

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 longest chronology covers the years 996–1986 and was constructed for eastern Pomerania. The delimitation of droughts based on instrumental data (eight long-term precipitation series) was conducted using two independent approaches (Standard Precipitation Index (SPI) calculated for 1-, 3-, and 24-month time scales, and new method proposed by authors). For delimitation of droughts (dry months), the criteria used were those proposed by McKee and modified for the climate conditions of Poland by Łabędzki.

More than one hundred droughts were found in documentary sources in period 1451-1800, including 17 megadroughts. A greater-than-average number of droughts was observed in the second halves of the 17th century, and of the 18th century in particular. 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. In the period 996–2015, a total of 758 negative pointer years were recorded.

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

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

1

2 **1 Introduction**

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

34 To estimate how unprecedented is the scale of climate drying in recent decades, a longer
35 perspective is needed. Therefore, in recent decades quite a lot of drought reconstructions
36 encompassing almost the entire millennium, or the shorter historical, pre-industrial period, were

1 constructed for different greater or smaller regions (e.g. Inglot, 1968; Piervitali and Colacino,
2 2001; Cook et al., 2004, 2010, 2015; Herweijer et al., 2007; Pfister et al., 2006; Brewer et al.,
3 2007; Domínguez-Castro et al., 2008, 2010; Woodhouse et al., 2010; Brázdil et al., 2013, 2016,
4 2018 (see references herein); Dobrovolný et al., 2015; Fragoso et al., 2018; Hanel et al., 2018).

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

21 Drought is the one of the most stressful factors for trees (Vitas, 2001; Allen et al., 2010; Sohar
22 et al., 2013). The measurement of tree ring widths is one of the ways to study the effect of climate
23 parameters on trees (Zielski et al., 2010). Some factors such as frost or summer drought may have
24 an immediate effect on ring width, whereas other factors, such as winter drought, may have a
25 delayed effect on ring widths. This delayed effect occurs because the meristematic tissues are
26 dormant during the winter months in temperate and cold climates. The effect of different factors
27 is seen as variations in ring size and structure, which change systematically, or vary slowly
28 throughout the life of the tree (Fritts, 1976). The effect of drought on tree rings is observed as
29 narrow rings (Koprowski et al., 2012; Opała, 2015). The relationships are significant enough to
30 reconstruct drought in temperate climate also in cold regions like Finland (Helama and Lindholm,
31 2003), Sweden (Seftigen et al., 2013) and Czech Republic (Dobrovolný et al., 2015). Therefore,
32 we have assumed that information derived from tree rings can complement the existing knowledge
33 about past droughts in Poland. According to studies by Somorowska (2016) the effect of drought
34 extends from the south-west towards the center part of the country and, in some cases, to the
35 north-east of Poland. Another study suggest that in the future some of the highest probability of

1 drought occurrence can be in the central part with the lowest probability in south-eastern Poland
2 (Diakowska et al., 2018).

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

16 2 Data

17 2.1. Documentary data

18 Records on drought for historical reconstruction of climate can be found in many different
19 historical sources from Poland. Their number has significantly increased since the mid-15th
20 century, which is why the mid-15th century was adopted as the initial chronological boundary for
21 the reconstruction of the number and intensity of droughts in the Polish territory using
22 documentary evidence. Below we describe the types of historical sources used to reconstruct
23 droughts in Poland.

24 Records of droughts in the Polish territory are most often found in narrative sources –
25 chronicles, yearbooks, memoirs, diaries, travel accounts. The information included in these
26 sources has a varying degree of accuracy. Often only one account concerning drought appeared,
27 such as, for example, “magna siccitas”. In many of the records, however, more detailed
28 descriptions of the course of droughts and accompanying phenomena were given. In the ancient
29 sources droughts were described above all when their manifestations were very clear and when
30 they had an impact on economic and social life. Another group of sources used by us are daily
31 records that have the character of meteorological observations. Sometimes, they were prepared by
32 scholars such as professors of the Jagiellonian University Marcin Biem (ca. 1470–1540) and
33 Michał of Wiślica (1499–1575), who conducted such observations in Kraków from 1499 to 1531
34 and from 1534 to 1551 (Limanówka, 2001), or townsmen with scientific ambitions such as
35 Gottfried Reyger (1704–1788), who began his observations in Gdańsk in 1721 as a 17-year-old
36 and continued them later, among others as a member of the *Naturforschende Gesellschaft* in

1 Gdańsk until 1786 (Filipiak et al., 2019). Sometimes daily observations were conducted by
2 amateurs, the best example of which are the records of the Polish nobleman from the eastern
3 territories of the Polish–Lithuanian Commonwealth, Jan Antoni Chrapowicki, which were
4 conducted for the years 1656–1685 (Nowosad et al., 2007). Sources of this kind are nonetheless
5 relatively rare.

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

23 In addition to the above mentioned historical sources collected during the queries in Polish,
24 Lithuanian, Ukrainian and German archives, the authors used several published collections (of
25 varied quality) of historical sources concerning the climate research in the period from the 10th
26 century to the end of the 18th for Poland, Europe Central or selected regions of Central Europe.
27 They include: the period from the 10th century to the end of the 16th (Girguś et al., 1965); the
28 Middle Ages (Malewicz, 1980); 1450–1586 (Walawender, 1935); the years 1648–1696
29 (Namaczyńska, 1937); and 1772–1848 (Szewczuk, 1939). In the last 20 years, two databases
30 containing over ten thousand weather records were made available in universities in Toruń and
31 Wrocław as part of cooperation between climatologists and historians. They have been used many
32 times to study Poland's climate in historical times (Wójcik et al., 2000; Przybylak et al., 2001,
33 2004, 2005, 2010; Przybylak, 2011, 2016); they have also contributed to widening the scope of
34 this research.

35 To sum up, for the purpose of this research over 200 accounts referring directly to droughts
36 and prolonged shortages of rainfall were used, along with a few hundred more descriptions from

1 everyday weather observations, the use and critical elaboration of which allowed periods of
2 drought to be indicated. The state of the preservation of sources for particular periods and for
3 individual regions is uneven. Most of them describe droughts in Silesia, Pomerania and Lesser
4 Poland. A large number of entries refers to droughts affecting the whole territory of Poland. In the
5 case of Silesia, the distribution of sources is fairly even for the whole period; in the case of other
6 regions their number increases with successive ages. The only exception is the first half of the 17th
7 century, in which the number of preserved records is definitely smaller. To some extent, this was
8 affected by the losses in the state of preserved sources that occurred during the Swedish invasion
9 on Polish territories in 1655-1660. Many sources from the first half of the 17th century were then
10 destroyed as a result of military actions.

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

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

24

25 **2.2. Dendrochronological data**

26 We used 22 chronologies (17 oak chronologies, 5 pine chronologies and 1 fir chronology) from
27 different locations in Poland to detect pointer years (Table 1, Fig. 1). Table 1 presents a list of
28 them, including also time coverage and sources. As results from this Table, the longest chronology
29 available to us covers the years 996–1986 and was constructed for western Pomerania (Site 5). For
30 Upper Silesia (Sites 16 and 18) and Lesser Poland (Sites 21 and 22), the pointer years were detected
31 by Opała and Mendecki (2014) and Opała (2015) for Upper Silesia, and by Szychowska-Krapiec
32 (2010) for Lesser Poland (Table 1, Fig. 1).

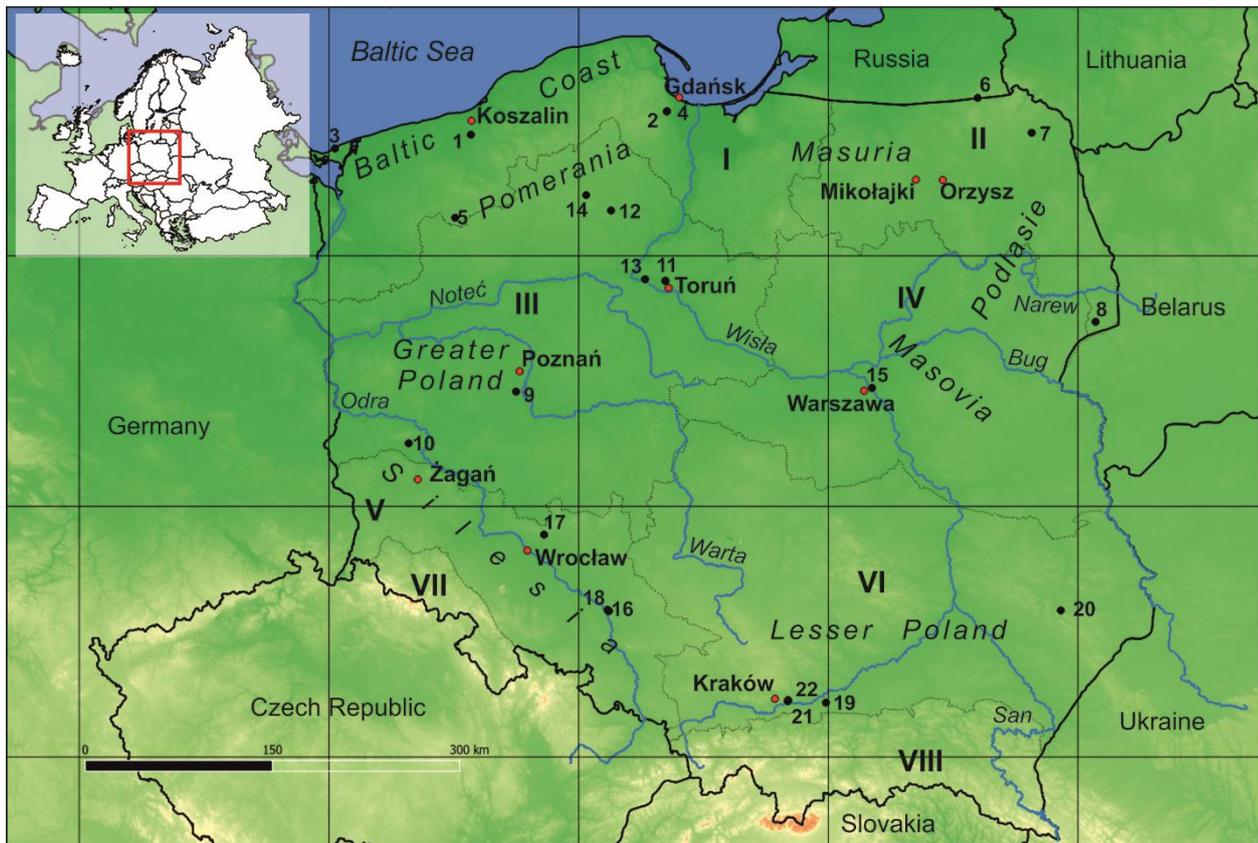
33

34 Table 1. Basic characteristic of the chronologies used for pointer year analysis. Location
35 of natural-forest regions (Zielony and Kliczkowska, 2010) and sites is shown in Fig. 1.
36 EPS- expressed population signal, rbar.tot- the mean of all correlations between different
37 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-Krapiec, 2010
Site 22	Lesser Poland	1109 – 2006	560	No data	No data	Fir	Szychowska-Krapiec, 2010

1



2

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

4

5 **2.3. Instrumental data**

6

2.3.1. Isolated series

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

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

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

28 Reyger usually presented remarks on general weather conditions supplemented by some
29 additional data. Months were usually described in a qualitative, even aggregate, manner. His notes
30 were very detailed and even the weather of the particular days or weeks was very often
31 characterised. Reyger paid special attention to particularly important weather and climate
32 phenomena (heavy rain, floods, droughts, and heat and cold waves). His notes after 1783 (Hanov's
33 death) were more accurate. Despite the lack of measured values of precipitation, detailed data on
34 the monthly number of rainfall and snowfall were presented (for more details including the
35 reconstruction of the air temperature and precipitation series since 1721 see Filipiak et al., 2019).
36 Some sources suggest an even earlier date for the beginning of Reyger's instrumental observations

1 (Hellmann, 1883, after Rojecki, 1965). Besides the short description in the mentioned literature no
2 other proof of such activity is available.

