On the economic impact of droughts in central Europe: the decade from 1531 to 1540 from the Polish perspective

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Abstract. The period from around 1450 to 1550 in Europe is extremely interesting from the perspective of research on extreme weather events. It was a period of events that strongly influenced the societies and economies of the Old Continent. So far, the literature has been more focused on western and northern Europe. Concerning the region of central Europe, the greatest attention was paid to the Czech Republic or Hungary. This article revolves around the Polish lands, which experienced their greatest economic boom in the 16th century. We consider whether and how the droughts of the decade from 1531 to 1540 might have affected the country’s economic development. We analyse a number of written sources which are the product of the treasury apparatus of the time (tax registers, data from water customs, tax exemptions, inventories of land estates etc.), but also information on fluctuations in product prices in the most important cities in this part of Europe. The work not only provides a detailed account of economic data, but also attempts to reflect on the relevance of linking information on fires in urban centres in the period characterized by weather extremes.

1 Introduction

In the most recent two decades research in the field of historical climatology has made a significant advance in our knowledge of how societies functioned in the past, and how they dealt with climate variability throughout the centuries (Brázdil et al., 2013a, b, 2018; Camenisch et al., 2016, 2020; Kiss, 2014, 2017, 2018, 2019; Kiss and Nikolić, 2015; Kiss and Pribyl, 2019; Huhtamaa and Helama, 2017; Ljungqvist et al., 2021). However, much still remains to be done. In this paper, we focus on a single but important decade and discuss the economic effects of droughts in early modern Poland. A direct inspiration for this study can be found in the article published in 2020 in the Climate of the Past entitled Central Europe, 1531–1540 CE: The driest summer decade of the past five centuries? (Brázdil et al., 2020). The researchers attempted to combine climatological data on droughts with the socio-economic response of past societies to them. Our study should possibly be treated as a comprehensive historical supplement of the above-mentioned paper in which we focus in particular on macro-economic issues in the 16th-century Kingdom of Poland. We aim to deeply understand the reactions of the economic system of the early modern state to...
extreme weather events. With a bird’s eye view of past economics, it is important to capture more accurately how society and the economy (as a whole) dealt with climate crises. However, focusing on the Polish lands one must be reminded that in the 16th century the Polish Crown had become a part of the global economic system and was undergoing a modernization process.

Drought is a recurring extreme weather event and affects both ecosystems and various sectors of the economy. Therefore, drought can be defined from different perspectives. Meteorological drought occurs when the atmospheric conditions result in the absence or reduction of precipitation. Atmospheric conditions that result in rainfall deficit depend on the geographic location and water resources; therefore, the understanding and scale of meteorological drought may differ from region to region. In turn, agricultural drought (or soil moisture drought) refers to a deficit of (mostly root zone) soil moisture. It is usually associated with meteorological drought, and this relationship is complex and dependent on many factors and determinants. The final effect of agricultural drought is a crop yield reduction. Hydrological drought is associated with the effects of periods of precipitation shortfalls on surface or subsurface water supply (i.e. streamflow, lake levels, groundwater). Socioeconomic drought is associated with the supply and demand of some economic goods with elements of all the above-mentioned types of drought (Heim, 2002; Łabędzki and Bąk, 2017; Wilhite and Glantz, 1985; Seneviratne et al., 2012).

Addressing the economic significance of droughts is important in the context of the current discussion on adaptation factors and methods with regard to changing climatic conditions (Degroot et al., 2021). Of particular relevance are the potential agricultural consequences associated with the occurrence of droughts. They can pose a serious threat to soil functions and productivity, especially in agricultural ecosystems (Liu et al., 2010). Soil moisture, despite climatic conditions, depends inter alia on soil organic matter (SOM) content, texture, porosity, relief and land use. Sandy soils, poor in organic matter, located on terrain elevations without access to groundwater, are particularly exposed to rapid drying. Soils devoid of vegetation are exposed to accelerated evaporation of the soil surface, leading to over-drying. If reduced, soil water content, a prerequisite for plant growth, limits the solubility and availability of nutrients for plants, lowers the biological and chemical activity of the soil and may contribute to disturbances in soil temperature regulation (He and Dijkstra, 2014; Wang et al., 2012; Mahajan et al., 2018; Siebielec et al., 2020; Al-Kayssi et al., 1990).

