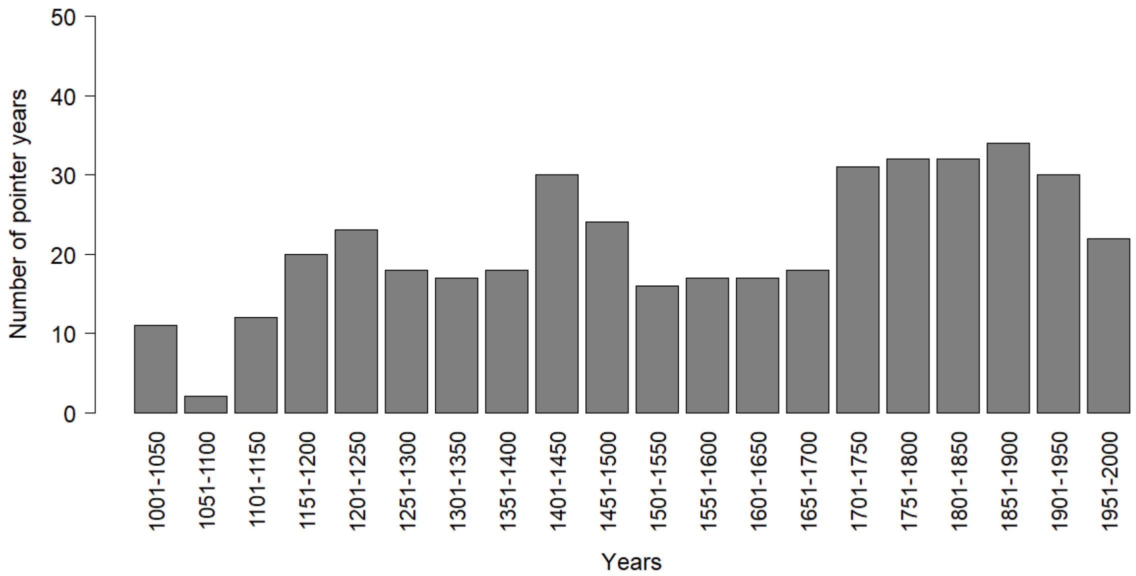

Fig. 7. Number of negative pointer years (without multiply observation – i.e. narrow rings in 1976 were observed on six samples but are treated as a one-pointer year) in Poland in 50-year periods, 1001–2000.

4.3 Droughts in Poland based on instrumental data

Instrumental observations of precipitation in Poland are among the longest-standing in the world (Filipiak 2007). As results from Table 2, they are available since 1722. In Figure 8 we present the SPI calculated for eight sites in Poland for 1-, 3-, and 24-month time scales. The values of SPI3 and SPI24 were filtered by 10-element and 30-element low-pass Gauss filters, respectively, in order to more clearly distinguish long-term dry periods. The analysis of Figure 8 reveals that the occurrence of droughts in different areas of Poland shows both similarities and discrepancies. It is very clear that in northern and central Poland, a long-term (24 months' duration, red line) and extreme drought occurred at the threshold of the 1850s/60s. Almost one hundred years later (at the threshold of the 1940s/50s) such a strong drought was present across the entire area of Poland (Fig. 8). Except for Kraków, and also Gdańsk in the last few years, severe droughts have not been observable at the turn of the 21st century. In Silesia, a very dry period occurred for almost the entire first half of the 19th century, and then significantly less severe droughts occurred here only in the 1950s and 1990s. For the 18th century we have mainly information for Gdańsk. Figure 8 shows that dry periods (moderate droughts) occurred here only at the threshold of the 1750s/60s and in the mid-1770s. The most extreme droughts in different parts of Poland occurred in different times. For example, in Gdańsk at the threshold of the 1910s/20s, in Koszalin and Orzysz-Mikołajki in the 1850s, in Toruń in the 1910s, in Poznań in the 1980s, and in Kraków in the 1980s and 1990s (Fig. 8).