3

4 **2.3.2. Long-term continuous series**

5 The series from Wrocław (formerly Breslau) that commenced in 1791 (Bryś and Bryś, 2010) is
6 the longest continuous Polish precipitation series. For the purpose of the present paper we
7 prolonged this series until 1781 based on precipitation measurements in Żagań (formerly Sagan)
8 within the Mannheim network of stations established for Europe and North America by the
9 Palatine Meteorological Society in 1780 (Przybylak et al., 2014). The cited authors proved that
10 there exist high correlations between the precipitation series from both places. Source data from
11 Żagań were taken from the publication *Ephemerides Societatis Meteorologicae Palatinae, 1783–*
12 *1795*. In addition, we must say that the Wrocław series is the only continuous series to have begun
13 before 1800 in the area currently belonging to Poland. The best known long-term climatological
14 series in Poland is the one from Kraków that commenced in 1792. The work on completing the
15 collections of the Kraków series continue till the present day, the effect of which are
16 reconstructions of monthly values of precipitation sums since 1863 (Twardosz, 2005, 2007). As
17 for other Polish cities, Lorenc (2000) performed a homogenisation of series of monthly
18 precipitation totals of Warszawa (Warsaw) since 1813. Miętus (2002) reconstructed atmospheric
19 precipitation sums from Koszalin (formerly Köslin) since 1848. In another paper, Kożuchowski
20 and Miętus (1996) presented series of precipitation totals in Szczecin (formerly Stettin) since 1848.
21 In 2011 a reconstruction was performed of the precipitation series from Gdańsk in 1880–2008
22 (further extended to 1851) (Filipiak, 2011). During the CLIMPOL project (Climate of northern
23 Poland during the last 1000 years: Constraining the future with the past) Filipiak reconstructed the
24 series of monthly precipitation totals since 1891 for Lake Żabińskie in NE Poland (54°07' N;
25 21°59' E) (Larocque-Tobler et al., 2015). Further, the series of Orzysz (formerly Arys) and
26 Mikołajki (formerly Nikolaiken), also in NE Poland, were collected for the years 1830–1904 and
27 since 1889, respectively. As both stations are located very close to one another (approximately 20
28 km) these two series have very much in common. The correlation coefficient calculated for the
29 overlapping periods 1889–1904 and 1981–2015 exceeds 0.85. Thus we decided to combine both
30 series: data from Orzysz covers the period between 1830 and 1890, the later data comes from
31 Mikołajki. A couple of series, e.g. Poznań (formerly Posen), Toruń (formerly Thorn), Racibórz
32 (formerly Ratibor, Silesia), Śnieżka (formerly Schneekoppe, Sudety Mountains), began around the
33 middle of the 19th century and are available in yearbooks that were initially released by the Royal
34 Prussian Meteorological Institute (Königlich Preussischen Meteorologischen Institut), then since
35 1918 by the Polish National Meteorological and Hydrological Service (PIM until 1945, further

1 PIHM and finally, after 1972 IMGW). The complete list of instrumental series employed in the
 2 current research and their sources are presented in Table 2.

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

No.	Station	Geographical region	Observation period	Location (φ, λ, h)	Sources of data
Isolated series					
1a	Gdańsk *	1	1722–1786	54°20'N 18°40'E 13 m a.s.l.	Reyger (1770, 1788) and Filipiak et al. (2019) for the periods 1722–1738 and 1773–1786; Hanov (1773) for the period 1739–1773
Long-term continuous series					
1b	Gdańsk	1	1851–2015	54°20'N 18°40'E 13 m a.s.l.	Filipiak (2010 modified 2018) for the whole period
2	Koszalin	1	1851–2015	54°12'N 16°11'E 46 m a.s.l.	Reichsamt für Wetterdienst (1939) for the period 1851–1930 corrected by Miętus (2002); Miętus (2002) for the period 1931–1990; Central Database of Historical Data of IMGW-PIB (Polish National Meteorological and Hydrological Service) for years 1991–2015
3a	Orzysz	2	1830–1890	53°48'N 21°56'E 122 m a.s.l.	Dove (1851) for the period 1830–1850; Reichsamt für Wetterdienst (1939) for the years 1851–1904
3b	Mikołajki	2	1891–2015	53°48'N 21°34'E 116 m a.s.l.	Central Database of Historical Data of IMGW-PIB for the whole period
4	Toruń	3	1871–2015	53°01'N 18°36'E 60 m a.s.l.	Pospieszyńska and Przybylak (2013) for the period 1871–2010; Central Database of Historical Data of IMGW-PIB for years 2011–2015
5	Poznań	3	1848–2015	52°25'N 16°56'E 66 m a.s.l.	Dove (1851) for the period 1848–1850; Central Database of Historical Data of IMGW-PIB for the years 1851–2015
6	Warszawa	4	1813–2015	52°13'N 21°01'E 97 m a.s.l.	Lorenc (2000, 2007) for the years 1813–1999; Central Database of Historical Data of IMGW-PIB for the years 2000–2015
7a	Żagań	5	1781–1790	51°37'N 15°19'E 102 m a.s.l.	<i>Ephemerides Societatis Meteorologicae Palatinae, 1783–1795</i> for the whole period
7b	Wrocław	5	1791–2015	51°07'N 17°05'E	Bryś and Bryś (2010) for the years 1791–2000; Central Database of

				120 m a.s.l.	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

1

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

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

6

7 **3. Methods**

8 **3.1. Documentary data**

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

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

28 During extreme droughts, there were frequent records of persistent very low water levels
29 in the largest rivers – the Odra and the Wisła (Table 3). The result was a lack of water for people
30 and animals, halting the work of water mills in whole provinces. The consequences of drought
31 were underlined – particularly a lack of food and high prices. Numerous fires broke out in cities,

1 villages and forests. The sources used such phrases as “*estas ferventissima et siccitas inaudita*”
 2 [very hot and incredible summer drought], “*sidere solari plus solito effervescente et nullas dante*
 3 *pluvias*” [extraordinary sun heat and continuous drought], “*unaufhörlich trockene Witterung*”
 4 [unbelievably dry weather], “*alle Bäche vertrockneten*” [all streams dried up] and the like,
 5 underlining the extreme nature of the drought. Superlative adjectives were very often used.

6

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

Year	Description	Translation	Source
1473	[...] <i>caumata et penuriam aquarum, adeo ut perennes aquae verterentur in aridam, et flumina Poloniae principalia ubique fuerunt permeabilia, insignis. [...] Fumabant in universis Poloniae regionibus silvae, borrae, arbusta, saltus, irremediabili igne, nec ante rescindi flamma poterat, donec ignis etiam radicem arborum voraret, ex quo ubique fragor ruentium saltuum audiebatur. Apum quoque et alveariorum arbores plurimae deletae, segetes vernaes exterminatae siccitate.</i>	[...] 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	[...] <i>fuit in aestate horrenda siccitas adeo, ut silices, montes et valles quasi igne flagrarent, duravit haec siccitas usque ad hyemem.</i>	[...] in the summer there was such a terrible drought that the rocks, mountains and valleys were burned down with fire; this drought lasted until winter	Archivum vetus et novum ecclesiae archipresbyteralis Heilsbergensis, in: MHW, vol. 8, p. 597

1590	<i>Ist ein sehr heisser truckener Sommer gewesen, also, dass auch die Landflüsse, als der Bober, Queiss, Katzbach, Weida, Olau, Lohe, und andere mehr gänzlich ausgetrucknet. Die Oder ist auch so klein worden, dass man sie an allen Orten durchwatten können.</i>	The summer was so hot [and] dry that regional rivers like the Bóbr, the Kwisa, the Kaczawa, the Widawa, the Oława, the Ślęza [Silesia, auth. suppl.] and many others dried up completely. The Odra also became very shallow, so you could cross it anywhere.	Pol, vol. 4, p. 156
	<i>38 Wochen regnete es nicht. Die Flüsse trockneten aus.</i>	It did not rain for 38 weeks. The rivers dried up.	Reinhold, 1846, p. 143
	<i>Zacken und andere Flüsse trockneten völlig aus</i>	The Kamienna and other rivers dried up completely.	Bergemann, J.G., 1830a, p. 84
	<i>Der Bober trocknete infolge starker Hitze ganz aus.</i>	The Bóbr dried up completely due to severe drought.	Bergemann, J.G. 1830b, vol. 3, p. 85

1

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

12

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

Year	Description	Translation	Source
1456	<i>Fuitque anno eodem precipue circa partes nostras, ubi plures</i>	And that year there was an exceptionally great drought in	Catalogus abbatum

	<i>sunt agri sabulosi et argillosi, post festa paschalia siccitas magna et usque ad messem continuata. Messis autem tante humiditatis et instabilitatis,</i>	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 [...]	Saganensium, in: <i>Scriptores rerum Silesiacarum</i> , vol. I, p. 340
1532	<i>Ein dürrer Sommer. Es regnete in sieben Wochen nicht. Das Getreide und die Weide verdorrete auf den Hügeln ganz aus. In etlichen Dörfern war kein gar Wasser. Auf dem Lande konnte man nicht mahlen. Zu 10. 12. 18. Meilen musste man zur Mühle führen. Die Olau trocknete und dorrete auch aus, und hatte kein Wasser bis auf Bartholomei [24.08].</i>	Dry summer. It did not rain for seven weeks. The grain and grass on the hillsides dried up. In some places there was almost no water. In the countryside, it was impossible to grind grain. One needed to go 10, 12, 18 miles to reach mills. The Oława River dried up [Silesia, auth. suppl.] and there was no water in it until the Saint Bartholomew's Day [August 24].	Pol, vol. 3, p. 72
1665	<i>Der Sommer des Jahres 1665 wird als ungemein heiss angegehen, und soll es die ganzen Hundstage [10.07.–20.08.] hindurch auch nicht einmal geregnet haben.</i>	The summer of 1665 was incredibly hot; not even once did it rain – so called “Dog Days”.	Wernicke, <i>Gesch. Thorns.</i> , vol. 2, p. 321

1

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

10

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

Year	Description	Translation	Source
1461	<i>Eodem anno fuit estas calidissima et fluvius Odere valde modicus, similiter et alii fluvii.</i>	That year the summer was the hottest and the water level of the Odra River fell, as did other rivers.	Sigismundi Rosiczii chronica, p. 78.
1552	<i>Den 5 Junii [...] nach der Vesper und grosser Dürre kam ein gewünschter Regen, aber mit grossem Wetter</i>	On June 5 [...] after the evening and after a great drought, came the desired rain with a great storm.	Pol, vol. 3, p. 158.
1661	<i>Es folgte aber ein dürrer Sommer.</i>	However, a dry summer came.	Happelius, p. 148.