If the decade from 1531 to 1540 is placed in a broad context, it can be seen that several years (1531, 1534, 1535, 1538 and 1540) can be distinguished for which dendrochronological data provide evidence of the occurrence of droughts in central Europe (Cook et al., 2015). Similarly, data for eastern Europe (1531, 1532 and 1533) show that periods of severe droughts occurred mostly at the beginning of the studied decade (Cook et al., 2020). Rudolf Brázdil and his collaborators indicated that droughts occurring in the years 1534, 1536, 1538 and 1540 had a pan-European character (Brázdil et al., 2020). Nevertheless, the year 1540, because of its importance in current discourse, should be treated separately (Wetter and Pfister, 2013; Wetter et al., 2014; Büntgen et al., 2015; Pfister et al., 2015; Orth et al., 2016; Pfister, 2017, 2018; Nowosad and Olisński, 2020). On the other hand, looking more specifically at the Polish context of climatological research one can observe that in the 16th century the smallest number of droughts in the Polish lands were recorded, and their intensity was not substantial (Przybylak et al., 2020).

Nevertheless, it should be remembered that all the phenomena described here fall within what in Polish historiography is called the “Polish Golden Age”. In a broader sense, this concept can refer to the issues of art, culture, statehood, religious tolerance and even the significant development of philosophical thought. However, at this point we are especially interested in the economic factors. We also want to see how the Polish state got rich in exporting crops and forest products to western Europe (Małowist, 2006). In this aspect, we assume that the Polish state has not been affected by any major crisis in the decade from 1531 to 1540. The period from the end of the 15th century to the middle of the 17th century can therefore be regarded as a period of fundamental economic development.

1.1 Historical dataset

We refer to data collected by the Polish economic historians, but also we use the archival materials related to the functioning of the Jagiellonian state and royal treasury apparatus. While selecting the final dataset, we tried to use as much information as possible related to the decade from 1531 to 1540. Sources were selected on the basis of three factors:

a. their mass character, i.e. the record of the course of economic processes, recurring and common, as well as everyday economic activity rather than the individual experience of, for instance, the chronicle’s author;

b. broad spatial coverage;

c. the homogeneity of the material, i.e. its standardized form resulting from its quantitative nature and a particular type of land ownership.

The three oldest records of state tax revenues (so-called tax summaries, in Polish sumariusze podatkowe) that have been preserved up to now were analysed (Boroda, 2013, 2016). They come from the years 1533, 1535 and 1543 (Archival sources AS 1–3). These sources were a synthesis of tax sums collected from former individual territories of Poland. Thus, they portray the economic totality of the state at that time. For the purposes of this article we were able to compare only data from four lands (Latin: terrae) included in preserved regis-
ters: Brześć Kujawski (terra Brestensis), Płock (terra Plo-
censis), Dobrzyń (terra Dobrinensis) and Sochaczew (terra 
Sochaczovienensis).

Additionally, in order to consider the relationship between 
climatic conditions and the spread of city and town fires we 
used the chancellery books of Polish kings (so-called Crown 
Metric; Archival sources AS 4 and Wierzbowski, 1910, 1912, 
1915, 1917, 1919). These books consist of many tax exemp-
tion documents granted by monarchs due to the occurrence 
of fire in a particular town or its part, which is particularly 
relevant in the context of observing the effects of an excep-
tional drought.

We consider cereals (mainly rye) to be the most reliable 
export commodity in the agricultural economy of that time. 
Therefore, we have analysed the data on harvests in ecclesi-
astical manors of the Cuyavia bishopric (Żytkowicz, 1962) 
and royal estates (Wawrzyńczyk, 1974), where we have fo-
cused in particular on the Malbork estates of eastern Prussia 
in northern Poland (Szpak, 1971).

Sets of historical prices from the largest Polish cities of the 
period such as Kraków, Gdańsk, or Lviv (Pecł, 1935, 1937; 
Hosowski, 1928) were also used. We have also analysed the 
average annual and quarterly prices of key agricultural prod-
ucts, i.e. various kinds of grain, as well as beer, the basic 
product of the processing sector connected with both agri-
culture and water management. Due to the large devaluation 
of money, the prices were converted into grams of silver in 
our analyses.