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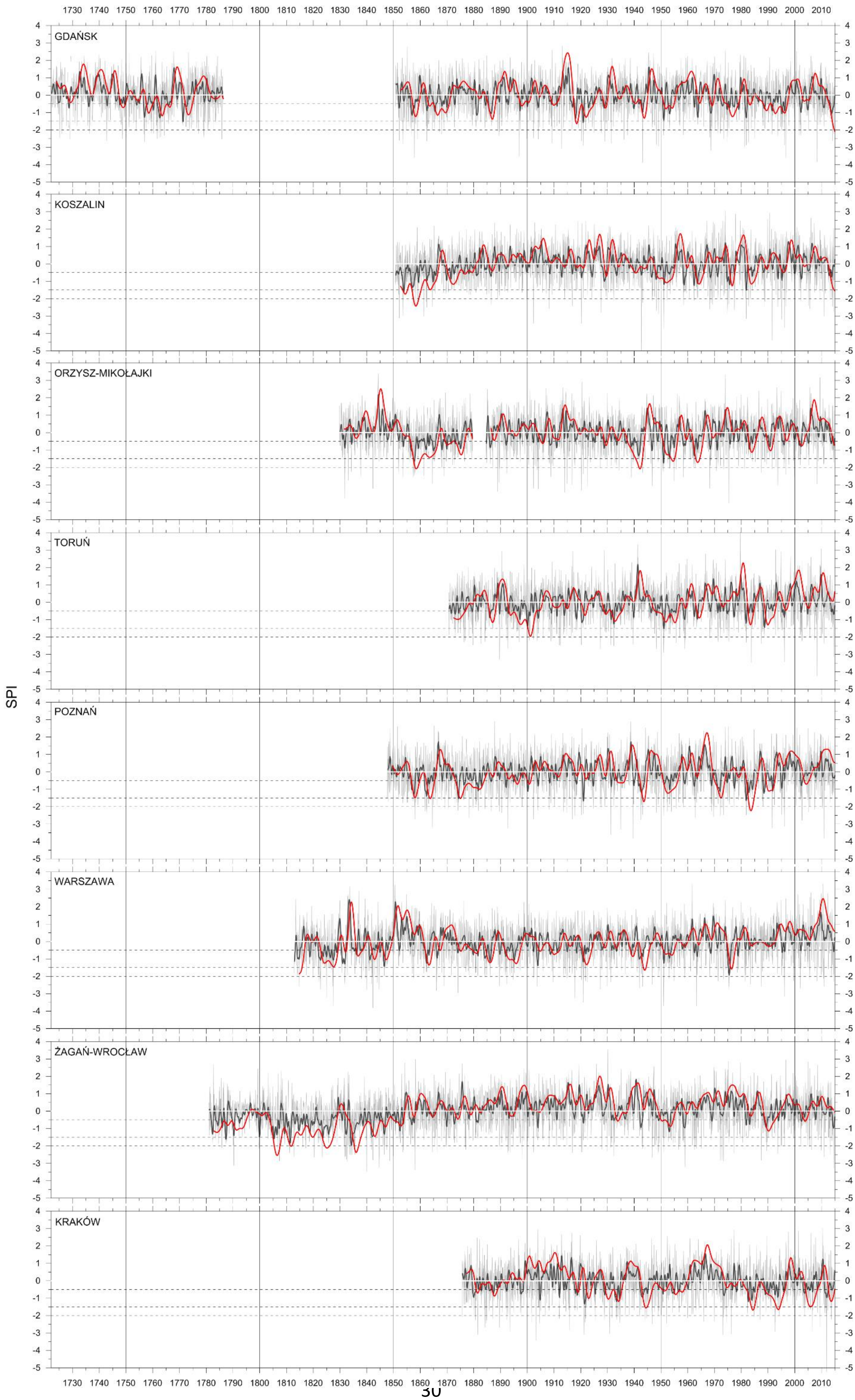

GDAŃSK
KOSZALIN
ORZYSZ-MIKOŁAJKI
TORUŃ
POZNAŃ
WARSZAWA
ŻAGAŃ-WROCŁAW
KRAKÓW
SPI

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

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

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

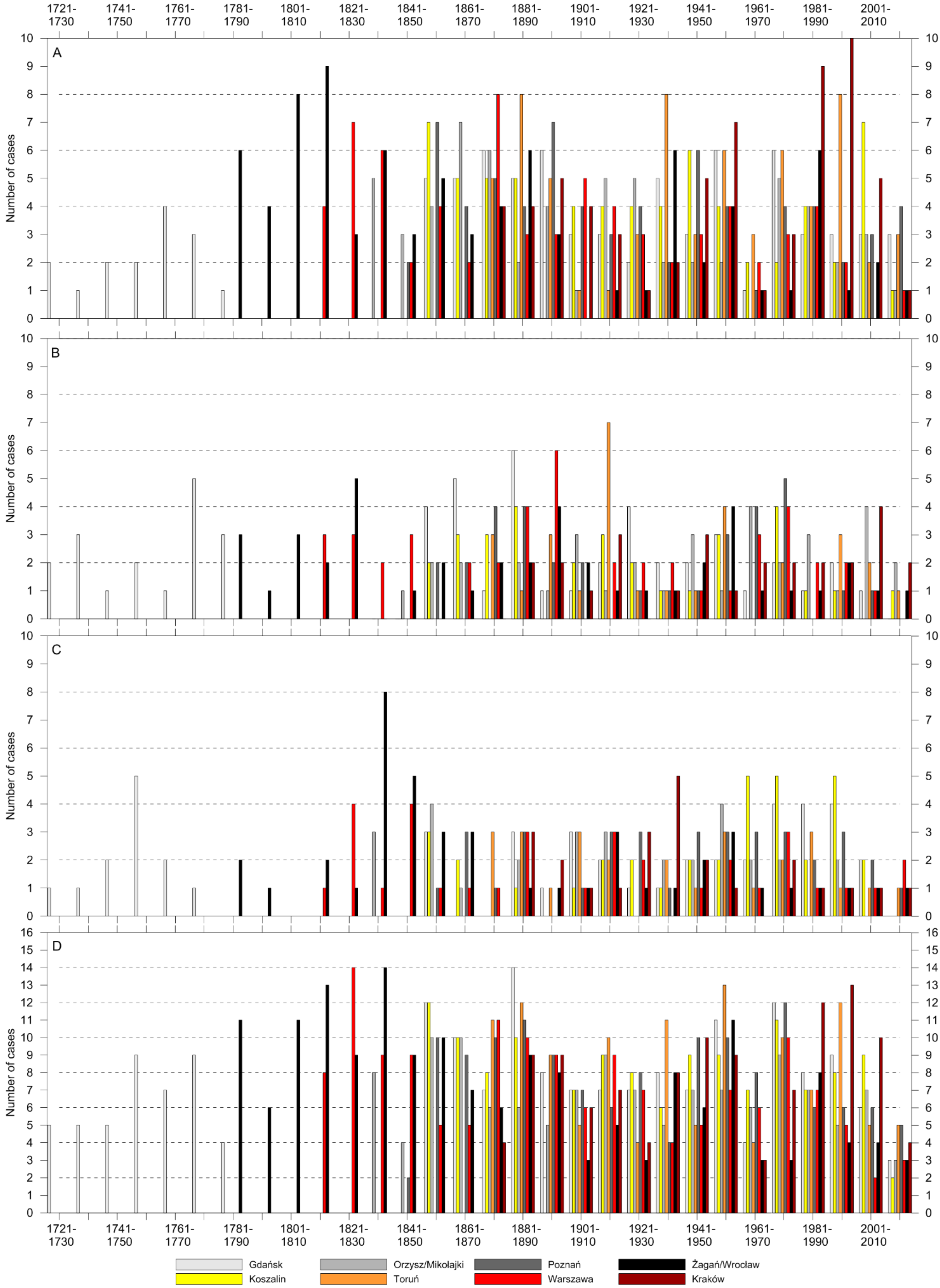

Fig. 9. Decadal frequency of droughts in Poland in 1722–2015 identified using SPI1