2

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

12

13 3.2 Dendrochronological data

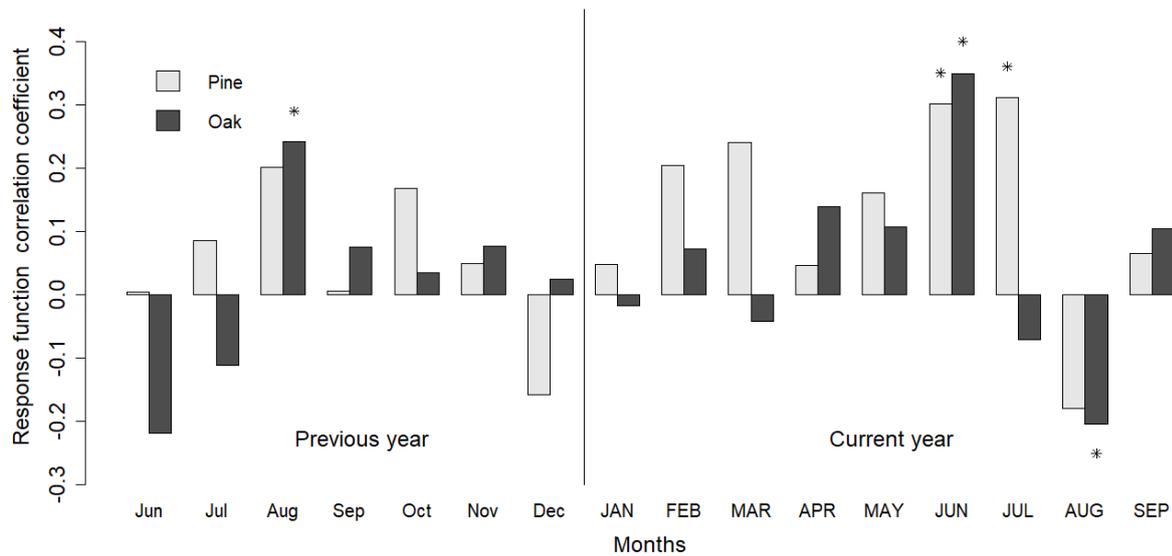
14 We hypothesised that narrow tree rings are linked with drought. The limited access to water during
 15 the vegetation season leads to a water deficit in trees and as a consequence the cambium activity
 16 decreases and produces fewer cells, which is positively correlated with tree-ring widths (Liang et
 17 al., 2013). De-trending of the chronology was done with the dplR software (Bunn 2008) using the
 18 smoothing spline option, which reflects trends in the chronology better than other options. The
 19 “n-year spline” was fixed at 2/3 the wavelength of n years (Cook et al. 1990). The residual version
 20 of the chronology was built by pre-whitening, performed by fitting an autoregressive model to the
 21 data with AIC model selection (Bunn 2008). At first the relationships between tree growth and
 22 precipitation was checked. We analysed the effect of climate monthly precipitation and
 23 temperature on tree-ring widths using the treeclim package (Zang and Biondi, 2015). Analysis of
 24 climate growth relationships for monthly data for Toruń revealed that precipitation during the

1 vegetation season plays a significant role for both pine and oak. For example a significant positive
 2 correlation was observed for June and July for pine, while for oak a positive correlation was
 3 observed for the previous August and current June and a negative correlation for August (Fig. 2).
 4 For each site the climate growth relationships were tested against monthly precipitation and
 5 temperature data starting from 1951 and covers maximum time span depending on the length of
 6 the chronology (Table 6). Because the time span was too short (for example for Site 2 when
 7 chronology covers the years 1951-1986) for some extended analysis going back to previous
 8 months, the common period from previous October to current September was taken into account.
 9 The sum of monthly precipitation was also included, the months were selected dependably on the
 10 significant correlation of the single months and period selected by daily data analysis.

11 Table 6. Climate growth relationships for analysed sites. Only highest correlation
 12 coefficient are presented with level of significance, $p < 0.05$.
 13

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 not presented due to lower statistical significance	Temperature of February 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



1

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

5

6 Next we used daily data for Toruń and tree-ring chronologies of pine and oak representing Region
 7 III. Daily data shows more precisely the period of the year which influences tree growth.
 8 According to previous findings, the climate growth relationships are comparable at different sites
 9 in Poland (Zielski et al., 2010), so we used the relationships between daily data and Site 11 and 13
 10 as a model for the rest of our study sites. The reason for this generalisation was also the limited
 11 access to daily data. A period of 90 days with the 1-year lag for the years 1947–2015 was used to
 12 find the significant relationships between the daily precipitation data and indexes of tree rings. For
 13 this purpose we used the dendroTools package (Jevšenak and Levanič, 2018). The optimal window
 14 of days was revealed to be from May 6 to August 3 for pine with maximal correlation coefficient
 15 0.435, and from April 21 to July 19 for oak with maximal correlation coefficient 0.305. The sums
 16 of daily precipitation for these periods were summed and correlated with indexed growth in years
 17 of growth reduction (narrow rings) and growth recovery (wide rings). The correlation coefficient
 18 is 0.79 ($p < 0.05$) for pine, and 0.65 ($p < 0.05$) for oak. Next, the same summed daily precipitations
 19 for the selected periods were correlated with the remaining tree ring indexes (after exclusion of
 20 wide and narrow ring indexes). The correlation coefficient is 0.40 for pine and 0.16 for oak.

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

1 reduction” was determined as between 85–95% of trees; and “moderate reduction” was between
2 75% and 85%.

3

4 **2.3 Instrumental data**

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

12 On the basis of the completed series of atmospheric precipitation, the possibility of
13 obtaining a synthetic precipitation index for the whole country was tested. A similar method was
14 adopted in Brázdil et al. (2007) to determine drought indices in the Czech Republic for the period
15 1881–2006. In Poland, Kożuchowski (1985) presented a 100-year series of average areal annual
16 atmospheric precipitation for 1881–1980 (his Table 3) calculated from data from 12
17 meteorological stations using precipitation regression equations relative to altitude above sea level.
18 Miętus (1996), in turn, presented mean areal precipitation for the Coast area. For the analysis, we
19 took 30-year moving correlation coefficients (r) for monthly totals of precipitation counted for the
20 period 1901–2000. All correlation coefficients were statistically significant ($p < 0.05$) with values
21 varying from 0.46 to 0.71 (see Table 6, upper part). Only the Kraków series had a significantly
22 lower value of r (the highest value of 0.33 described the relationship between Kraków and
23 Wrocław). For annual precipitation totals in the period 1951–2000, Kożuchowski and Żmudzka
24 (2003) obtained only slightly higher values of correlation coefficients, varying from 0.6 to 0.8.
25 Unsatisfactory results of r , particularly related to the series for Kraków, suggested that we should
26 not construct monthly precipitation series for the entire Poland. It seems that the number of long-
27 term precipitation series is probably relatively too small for a country of such area (312,679 km²).
28 Further analysis was thus carried out on regions delimited by a landscape criterion, though this
29 excludes mountains, whose atmospheric precipitation is spatially and temporally far more variable
30 (Kożuchowski, 1985).

31

32 Table 76. Correlation coefficients between monthly totals of atmospheric precipitation
33 (upper part of table) and SPI1 (lower part of table) in area of Poland calculated based on data from
34 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	<i>0.56</i>		<i>0.71</i>	<i>0.55</i>	<i>0.55</i>	<i>0.52</i>	<i>0.46</i>	<i>0.20</i>
Gdańsk	<i>0.62</i>	<i>0.69</i>		<i>0.66</i>	<i>0.58</i>	<i>0.61</i>	<i>0.55</i>	<i>0.26</i>
Orzysz-Mikołajki	<i>0.55</i>	<i>0.53</i>	<i>0.60</i>		<i>0.55</i>	<i>0.71</i>	<i>0.54</i>	<i>0.31</i>
Poznań	<i>0.66</i>	<i>0.57</i>	<i>0.55</i>	<i>0.49</i>		<i>0.58</i>	<i>0.68</i>	<i>0.25</i>
Warszawa	<i>0.58</i>	<i>0.48</i>	<i>0.52</i>	<i>0.63</i>	<i>0.53</i>		<i>0.61</i>	<i>0.28</i>
Żagań-Wrocław	<i>0.56</i>	<i>0.44</i>	<i>0.47</i>	<i>0.45</i>	<i>0.64</i>	<i>0.53</i>		<i>0.33</i>
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

1

2

3 The aim of analysis of instrumental series was to calculate the number, length and category
4 of droughts in the area of Poland since 1722, i.e. for almost 300 years. The Standardised
5 Precipitation Index (SPI, McKee et al., 1993) was calculated from monthly precipitation totals to
6 explore the occurrence of droughts in the analysed locations (Table 2). This index is one of the
7 simplest methods used to identify meteorological droughts, since it uses only monthly totals of
8 precipitation and is therefore widely used in the literature. Osuch et al. (2015) state that the SPI is
9 used for both research and operational purposes in over 60 countries. The SPI index is also most
10 popularly used in Poland (e.g. Łabędzki, 2007; Kalbarczyk, 2010; Bąk et al., 2012; Bartczak et al.,
11 2014; Osuch et al., 2015, 2016; Bąk and Kubiak-Wójcicka, 2017). What is more, the SPI is used
12 also by two institutes mentioned in Section 1 (IMGW-PIB, and the Institute of Technology and
13 Life Sciences [ITP]) and also by the Institute of Soil Science and Plant Cultivation, which is
14 responsible for agricultural drought monitoring in Poland (for more details see Łabędzki and Bąk,
15 2014). Hence our decision to also use this index in our work.

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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.

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

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

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

1 severe and moderate droughts, respectively. In the case of documentary data such droughts were
2 described using indices -3, -2 and -1.