Key: A – moderate droughts, B – severe droughts, C – extreme droughts, D – all-category droughts

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

For comparison against the number of droughts delimited using documentary evidence, 50-year frequencies of the three categories of droughts were calculated for climatological seasons (Fig. 10). It comes as little surprise that the frequency of all-category droughts was greatest in winter. Other seasons show more-or-less similar frequencies. In winter, droughts evidently dominated in the study period in the second half of the 19th century, this is particularly well seen in the case of severe droughts, and slightly less so for moderate droughts, which were also quite frequent in the first half of the 20th century. Extreme droughts in winter 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. Moreover, in addition to winter droughts it should be pointed out the deficit in precipitation during this season is usually connected to temporarily increasing continentality of climate conditions which are related to the advection of very cold and dry polar continental air masses from the east, sometimes even with the mixture of very cold arctic air masses. During such conditions deep soil frost increases which does not allow the water infiltration into deeper layers. Thus, almost all melting snow is transformed into spring surface run-off volume and only the negligible part of this volume is transformed into groundwater. Such conditions may lead to the occurrence of very dry spell in spring. In spring, moderate droughts prevailed still in the period 1851–1950 (usually 4–6 cases), with a greater frequency in the first 50-year period. Both severe and extreme droughts were most frequent (usually 1–3 cases) in 1851–1900, and in particular in 1951–2000 (Fig. 10). In summer there is a clear change in the time pattern of drought occurrence: drought frequency rises in the 20th century (except severe droughts), and in the case of moderate droughts particularly in its second half. Frequency of extreme droughts is evidently higher in the 20th century compared to pre-1900 period. In autumn, moderate droughts do not show great changes in the last two centuries, while severe and extreme droughts were most frequent in the 20th century-(Fig. 10).

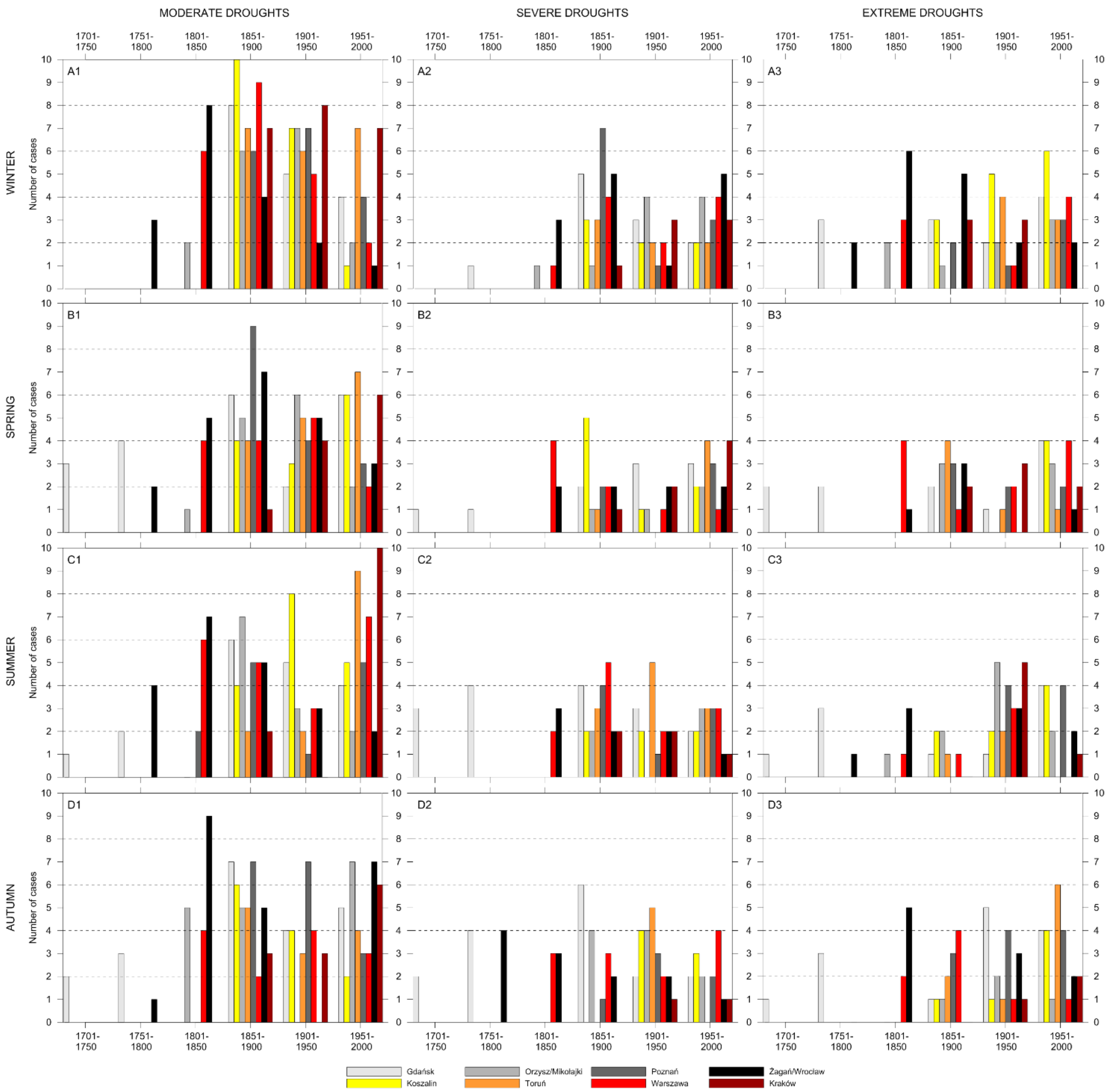

Fig. 10. Seasonal 50-year frequency of droughts in Poland in 1722–2015 identified using SPI1

The frequencies of droughts per 100 years calculated for different their durations (2 months, 3 months, etc.) are shown in Figure 11. The greatest number of all-category droughts occurred in Gdańsk (165) and in Żagań/Wrocław (155), while the smallest was in Kraków (104). In line with expectations, moderate droughts clearly dominate (55–75). The number of severe and extreme droughts is more-or-less comparable, most often ranging between 25 and 40. Both these two categories of droughts were most frequent in the coastal part of Poland, and least frequent in Lesser Poland (Fig. 11). Most droughts lasted two months (about 60–70%), and then 3–4 months (10–20%). The frequency of droughts of 5-or-more months was less than 10%. The longest droughts had durations of 7–8 months and occurred in Gdańsk from January to July of 1771, in Wrocław from March to September of 1805, in Poznań from May to November of 1874, in Toruń from March to September of 1900, and in Wrocław (again) from August 1953 to March of 1954 (8 months).

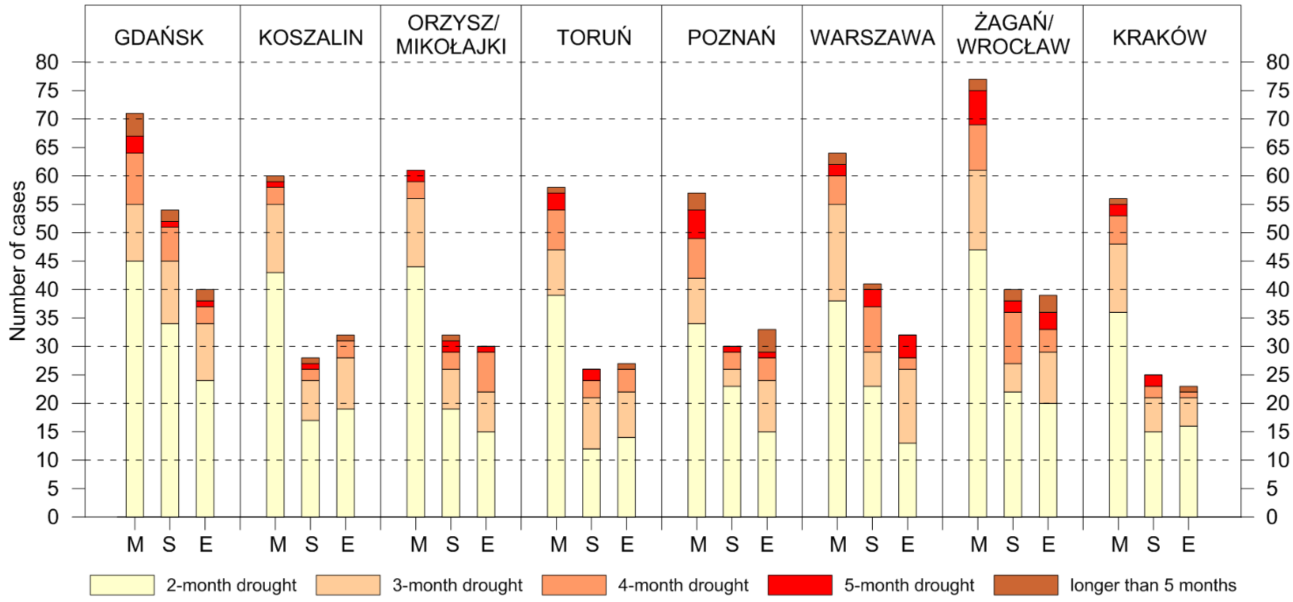

Fig. 11. Average frequency of three categories of droughts (M – moderate, S – severe, E – extreme) in Poland per 100 years stratified by duration, 1722–2015