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

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

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

14
15
16
17 where:

18 $N_{i,100}$ – the number of droughts for a timescale i in 100 years

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

20 i – timescale (1, 3, 24, months)

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

22

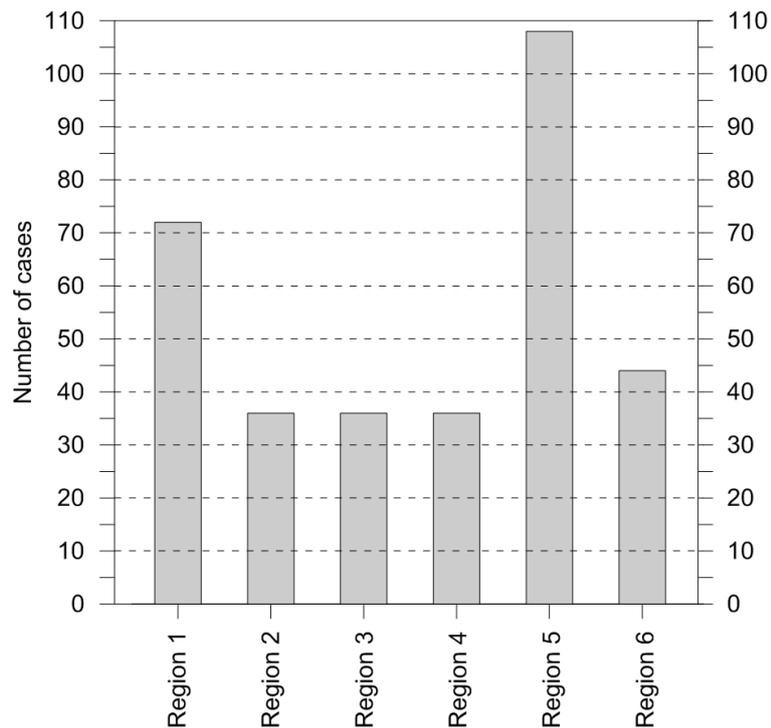
23 **4. Results**

24 **4.1 Droughts in Poland based on documentary data**

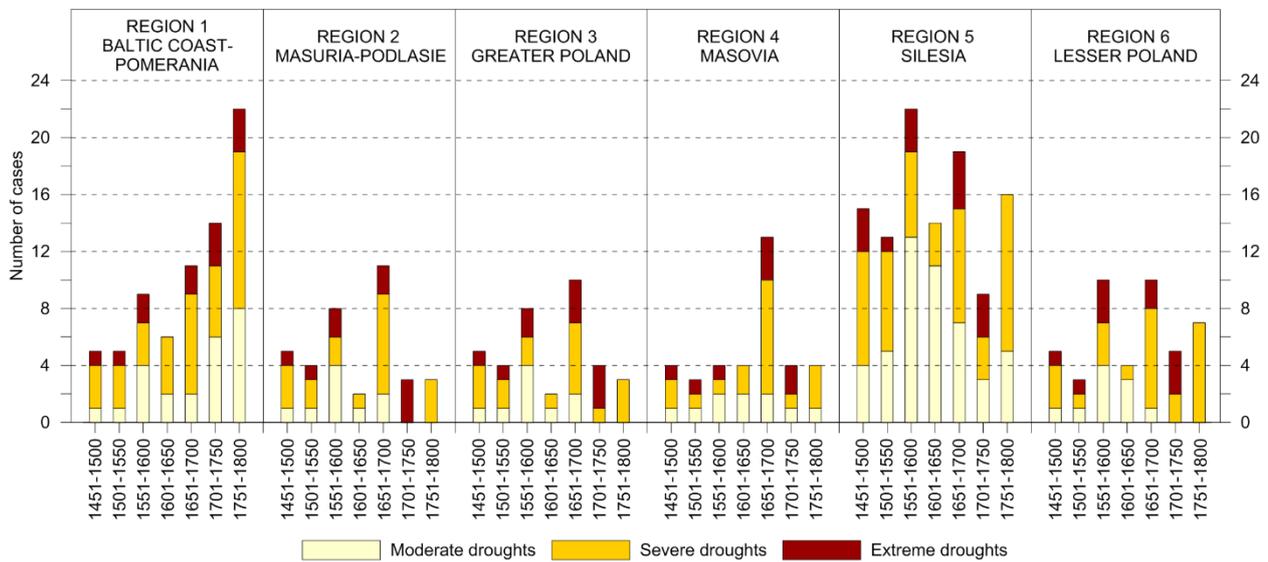
25 It seems that droughts were not very frequent in Poland. In particular regions (including droughts
26 presented in sources as nationwide, and therefore also noticeable in individual regions) in total
27 from 33 to 71 droughts were recorded between 1451 and the end of the 18th century (Fig. 3). Most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

1 probable that the number of droughts in these regions was actually higher, and close to the number
2 of droughts in Silesia or Pomerania.

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



11
12 Fig. 3. Number of years with droughts in six geographical regions of Poland (including information
13 related to the whole country) 1451–1800. See Table 2 or Fig. 4 for names of regions.

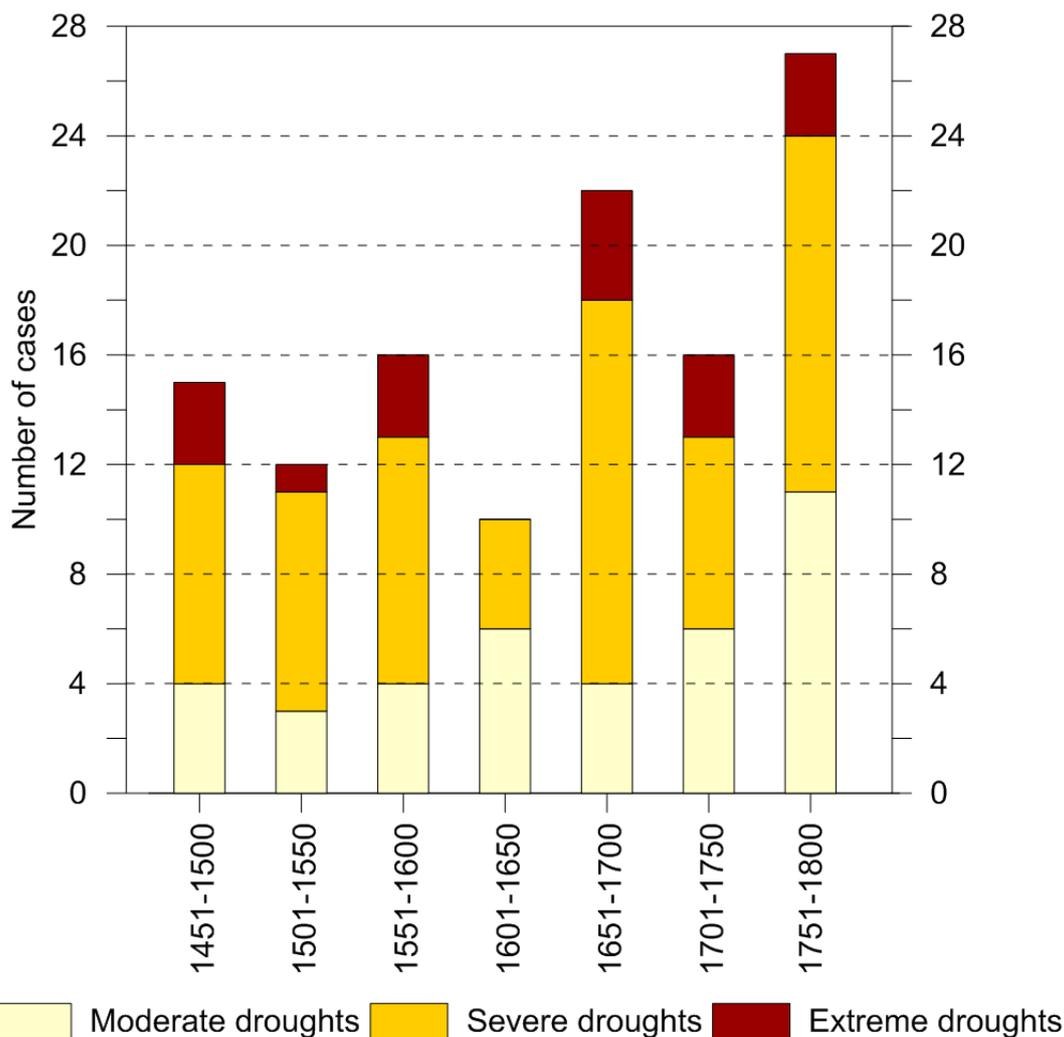


1

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

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

10



1

2 Fig. 5. Frequency of occurrence of three categories of droughts in Poland in 50-year periods, 1451–
3 1800

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

8 However, the total frequency of extreme (-3) and severe (-2) droughts amounted to 80 and
9 ranged from 4 to 12 in particular fifty-year periods, except for the second half of the 17th century
10 and the second half of the 18th century, when there occurred as many as 18 and 16 droughts,
11 respectively (Fig. 5). The increase in the number of identified droughts in the second half of the
12 17th century was certainly due to the availability of detailed weather records from the period 1656–
13 1685 taken from the memoirs of Jan Antoni Chrapowicki (Nowosad et al., 2007). However, the
14 minimum number of droughts (only 4) took place in the first half of the 17th century (Fig. 5), for
15 which, in turn, we recorded significant losses in the sources.

16 The number of moderate droughts (-1) varied in all 50-year periods from 3 to 6, except for
17 the second half of the 18th century, when there were recorded as many as 11 droughts belonging

1 to this category (Fig. 5). A larger number of such droughts starting from the beginning of the 18th
2 century undoubtedly results from regional sources being more accurate. In this century, many
3 historical sources were created; they now allow for a fairly accurate reconstruction of the weather
4 conditions, including the appearance of smaller droughts and prolonged shortages of rainfall.

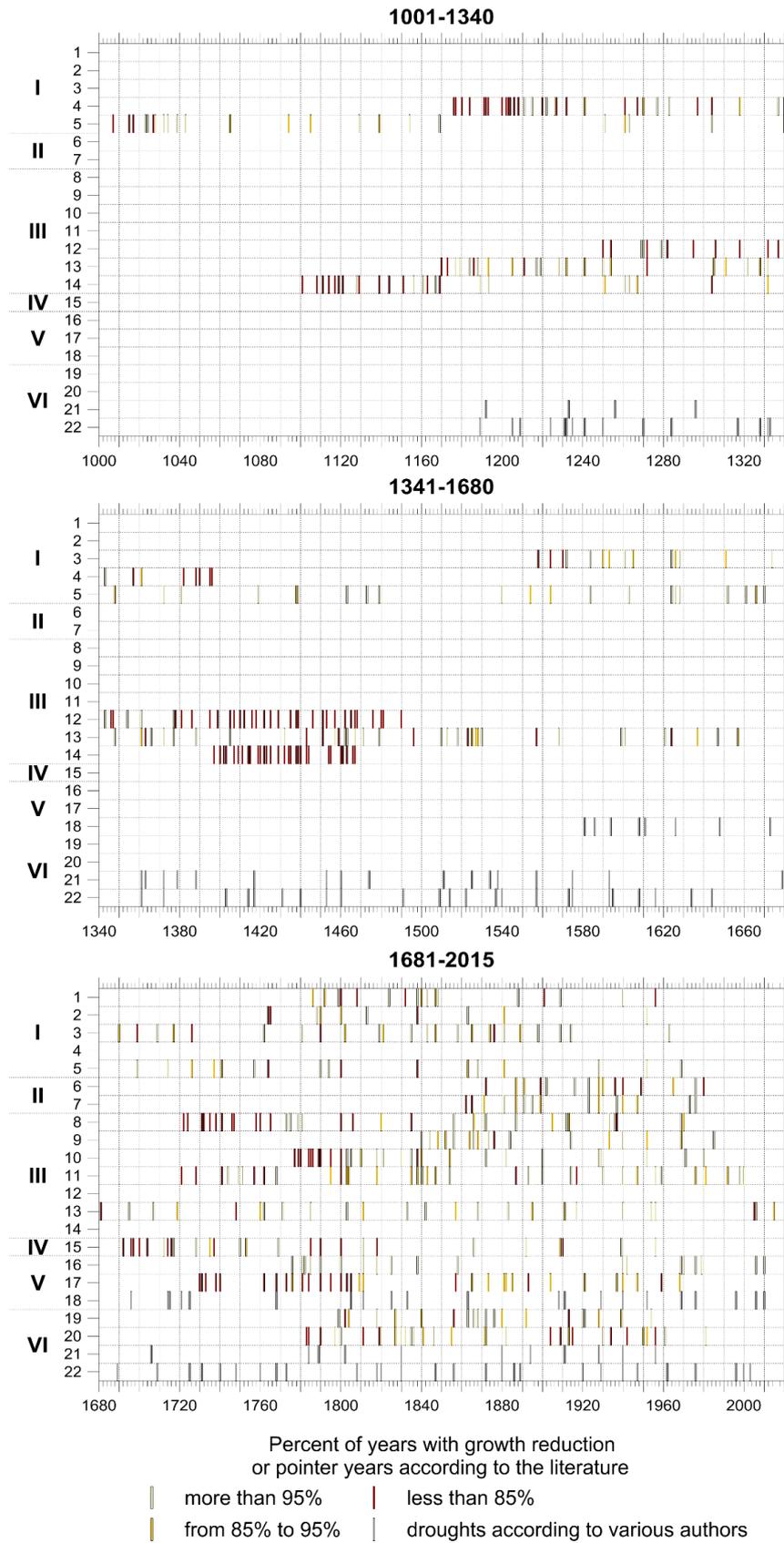
5 Spring (31) and summer (37) droughts prevailed among the recorded droughts. Also,
6 droughts in spring–summer were often mentioned (22), but much less frequently in summer and
7 autumn (4). Rare were droughts that occurred only in autumn (4). Winter droughts were reported
8 only in three years. In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