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

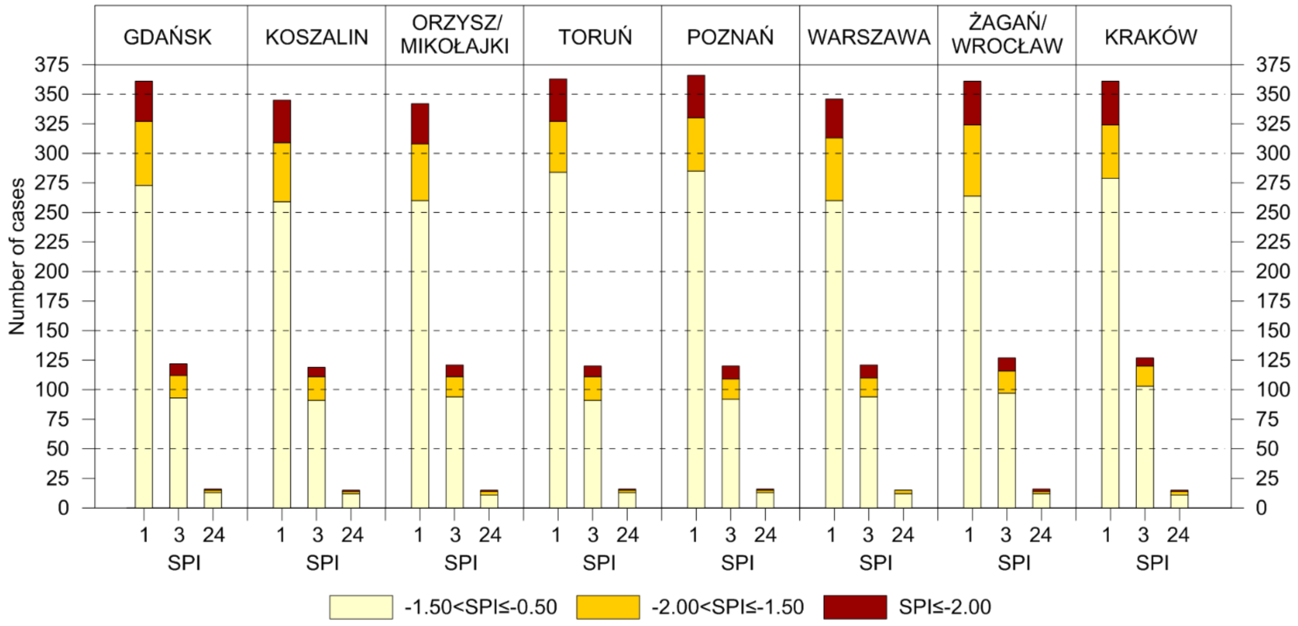

Fig. 12. Frequencies of dry months (SPI1), short-term droughts (SPI3) and long-term droughts (SPI24) in Poland, including three intensity categories calculated using Łabędzki's formula

4.4 Selected megadroughts in Poland from historical times

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

4.4.1 The year 1473

This drought affected the whole of Europe. In the case of Poland, it was quite well described by Jan Długosz in "Annales", as Długosz himself observed its course. He wrote about extraordinary heat and a prolonged lack of rain. He emphasised the extremely low level of water in the Wisła River and many other rivers that could be easily waded across. Water reservoirs were completely dry. The lack of water was marked throughout the whole country. Fires were another commonplace phenomenon. There were forest fires. Długosz also mentioned economic consequences. Fires destroyed wild beehives in the forests. Drought destroyed the spring sowing. Animals got sick. Fires affected such cities as Kraków, Wieliczka, Konin, Bełz, Chełm, Lubomia, Łęczyca, Sandomierz and others (Długosz Ks.) (see Fig. 13). According to the Silesian chronicler Peter Eschenloer, the drought lasted from 23 April to 11 November. This chronicler recorded an extremely low level of water in the Odra River. Water mills could not operate. There was no water in wells. Even wild animals were affected by the lack of water. Similar information was provided by another Silesian chronicler, Nicolaus Pol. Meanwhile, the author of *Roczniki głogowskie*, Kaspar Borgeni, reported that the drought lasted only 10 weeks. However, he provided many detailed dates in his narrative about the harvest time and their quality; there was no rain from April 4 to September 22, so it should be considered that the drought lasted almost 6 months.

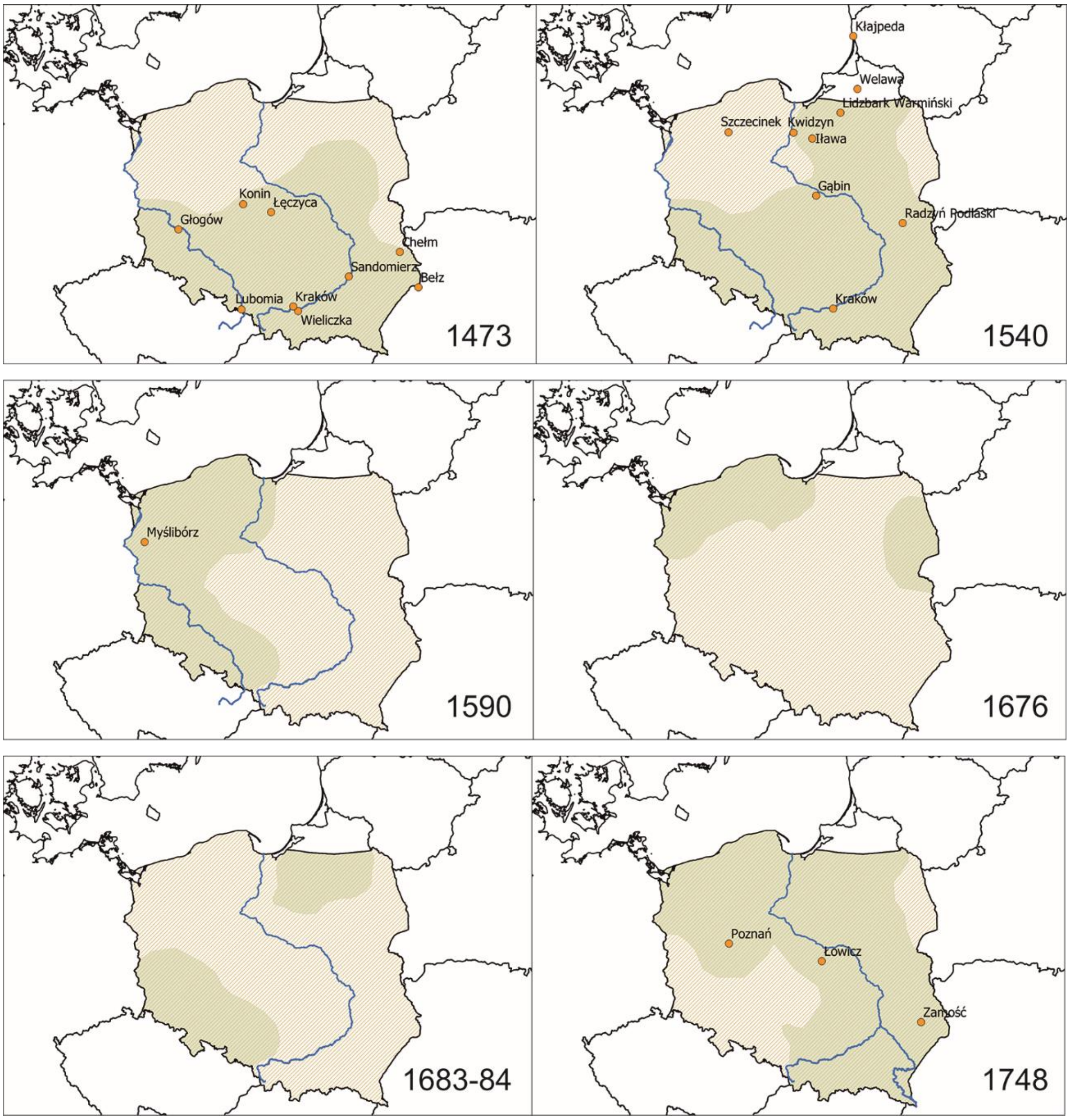

Fig. 13. The most severe megadroughts, with spatial coverage (dark colour). Location of sites and rivers mentioned in Section 4.4 and Table 3 is shown.

4.4.2 The year 1540

This drought belongs to one of the best described droughts in old Europe. In Poland, however, the year 1540 began with numerous floods in the winter (Poznań) and early spring (Żuławy and Gdańsk). Heavy rainfalls also caused floods in Świecie located on the Wisła River in its lower part. Polish sources are quite laconic, if unambiguous, about the drought of 1540, considering its scale. A parish priest from Lidzbark Warmiński wrote about a terrifying drought. The Silesian chronicler Nicolaus Pol wrote about the drying of many waters and the greening of the Odra River, probably as a result of the development of algae at high temperatures. It was reported that grass was drying out, cereal harvests were poor, cattle had to go many miles to watering places. The detailed observations of the Kraków professor Marcin Biem leave no doubt as to the lack of rainfall and the extreme nature of the drought in the vicinity of Kraków. The drought lasted until October. There were many fires, including in such cities as Kwidzyn, Welawa, Klaipeda in the Prussian state, Gąbin in Mazowsze, and Radzyń Podlaski (see Fig. 13). Fires were also reported in Iława and Szczecinek (Nowosad and Oliński, 2019).

4.4.3 The year 1590

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

4.4.4 The year 1676

The drought of 1676 was described independently in several sources. Spring is supposed to have abounded in storms that caused numerous fires. There was drought in the summer. In Pomerania (see Fig. 13) it rained only twice in the summer. The whole summer was dry and hot. The drought caused damage to crops in slightly higher areas. The harvest of fruits and vegetables was also poor due to the drought. In Podlasie, the beginning of January was exceptionally warm, although frosts arrived later. According to the records from Antoni Chrapowicki's diary, June and July were very dry months in Podlasie. Chrapowicki wrote that crops “burned out” in the fields. In August and September, Chrapowicki stayed in eastern Belarus, which is why his records concerning the late summer and autumn cannot be taken into account (Diaryusz Życia JWJmci Pana Jan Antoni Chrapowicki). The research into the memoirs of Chrapowicki indicates that the precipitation in 1676 was the slightest of all the years covered by his diary (1656–1684) (Przybylak and Marciniak, 2010). In other sources, the high prices that prevailed in the country this year were also underlined (Namaczyńska, 1937).

4.4.5 The years 1683–1684

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

4.4.6 The year 1748

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

On 1st July, in Toruń, it was recorded that there had been light rains from time to time, but above all, a great drought had been felt. No fires had broken out in the vicinity yet, but they had in many places in Poland and Lithuania: fires were recorded in Poznań and Zamość (see Fig. 13). In Gdańsk, rainless weather prevailed throughout the first half of July, while in the second half there were only five days with rain. In mid-July, high prices resulting from the prolonged drought were reported. Transport on the Wisła River was extremely difficult due to the low water level. Information about the drought also came from other European countries. In addition, locusts appeared in Hungary and Transylvania. In Toruń and Gdańsk, rain fell for a few days after the solar eclipse of 25th July. Similar rains fell at that time in Warszawa. At the beginning of August, however, the drought was reported again. In Toruń, rain fell on 5th August, then on 8th August. At that time, the water level in the Wisła River also increased for a short time, but at the same time, there were reports of fires having destroyed Łowicz. In Toruń, the drought prevailed until the end of August and the first half of September. In Gdańsk, the whole month of August was very dry. Rain fell there in early September, but in the following days the drought returned and did not stop until mid-September. The autumn was very cold. The end of the drought was not seen in Toruń until mid-October, but complaints about the very low water level in the San River were still being reported (Reyger, Brauer).