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

15 16 **4.2 Droughts in Poland based on dendrochronological data**

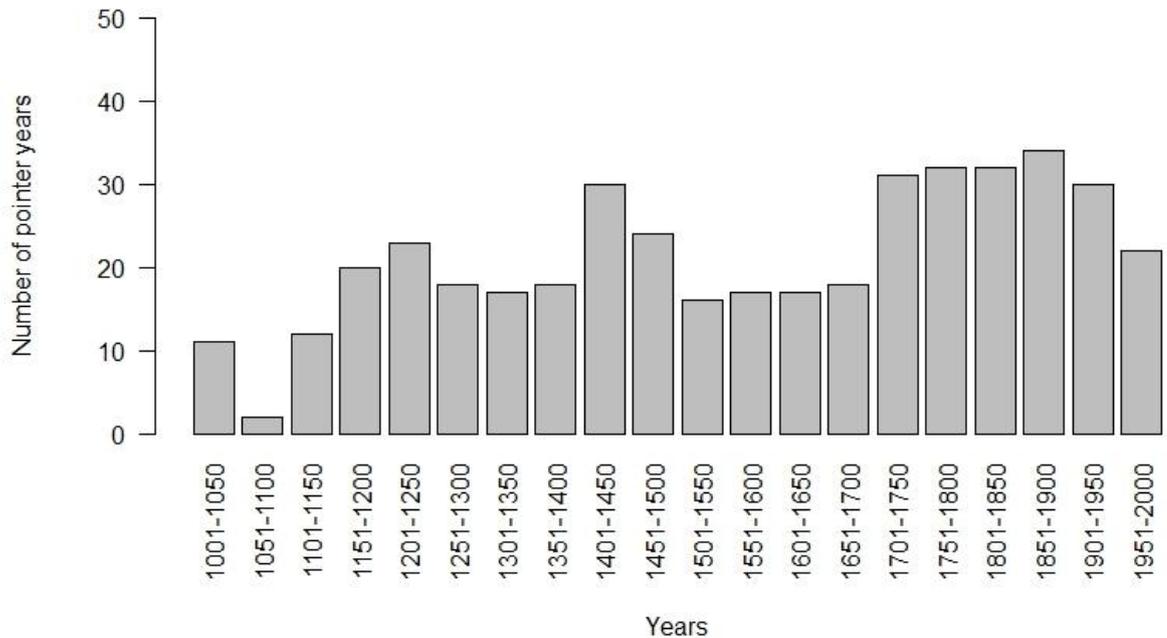
17 Twenty-two local chronologies of trees (pine, oak, and fir) from Poland were taken into account
18 for detecting negative pointer years, showing narrow rings. In a year in which we have narrow
19 rings at more than 1 site, we count this pointer year as a “multiple observation” year, whereas, in
20 a year with only one observation, at one site, we call it a year “without multiple observation”. In
21 total, 758 pointer years with multiple observations were detected and 432 years without multiple
22 observations. There are 237 multiple observation years of extreme reduction, 122 of great
23 reduction, 252 of moderate reduction and 147 negative pointer years from the literature (Opała and
24 Mendecki, 2014; Opała, 2015; Szychowska-Krapiec, 2010) (Fig. 6). The number of pointer years
25 in selected 50-year periods varies (Fig. 7). At least 30 pointer years were noted within the years
26 1401–1450 and within each of the 50-year intervals from 1701 to 1950. The evidently smallest
27 number of negative pointer years occurred in the first 150 years (Fig. 7). In the years 996–1000,
28 drought did not occur, and therefore this period was omitted in Figures 6 and 7. However the small
29 number of pointer years from 996 to 1200 may be related to the low number of samples. This
30 period is called as medieval climate anomaly and reconstruction for northern-central Europe
31 revealed considerably drier conditions for this years (Scharnweber et al., 2019). This period is
32 relatively dry in for The number of chronologies varies and depends on region. More chronologies
33 in the last 300 years result from existing old trees. It also led to the detection of more pointer years.
34 According to Neuwirth et al. (2007) during extreme climatic conditions trees react in the same
35 way, but during years of less pronounced weather conditions regional differences in growth

- 1 reactions increase. Narrow rings observed in the same year in trees from different regions suggests
- 2 extreme climatic conditions.



3

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



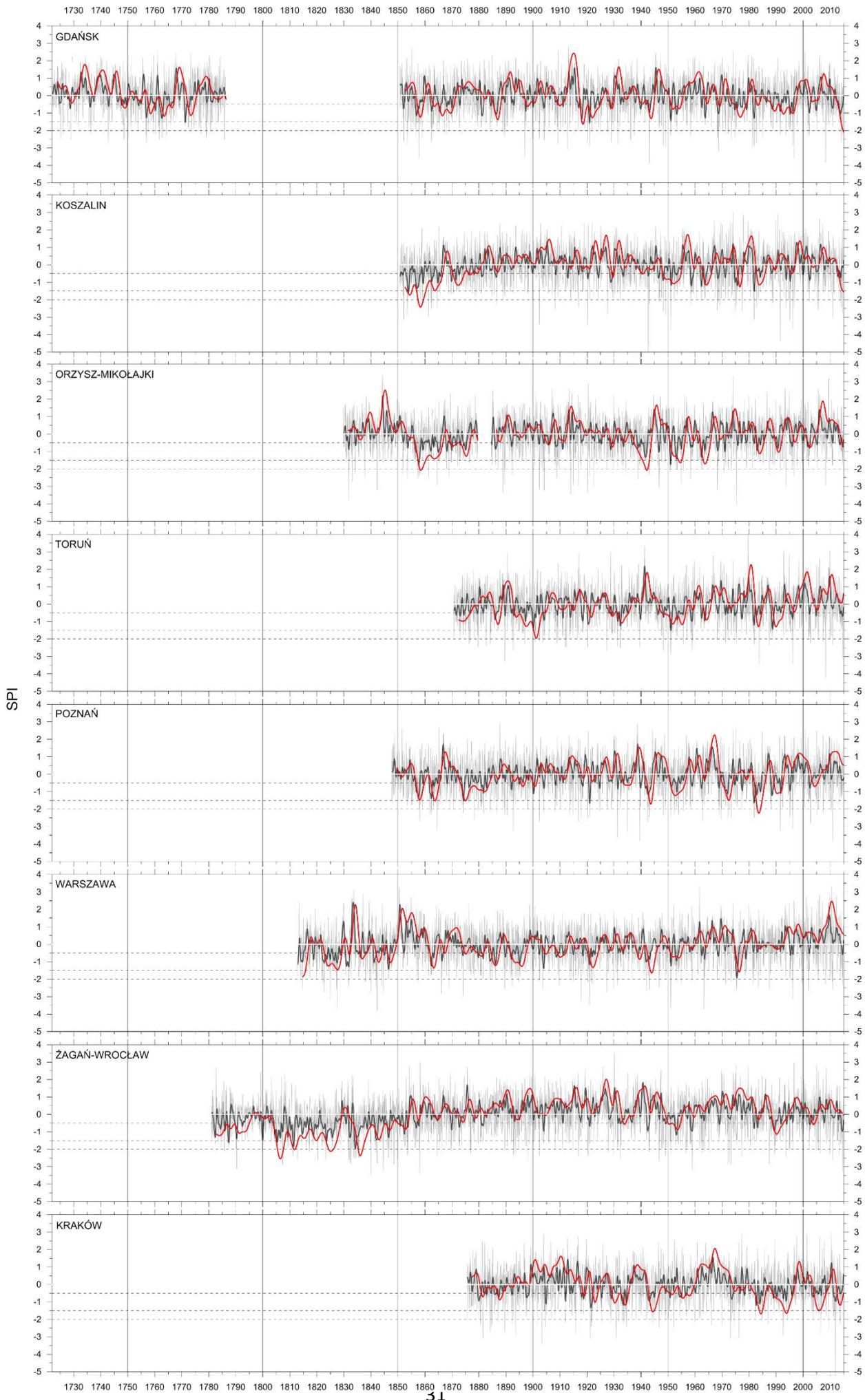
1
 2 Fig. 7. Number of negative pointer years (without multiply observation – i.e. narrow
 3 rings in 1976 were observed on six samples but are treated as a one-pointer year) in
 4 Poland in 50-year periods, 1001–2000.

5

6 **4.3 Droughts in Poland based on instrumental data**

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

- 1 the 1850s, in Toruń in the 1910s, in Poznań in the 1980s, and in Kraków in the 1980s and 1990s
- 2 (Fig. 8).

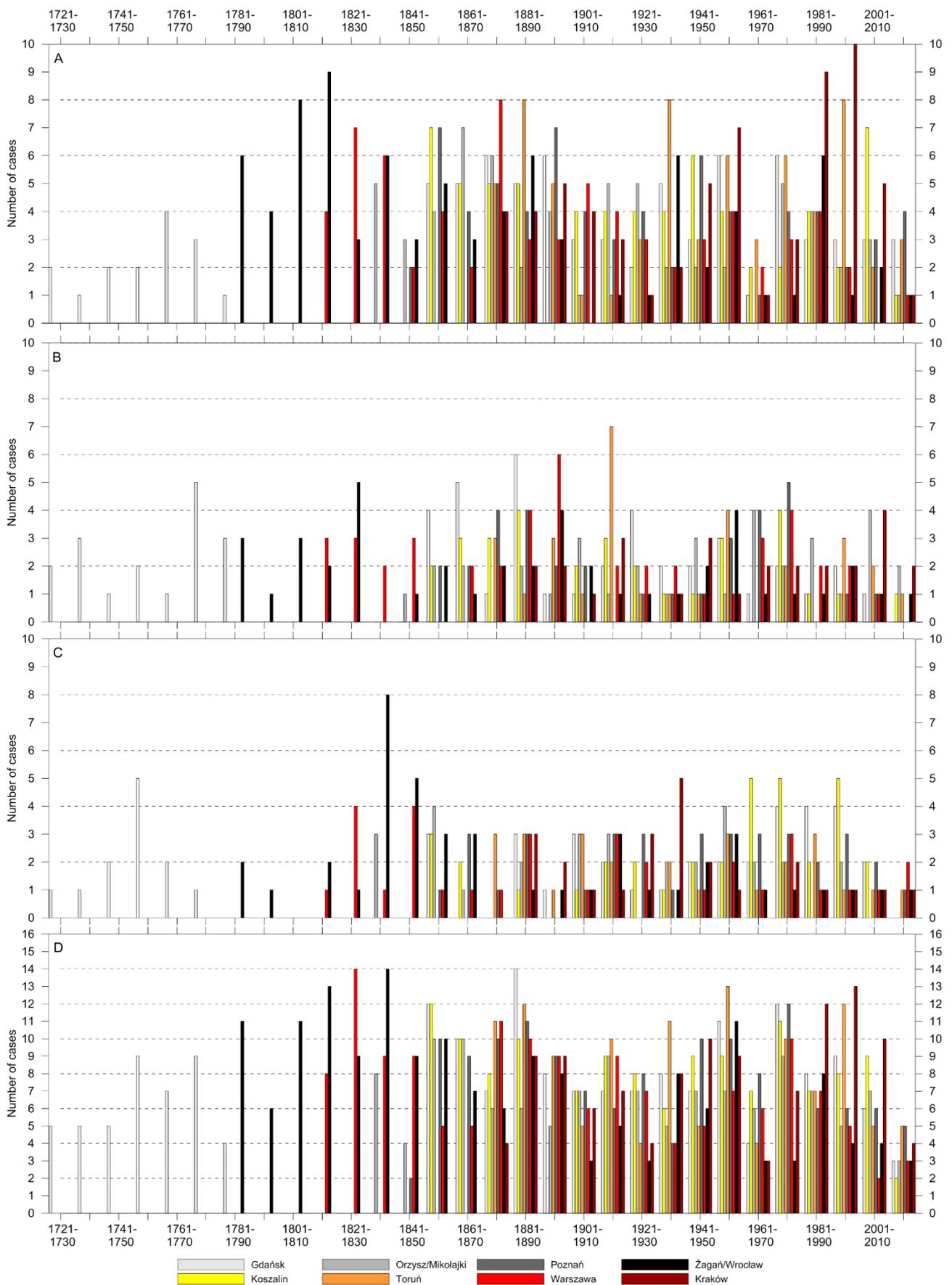


1 Fig. 8. Variability in SPI: 1-month (grey curve), 3-month (black curve) and 24-month (red curve)
2 calculated from the Polish instrumental series listed in Table 2 (oriented from north to south) in
3 the period 1722–2015. SPI-3 and SPI-24 were filtered by 10-element and 30-element low-pass
4 Gauss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

6

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

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



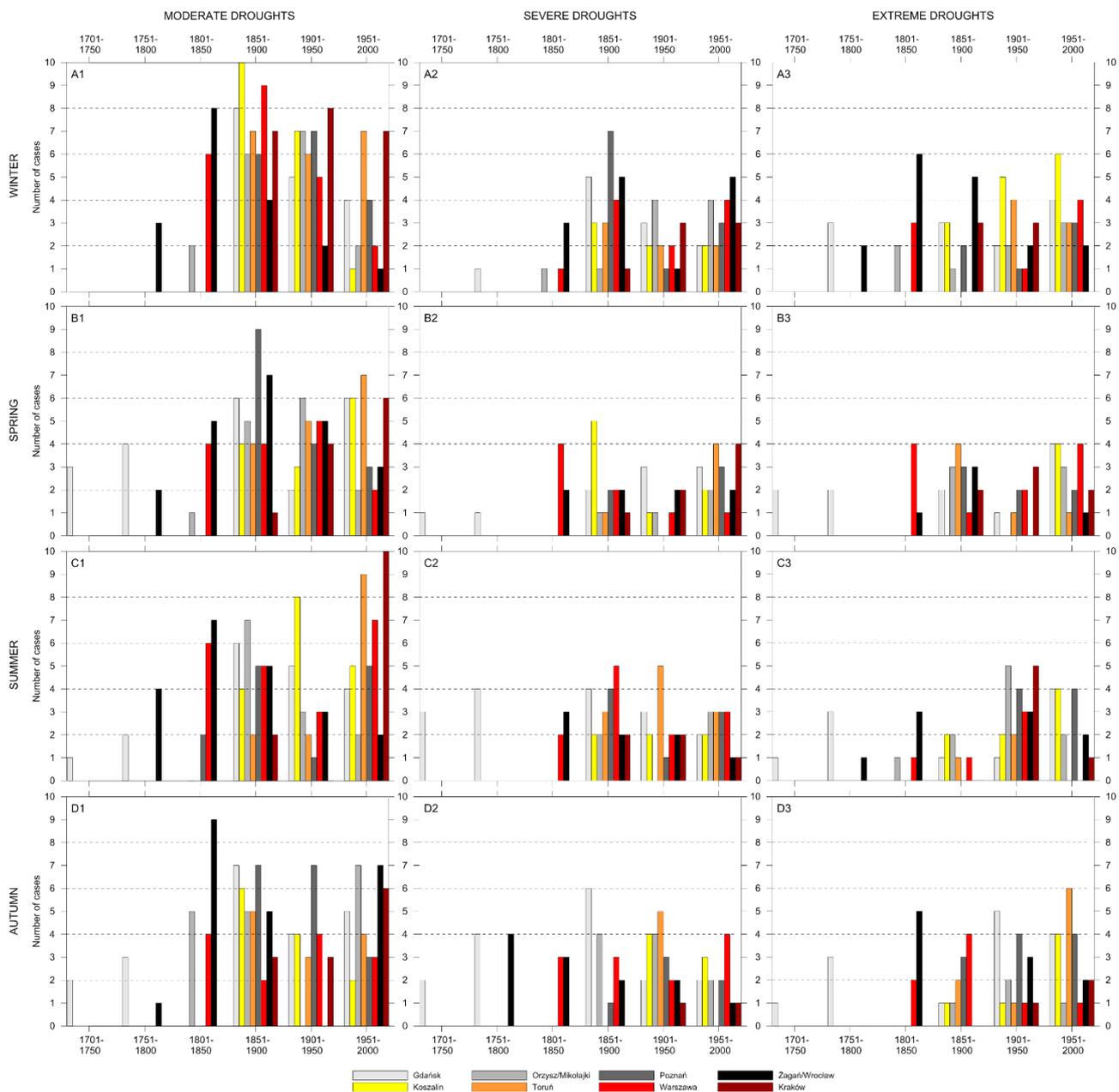
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Fig. 9. Decadal frequency of droughts in Poland in 1722–2015 identified using SPI1
Key: A – moderate droughts, B – severe droughts, C – extreme droughts, D – all-category droughts

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

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

22



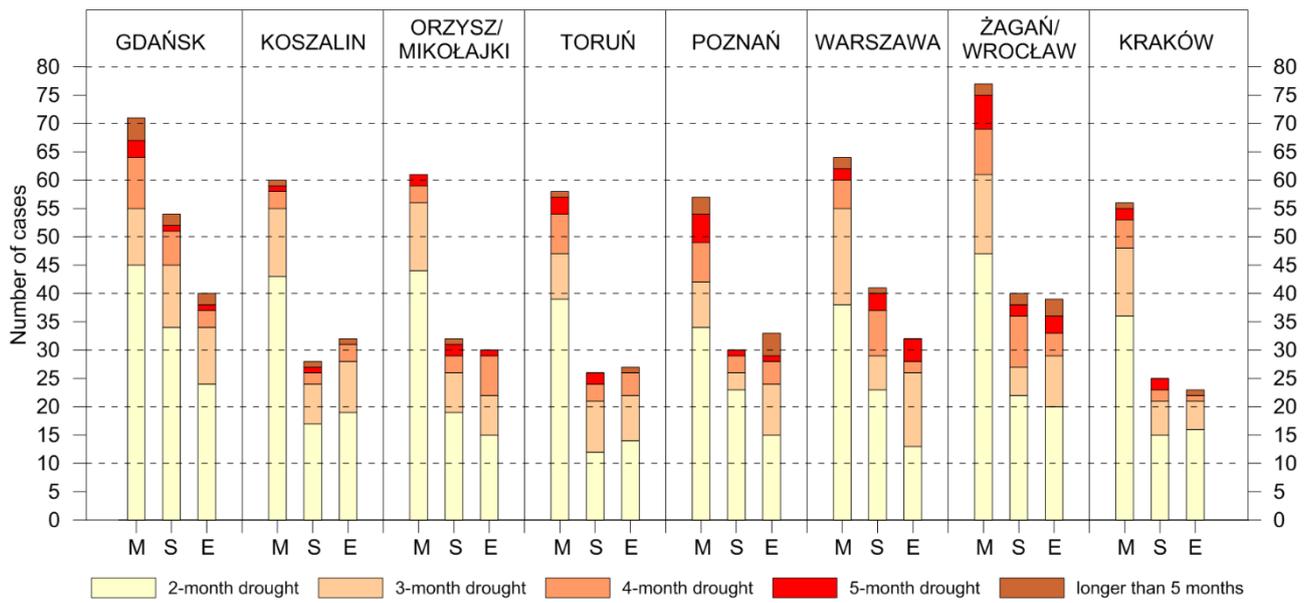
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Fig. 10. Seasonal 50-year frequency of droughts in Poland in 1722–2015 identified using SPI1