5 Discussion

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

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

Extreme and severe drought occurrence in spring and summer, as identified by documentary data, corresponds closely with the occurrence of negative pointer years (droughts). In the period 1451–1800, 48 severe and extreme droughts in the mentioned seasons have been determined to have occurred across all of Poland or in at least two geographical regions (see Fig. 1). Dendrochronological data showed significantly smaller rings having formed during 52.1% of these. Dobrovolný et al. (2015) found very similar results for the Czech Republic based on a set of 3,194 oak-ring-width samples for the last 1,250 years (761–2010). Negative tree-ring-width extremes were confirmed in documentary sources in 53% of cases. Analysis of extreme and severe droughts that occurred in only one geographical region in Poland reveals a better correspondence between analysed proxies than those described earlier for the greater area of Poland (at least two regions). In this case negative pointer years in tree rings were noted in as many as 59.1% of detected droughts by historical sources.

Even better agreement between both kinds of proxy data was found when megadroughts identified by documentary evidence were taken into account. In four (1473, 1540, 1590 and 1748) of the six described here (see Section 4), clear signals in dendrochronological data were detected (negative pointer years). Using documentary sources, two megadroughts (1540 and 1590) were also qualified as very outstanding droughts in the Czech Republic (Brázdil et al., 2013). Of those, however, only the year 1590 had a negative tree-ring width index (TRW) (of -1.818), although this value was not very high (see Table S1 in Supplement in Dobrovolný et al., 2015). Brázdil et al. (2013) using documentary evidence also distinguished three other outstanding droughts in the Czech Lands (1616, 1718 and 1719). All of those also occurred in Poland, but their category using documentary evidence was estimated by us as -2 (severe). In all those years except 1718, negative pointer years were also found in one Polish region (see Fig. 6), while in the Czech Republic an extreme negative TRW index (-2.474) was found only for the year 1616 (see Table S1 in Supplement in Dobrovolný et al., 2015). Based on the published list of TRW indices for Czech Republic (oak chronology) by Dobrovolný et al. (2015) we found 33 extreme negative TRW indices in the period 1451–1800, which suggests favourable conditions for drought occurrence. We excluded the two last years (1790 and 1800), which were identified for Scots pine tree rings from Upper Silesia (Opala and Mendecki, 2014). For almost half of this set of years (48.5%), we confirmed the existence of strong negative pointer years also in Poland's tree dendrochronologies. Significantly better agreement (89%), between the occurrence of narrow rings in the Czech Republic on the one side, and Upper Silesia (Opała and Mendecki, 2014) and southern Poland (Opała, 2015) on the other, was found by Dobrovolný et al. (2015) for the overlapping period 1770–1932. These quite good correspondence patterns between negative TRW in the Czech Republic and Poland (in particular its southern part), which are also very clear in analysis of drought occurrence and areal coverage (which are presented in the Old World Drought Atlas [OWDA, Cook et al., 2015]), are the result of large positive sea-level-pressure anomalies over the whole of central Europe (including Poland) in MAM and JJA during the occurrence of negative extremes in TRW (see Fig. 5 in Dobrovolný et al., 2015). Significantly weaker agreement (about 30%) was found between the timings of droughts in Poland delimited using documentary evidence and droughts reconstructed for the whole of Europe using tree rings (Cook et al., 2015). This is caused by the fact that Cook et al. (2015) used significantly fewer dendrochronologies from Poland (only four – and those mainly from northern Poland, see their Supplementary Materials) than we used in the present paper (22, see Table 1 for details).

The megadrought year of 1473 was detected in the Baltic Province on the basis of an oak chronology from Eastern Pomerania (Ważny, 1990). Narrow rings were observed in 80 percent of the samples for this year. The effect of the drought in 1473 can also be shifted and observed in southern Poland in 1474 (Szychowska-Krąpiec, 2010). Reconstruction based on dendrochronological data (OWDA, Cook et al. 2015) shows that, in this year, severe droughts were common in almost the entirety of Europe (but particularly in southern Germany, western

Czech Republic and Austria) excluding only its northern and north-eastern parts and Spain. The drought in 1540 was observed in different parts of Europe; particularly strong evidence is available in documentary sources (Wetter et al., 2014; Pfister et al., 2015; Brázdil et al., 2016). Additionally, many dendrochronological data confirm the existence of strong droughts in much of Europe, in particular from France to Latvia, Belarus and Ukraine and from the southern Scandinavian Peninsula to northern parts of Italy (OWDA, Cook et al., 2015). Čufar et al. (2008) identified the existence of droughts in Slovenia in 1540 based on tree rings. The scale and intensity of the 1540 megadrought in Europe described by Wetter et al. (2014) as "an unprecedented 11-month-long Megadrought" (more severe than the 2003 drought in Western Europe and the 2010 drought in Russia) was, however, recently questioned by Büntgen et al. (2015), who analysed this year in light of 24,303 individual tree-ring-width measurement series. It is also worth adding here that in different parts of Europe the effect in tree rings was shifted and observed in 1541 (Büntgen et al., 2011). Analysis of our 22 dendrochronologies reveals the occurrence of narrow rings in trees growing in the Baltic Province and in the Lesser Poland Province, and thus not in the whole of Poland as shown in the OWDA (Cook et al., 2015). In 1590, narrow rings were observed in the Baltic Province, but the decidedly strongest droughts in Europe in view of this proxy were those occurring in France and Germany (Cook et al., 2015). Narrow rings were also noted in most sites in central and eastern Europe, as well as in Scandinavia. The megadroughts occurring in Poland in the 17th century (1676 and 1683–84) were the least territorially extensive of all the megadroughts analysed here (see Fig. 13). Analysis of tree-ring reconstructed droughts (Cook et al. 2015) generally confirms this, except for the year 1684. In all those years strong droughts were common in Europe also, but their greatest intensity was observed in Germany, France, the Low Countries and England (1676 and 1684), but in southern Europe in 1683. The year 1748 seems to have a somewhat regional character; narrow rings were noted in the Greater Poland and Pomerania Province and in the Lesser Poland Province. There is no information about tree reaction for this drought in selected sites in central Europe (Büntgen et al., 2011). Looking at OWDA we see the occurrence of droughts in this year mainly in northern and western parts of Poland (although their severity is not so large). Evidently more severe droughts in this year in Europe were particularly observed in southern Germany, the whole of Austria and the western borders of the Czech Republic (Cook et al., 2015).