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

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

3



4

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

7

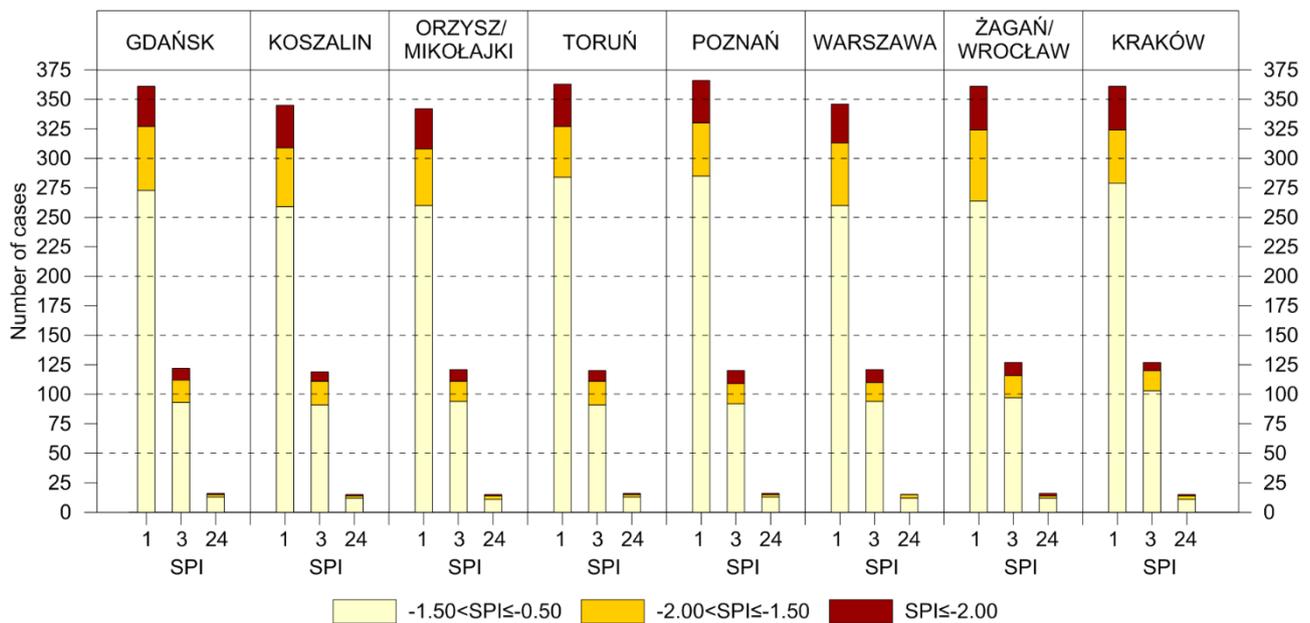
8 Łabędzki (2007) proposed a simple formula to calculate the frequency of occurrence of dry
 9 months and droughts per 100 years based on SPI values (see methods). Using his formula we
 10 calculated frequencies of dry months using SPI1, short-term droughts (SPI3) and long-term
 11 droughts (SPI24),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

22

23

24

25



1

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

4

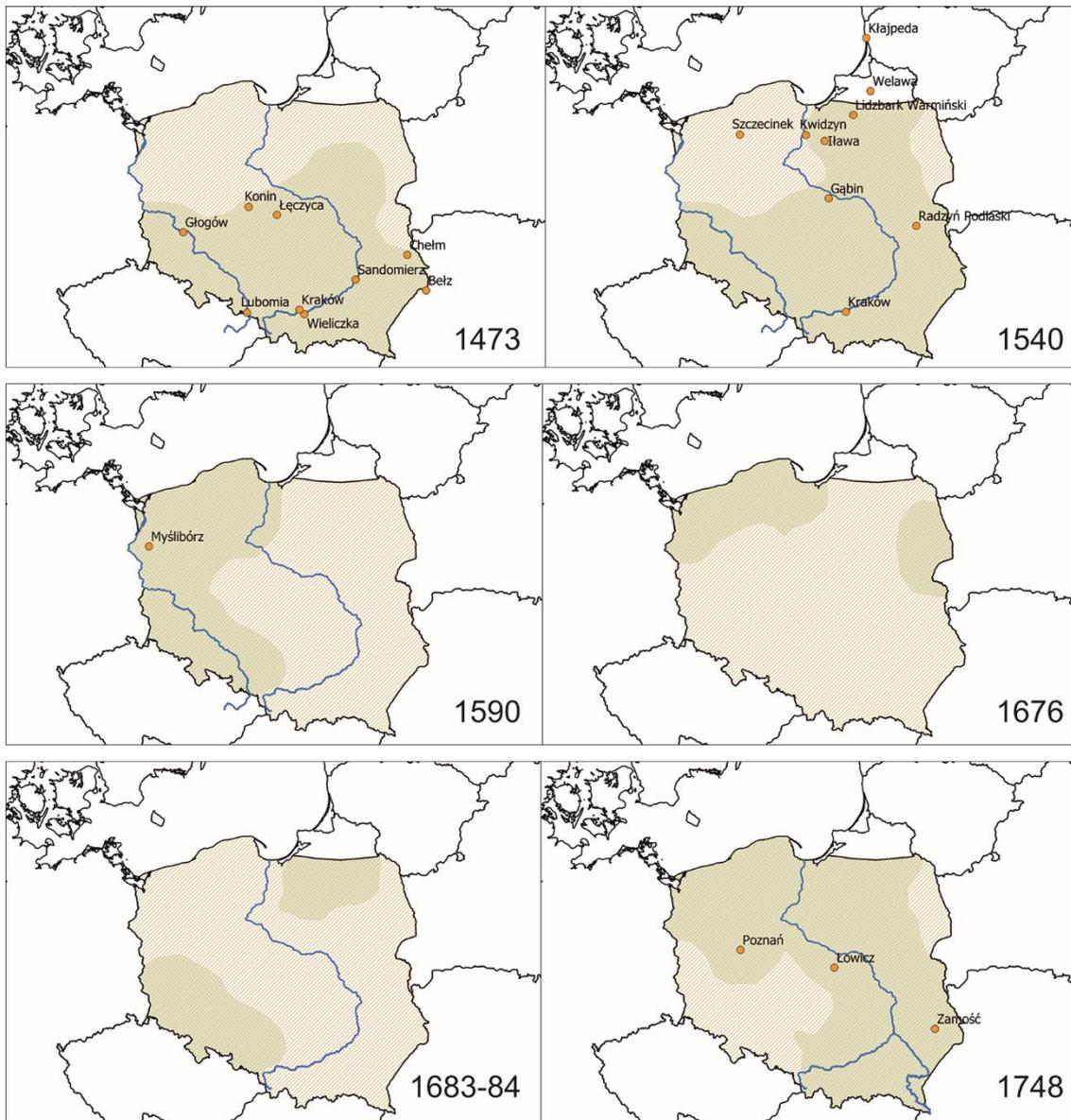
5 **4.4 Selected megadroughts in Poland from historical times**

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

11 **4.4.1 The year 1473**

12 This drought affected the whole of Europe. In the case of Poland, it was quite well described by
 13 Jan Długosz in “Annales”, as Długosz himself observed its course. He wrote about extraordinary
 14 heat and a prolonged lack of rain. He emphasised the extremely low level of water in the Wisła
 15 River and many other rivers that could be easily waded across. Water reservoirs were completely
 16 dry. The lack of water was marked throughout the whole country. Fires were another commonplace
 17 phenomenon. There were forest fires. Długosz also mentioned economic consequences. Fires
 18 destroyed wild beehives in the forests. Drought destroyed the spring sowing. Animals got sick.
 19 Fires affected such cities as Kraków, Wieliczka, Konin, Bełz, Chełm, Lubomia, Łęczyca,
 20 Sandomierz and others (Długosz Ks.) (see Fig. 13). According to the Silesian chronicler Peter
 21 Eschenloer, the drought lasted from 23 April to 11 November. This chronicler recorded an
 22 extremely low level of water in the Odra River. Water mills could not operate. There was no water
 23 in wells. Even wild animals were affected by the lack of water. Similar information was provided
 24 by another Silesian chronicler, Nicolaus Pol. Meanwhile, the author of *Roczniki głogowskie*,

1 Kaspar Borgeni, reported that the drought lasted only 10 weeks. However, he provided many
 2 detailed dates in his narrative about the harvest time and their quality; there was no rain from April
 3 4 to September 22, so it should be considered that the drought lasted almost 6 months.



4
 5 Fig. 13. The most severe megadroughts, with spatial coverage (dark colour). Location of
 6 sites and rivers mentioned in Section 4.4 and Table 3.

7 4.4.2 The year 1540

8 This drought belongs to one of the best described droughts in old Europe. In Poland, however, the
 9 year 1540 began with numerous floods in the winter (Poznań) and early spring (Żuławy and
 10 Gdańsk). Heavy rainfalls also caused floods in Świecie located on the Wisła River in its lower
 11 part. Polish sources are quite laconic, if unambiguous, about the drought of 1540, considering its
 12 scale. A parish priest from Lidzbark Warmiński wrote about a terrifying drought. The Silesian
 13 chronicler Nicolaus Pol wrote about the drying of many waters and the greening of the Odra River,
 14 probably as a result of the development of algae at high temperatures. It was reported that grass

1 was drying out, cereal harvests were poor, cattle had to go many miles to watering places. The
2 detailed observations of the Kraków professor Marcin Biem leave no doubt as to the lack of rainfall
3 and the extreme nature of the drought in the vicinity of Kraków. The drought lasted until October.
4 There were many fires, including in such cities as Kwidzyn, Welawa, Klaipeda in the Prussian
5 state, Gąbin in Mazowsze, and Radzyń Podlaski (see Fig. 13). Fires were also reported in Ława
6 and Szczecinek (Nowosad and Oliński, 2019).

7 4.4.3 The year 1590

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

20 4.4.4 The year 1676

21 The drought of 1676 was described independently in several sources. Spring is supposed to have
22 abounded in storms that caused numerous fires. There was drought in the summer. In Pomerania
23 (see Fig. 13) it rained only twice in the summer. The whole summer was dry and hot. The drought
24 caused damage to crops in slightly higher areas. The harvest of fruits and vegetables was also poor
25 due to the drought. In Podlasie, the beginning of January was exceptionally warm, although frosts
26 arrived later. According to the records from Antoni Chrapowicki's diary, June and July were very
27 dry months in Podlasie. Chrapowicki wrote that crops "burned out" in the fields. In August and
28 September, Chrapowicki stayed in eastern Belarus, which is why his records concerning the late
29 summer and autumn cannot be taken into account (*Diaryusz Życia JWJmci Pana Jan Antoni*
30 *Chrapowicki*). The research into the memoirs of Chrapowicki indicates that the precipitation in
31 1676 was the slightest of all the years covered by his diary (1656–1684) (Przybylak and Marciniak,
32 2010). In other sources, the high prices that prevailed in the country this year were also underlined
33 (Namaczyńska, 1937).

34 4.4.5 The years 1683–1684

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

9 4.4.6 The year 1748

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

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

1 seen in Toruń until mid-October, but complaints about the very low water level in the San River
2 were still being reported (Reyger, Brauer).