Both documentary evidence and dendrochronological data clearly indicate that in the period 1451–1800 the greatest frequency of droughts in Poland occurred in the 18th century, and particularly the second half (32 cases). Similar results are also seen in the Czech Republic (see Fig. 4a in Brázdil et al., 2013). The smallest number of droughts was noted in the 16th century (about 35), and was different than in the Czech Lands, where the evidently smallest number occurred in the 17th century. In the study period, the total number of all-category droughts in

Poland identified reached 148 and 156 – using documentary evidence and dendrochronological data, respectively. This means that both proxies reconstruct quite a similar frequency of drought occurrence in time scales from centuries to decades. The overall numbers of droughts identified using documentary evidence in Poland (present study) and the Czech Lands (Fig. 4a in Brázdil et al., 2013) in the overlapping period 1501–1800 were very similar and reached 132 and 126 cases, respectively.

All the dendrochronologies and long-term series of precipitation that we gathered and used for SPI calculation are available only for the common period 1876–1985. Therefore, for this period, statistics were calculated to compare the timings of dry periods (droughts) in Poland identified using both of these kinds of data. The agreement between droughts occurring at least in two geographical ($SPI1_{May–Jul}$ delimited droughts) and two natural-forest regions (significant negative pointer years) was 25.5%. On the other hand, for a less strict criterion, i.e. the occurrence of droughts at least in one region, the agreement reached 50.9%. Thus, the latter number is close to the value of agreement of drought timings identified using documentary evidence and the occurrence of negative pointer years (59.1%).

Having those series for the abovementioned period, we also conducted a correlation analysis to investigate how spatially coherent the association is between climate ($SPI1_{May–Jul}$) and tree-ring widths in the area of Poland. Coefficients of Pearson's linear correlation were calculated for 1–2 dendrochronologies representing each natural-forest region, with $SPI1_{May–Jul}$ values calculated for long-term series of precipitation taken from meteorological stations in the same region and closest to the area covered by the dendrochronologies. The closest relationships between climate and tree-ring growth were obtained for the Greater Poland and Pomerania Province and the Silesia Province, where the correlation coefficient *r* reached: 0.40 (site 9, Poznań in Table 1), 0.44 (site 11, Kuyavia-Pomerania) and 0.46 (site 17, Wrocław). Such good correlation (r=0.43) was also found by Dobrovolný et al. (2015) for the Czech Republic between 18 variants of Czech oak chronology and March–June precipitation totals. In three other Polish provinces (Baltic Coast, Masuria and Masovia, see Fig. 1) correlation coefficients are still statistically significant, but are clearly smaller: 0.25 (site 3, Wolin in Table 1), 0.14 (site 1, Koszalin), 0.24 (site 7, Suwałki), 0.13 (site 8, Hajnówka) and 0.21 (site 15, Warszawa). A similar correlation value (about 0.20) between tree-ring width and precipitation in June and July was found by Helama et al. (2014) for south-western Finland. On the other hand, a significantly better correlation (about 0.4) was calculated by Seftigen et al. (2013) for south-eastern Sweden. The increased strength of correlation here was probably due to the selection of trees growing at xeric sites, where the radial growth was most likely limited by moisture availability. The climate–tree-ring-growth relationship in Lesser Poland Province was not stated – the coefficient of correlation was equal to 0.0. The reasons for this different climate–tree-growth behaviour in this part of Poland in comparison to other studied regions are unknown.

From the perspective of available historical sources from the period 1451–1800, an increasing number of droughts was reported from the second half of the 16th century onwards, excluding the first half of the 17th century. The decrease in their occurrence in this period can be explained by large source deficiencies. They resulted from the destruction of many documents during the Swedish invasion on Polish territories in 1655-1660. The number of droughts in the first half of the 17th century is likely to have been higher. Summer and winter air temperature reconstructions for Poland for the period 1401–1800 (see Przybylak 2011, 2016) indicate that thermal conditions were more favourable for the occurrence of droughts in the first half of the 17th century than in the period 1751–1800, which was colder. Only in the second halves of the 15th and 16th centuries were conditions better for the occurrence of summer droughts than in the first half of the 17th century. This means that the low number of droughts in the latter period is not the result of climate but is of the significantly smaller number of available sources, as we mentioned earlier.

As information about moderate droughts is quite accidental, the sources certifying extreme and severe droughts seem more reliable and complete. According to our research, droughts occurred most frequently in the second half of the 18th century. This rectifies the previously accepted data on drought in Poland available in some geographic works (see e.g. Słota et al., 1992; Kaca et al., 1993; Łabędzki, 2006), which include information that in the 14th century there were 20 droughts in Poland, 25 in the 15th century, 19 in the 16th century, 24 in the 17th century, and 22 in the 18th century. However, these numbers refer to the frequency of hot summer seasons distinguished by Sadowski (1991, Sadowski also assumed the year 1300, 1400, etc. to be the first year of a century). On the basis of the research presented in this paper, we conclude that severe and extreme droughts (indexes -2, -3, respectively) were in fact slightly less frequent, while their occurrence in the period from the 15th to the 18th century, as previously stated, was slightly increasing.

Summary and concluding remarks

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

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

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

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

Competing interests. The authors declare that they have no conflict of interest.

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