4 **5 Discussion**

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

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

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

35 Even better agreement between both kinds of proxy data was found when megadroughts
36 identified by documentary evidence were taken into account. In four (1473, 1540, 1590 and 1748)

1 of the six described here (see Section 4), clear signals in dendrochronological data were detected
2 (negative pointer years). Using documentary sources, two megadroughts (1540 and 1590) were
3 also qualified as very outstanding droughts in the Czech Republic (Brázdil et al., 2013). Of those,
4 however, only the year 1590 had a negative tree-ring width index (TRW) (of -1.818), although this
5 value was not very high (see Table S1 in Supplement in Dobrovolný et al., 2015). Brázdil et al.
6 (2013) using documentary evidence also distinguished three other outstanding droughts in the
7 Czech Lands (1616, 1718 and 1719). All of those also occurred in Poland, but their category using
8 documentary evidence was estimated by us as -2 (severe). In all those years except 1718, negative
9 pointer years were also found in one Polish region (see Fig. 6), while in the Czech Republic an
10 extreme negative TRW index (-2.474) was found only for the year 1616 (see Table S1 in
11 Supplement in Dobrovolný et al., 2015). Based on the published list of TRW indices for Czech
12 Republic (oak chronology) by Dobrovolný et al. (2015) we found 33 extreme negative TRW
13 indices in the period 1451–1800, which suggests favourable conditions for drought occurrence.
14 We excluded the two last years (1790 and 1800), which were identified for Scots pine tree rings
15 from Upper Silesia (Opała and Mendecki, 2014). For almost half of this set of years (48.5%), we
16 confirmed the existence of strong negative pointer years also in Poland’s tree dendrochronologies.
17 Significantly better agreement (89%), between the occurrence of narrow rings in the Czech
18 Republic on the one side, and Upper Silesia (Opała and Mendecki, 2014) and southern Poland
19 (Opała, 2015) on the other, was found by Dobrovolný et al. (2015) for the overlapping period
20 1770–1932. These quite good correspondence patterns between negative TRW in the Czech
21 Republic and Poland (in particular its southern part), which are also very clear in analysis of
22 drought occurrence and areal coverage (which are presented in the Old World Drought Atlas
23 [OWDA, Cook et al., 2015]), are the result of large positive sea-level-pressure anomalies over the
24 whole of central Europe (including Poland) in MAM and JJA during the occurrence of negative
25 extremes in TRW (see Fig. 5 in Dobrovolný et al., 2015). Significantly weaker agreement (about
26 30%) was found between the timings of droughts in Poland delimited using documentary evidence
27 and droughts reconstructed for the whole of Europe using tree rings (Cook et al., 2015). This is
28 caused by the fact that Cook et al. (2015) used significantly fewer dendrochronologies from Poland
29 (only four – and those mainly from northern Poland, see their Supplementary Materials) than we
30 used in the present paper (22, see Table 1 for details).

31 The megadrought year of 1473 was detected in the Baltic Province on the basis of an oak
32 chronology from Eastern Pomerania (Ważny, 1990). Narrow rings were observed in 80 percent of
33 the samples for this year. The effect of the drought in 1473 can also be shifted and observed in
34 southern Poland in 1474 (Szychowska-Krapiec, 2010). The drought in 1540 was observed in
35 different parts of Europe; particularly strong evidence is available in documentary sources (Wetter
36 et al., 2014; Pfister et al., 2015; Brázdil et al., 2016). Additionally, many dendrochronological data

1 confirm the existence of strong droughts in much of Europe, in particular from France to Latvia,
2 Belarus and Ukraine and from the southern Scandinavian Peninsula to northern parts of Italy
3 (OWDA, Cook et al., 2015). Čufar et al. (2008) identified the existence of droughts in Slovenia in
4 1540 based on tree rings. The scale and intensity of the 1540 megadrought in Europe described by
5 Wetter et al. (2014) as “an unprecedented 11-month-long Megadrought” (more severe than the
6 2003 drought in Western Europe and the 2010 drought in Russia) was, however, recently
7 questioned by Büntgen et al. (2015), who analysed this year in light of 24,303 individual tree-ring-
8 width measurement series. It is also worth adding here that in different parts of Europe the effect
9 in tree rings was shifted and observed in 1541 (Büntgen et al., 2011). Analysis of our 22
10 dendrochronologies reveals the occurrence of narrow rings in trees growing in the Baltic Province
11 and in the Lesser Poland Province, and thus not in the whole of Poland as shown in the OWDA
12 (Cook et al., 2015). In 1590, narrow rings were observed in the Baltic Province, but the decidedly
13 strongest droughts in Europe in view of this proxy were those occurring in France and Germany
14 (Cook et al., 2015). Narrow rings were also noted in most sites in central and eastern Europe, as
15 well as in Scandinavia. The year 1748 seems to have a somewhat regional character; narrow rings
16 were noted in the Greater Poland and Pomerania Province and in the Lesser Poland Province.
17 There is no information about tree reaction for this drought in selected sites in central Europe
18 (Büntgen et al., 2011). Looking at OWDA we see the occurrence of droughts in this year mainly
19 in northern and western parts of Poland (although their severity is not so large). Evidently more
20 severe droughts in this year in Europe were particularly observed in southern Germany, the whole
21 of Austria and the western borders of the Czech Republic (Cook et al., 2015).

22 Both documentary evidence and dendrochronological data clearly indicate that in the
23 period 1451–1800 the greatest frequency of droughts in Poland occurred in the 18th century, and
24 particularly the second half (32 cases). Similar results are also seen in the Czech Republic (see
25 Fig. 4a in Brázdil et al., 2013). The smallest number of droughts was noted in the 16th century
26 (about 35), and was different than in the Czech Lands, where the evidently smallest number
27 occurred in the 17th century. In the study period, the total number of all-category droughts in
28 Poland identified reached 148 and 156 – using documentary evidence and dendrochronological
29 data, respectively. This means that both proxies reconstruct quite a similar frequency of drought
30 occurrence in time scales from centuries to decades. The overall numbers of droughts identified
31 using documentary evidence in Poland (present study) and the Czech Lands (Fig. 4a in Brázdil et
32 al., 2013) in the overlapping period 1501–1800 were very similar and reached 132 and 126 cases,
33 respectively.

34 All the dendrochronologies and long-term series of precipitation that we gathered and used
35 for SPI calculation are available only for the common period 1876–1985. Therefore, for this
36 period, statistics were calculated to compare the timings of dry periods (droughts) in Poland

1 identified using both of these kinds of data. The agreement between droughts occurring at least in
2 two geographical (SPII_{May-Jul} delimited droughts) and two natural-forest regions (significant
3 negative pointer years) was 25.5%. On the other hand, for a less strict criterion, i.e. the occurrence
4 of droughts at least in one region, the agreement reached 50.9%. Thus, the latter number is close
5 to the value of agreement of drought timings identified using documentary evidence and the
6 occurrence of negative pointer years (59.1%).

7 Having those series for the abovementioned period, we also conducted a correlation
8 analysis to investigate how spatially coherent the association is between climate (SPII_{May-Jul}) and
9 tree-ring widths in the area of Poland. Coefficients of Pearson's linear correlation were calculated
10 for 1–2 dendrochronologies representing each natural-forest region, with SPII_{May-Jul} values
11 calculated for long-term series of precipitation taken from meteorological stations in the same
12 region and closest to the area covered by the dendrochronologies. The closest relationships
13 between climate and tree-ring growth were obtained for the Greater Poland and Pomerania
14 Province and the Silesia Province, where the correlation coefficient r reached: 0.40 (site 9, Poznań
15 in Table 1), 0.44 (site 11, Kuyavia-Pomerania) and 0.46 (site 17, Wrocław). Such good correlation
16 ($r=0.43$) was also found by Dobrovolný et al. (2015) for the Czech Republic between 18 variants
17 of Czech oak chronology and March–June precipitation totals. In three other Polish provinces
18 (Baltic Coast, Masuria and Masovia, see Fig. 1) correlation coefficients are still statistically
19 significant, but are clearly smaller: 0.25 (site 3, Wolin in Table 1), 0.14 (site 1, Koszalin), 0.24
20 (site 7, Suwałki), 0.13 (site 8, Hajnówka) and 0.21 (site 15, Warszawa). A similar correlation value
21 (about 0.20) between tree-ring width and precipitation in June and July was found by Helama et
22 al. (2014) for south-western Finland. On the other hand, a significantly better correlation (about
23 0.4) was calculated by Seftigen et al. (2013) for south-eastern Sweden. The increased strength of
24 correlation here was probably due to the selection of trees growing at xeric sites, where the radial
25 growth was most likely limited by moisture availability. The climate–tree-ring-growth relationship
26 in Lesser Poland Province was not stated – the coefficient of correlation was equal to 0.0. The
27 reasons for this different climate–tree-growth behaviour in this part of Poland in comparison to
28 other studied regions are unknown.

29 From the perspective of available historical sources from the period 1451–1800, an
30 increasing number of droughts was reported from the second half of the 16th century onwards,
31 excluding the first half of the 17th century. The decrease in their occurrence in this period can be
32 explained by large source deficiencies. They resulted from the destruction of many documents
33 during the Swedish invasion on Polish territories in 1655-1660. The number of droughts in the
34 first half of the 17th century is likely to have been higher. As information about moderate droughts
35 is quite accidental, the sources certifying extreme and severe droughts seem more reliable and
36 complete. According to our research, droughts occurred most frequently in the second half of the

1 18th century. This rectifies the previously accepted data on drought in Poland available in some
2 geographic works (see e.g. Słota et al., 1992; Kaca et al., 1993; Łabędzki, 2006), which include
3 information that in the 14th century there were 20 droughts in Poland, 25 in the 15th century, 19 in
4 the 16th century, 24 in the 17th century, and 22 in the 18th century. However, these numbers refer
5 to the frequency of hot summer seasons distinguished by Sadowski (1991, Sadowski also assumed
6 the year 1300, 1400, etc. to be the first year of a century). On the basis of the research presented
7 in this paper, we conclude that severe and extreme droughts (indexes -2, -3, respectively) were in
8 fact slightly less frequent, while their occurrence in the period from the 15th to the 18th century, as
9 previously stated, was slightly increasing.

10

11 **Summary and concluding remarks**

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

- 13 1. More than one hundred droughts were found in documentary sources from the mid-15th
14 century to the end of the 18th century, including 17 megadroughts. A greater-than-average
15 number of droughts was observed in the second halves of the 17th and, particularly, the 18th
16 century. Dendrochronological data confirmed this general tendency in the mentioned
17 period. The clearly greatest number of negative pointer years occurred in the 18th century
18 and then in the period 1451–1500.
- 19 2. Droughts in the period 1451–1800 occurred most frequently in the Baltic Coast–Pomerania
20 and Silesia regions, while in the rest of the analysed regions their frequency was more-or-
21 less similar. Generally similar results have been found for the period 1722–2015 based on
22 instrumental data.
- 23 3. Analysis of SPI (including its lowest values – droughts) showed that the long-term
24 frequency of droughts in Poland has been stable in the last two or three centuries.
- 25 4. Most droughts in the period 1722–2015 lasted for two months (about 60–70%), and the
26 next most common duration was 3–4 months (10–20%). Frequencies of droughts of 5 or
27 more months were below 10%. The longest droughts lasted for 7–8 months.
- 28 5. The frequency of all-category droughts in Poland in the period 1722–2015 was greatest in
29 winter. This fact should be taken into account when droughts delimited using documentary
30 evidence are analysed. In light of this information, droughts in spring and summer clearly
31 dominated in Poland in the period 1451–1800, while in winter only three cases were
32 mentioned.
- 33 6. Analysis of the occurrence of negative pointer years (a good proxy for droughts) showed a
34 good correspondence with droughts delimited based on documentary and instrumental data
35 in the periods 1451–1800 and 1722–2015, respectively.

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

13
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15
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25

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