An important supplement to the above data was the infor-
mation on the grain exports from Baltic ports. We have 
taken into account both the production from eastern Pomer-
ania and that sent down the Vistula river from inland based 
on the lists of the water duty in Włocławek from the 16th cen-
tury (Kutrzeba and Duda, 1915). Also, Sundtoll data were 
used (Ellinger and Korst, 1906).

In addition to the above-mentioned sources recording the 
course of economic processes, the most popular early mod-
ern Polish agricultural handbooks were used in our text, 
showing the reflections of the contemporaries on the weather 
conditions affecting farming.

1.2 Methodology

The set of historical data used in this research have been col-
llected in a form that permits a quantitative analysis. All eco-
nomic datasets were collected as databases aggregated to the 
level of the individual royal or ecclesiastical estates (in the 
case of inventories). Data on fires were extracted from narra-
tive documents. Based on these, a table was developed con-
taining information on the town where the fire occurred, its 
date, description and length of exemption.

An important element in the process of organizing the ob-
tained information was to divide it into three time periods, 
which were classified as those relating to the period before, 
during and after the decade we are interested in White et al. (2022). This approach resulted from the desire to capture 
as broad a view as possible of the phenomena occurring in 
the economy at the time. We have carried out the main part 
of our work looking at the decade from 1531 to 1540 as a 
coherent epoch. However, the observations may be heavily 
fluenced by the climatic events of the 1540 mega-drought 
(see Sect. 1.1).

The available source material did not allow us to anal-
yse data from inventories related to the cultivation of peren-
nial crops (e.g. vine bushes) as is the case in research in 
other parts of central Europe (Chuine et al., 2004; Krieger 
et al., 2011; Labbé et al., 2019). The sources were related to 
the most important economic products of Poland at that 
time, i.e. various types of cereals, which formed the basis of 
the diet of people of all social groups and were predomin-
antly exported to western Europe during the 16th century 
(Wyczasiński, 1985; Boroda, 2016). We hypothesized that in-
tense weather- and climate-induced economic crises should 
have a significant impact on the macroeconomics of a given 
region.

Statistical analyses were performed with the use of the R 
language and visualized with its ggplot2 library. Since our 
data were limited and came form sources with different qual-
ity, we decided to restrict statistical analysis to the compar-
ison of decadal means and their 95 % confidence intervals. 
Those intervals are represented in the figure with the areas 
of different colours, while the means are represented with 
the black lines. In addition, although those results are not re-
ported in the paper, we have run one-way ANOVA analysis 
to further confirm our results.

2 Results and discussion

The majority of our analysis is based on indicators related to 
the production, trade and exports of cereal products. These 
were the signs that accounted for the economic strength of 
the country in the period under scrutiny. Cereals in early 
modern Poland should be divided into winter (rye, wheat, 
barley) and spring (oats, barley, buckwheat, rye and wheat). 
Among them, winter rye was the leading crop, followed by 
spring oats, spring barley and winter wheat. Spring rye and 
spring wheat played a secondary role in the economy. Their 
sowing was recommended by the authors of farming hand-
books only if winter sowing failed (Gostomski, 1951; Ros-
taxiński, 1891). The authors wrote that the time of spring 
sowing was in March (very close to St. Bartholomew’s Day – 
12 March). In turn, the time of sowing rye and winter wheat 
fell between the end of August and the beginning of Octo-
ber (Gostomski, 1951; Piprek, 1954; Chomętowski, 1878; 
Rostański, 1891). Agricultural literature, however, does not 
provide precise dates for sowing rye and spring wheat.

There is much less information about the harvesting pe-
riod, which was a direct result of the local conditions. Ac-
cording to the recommendations in agricultural literature of
the period the harvest of winter crops should end in August (Chomętowski, 1878). Winter barley ripened earliest (approx. 25 June), followed by winter rye (approx. 4 July). The authors reported that rye was harvested earlier than wheat (Piprek, 1954). On the other hand, the harvest of spring cereals began in the last days of August (Chomętowski, 1878; Rostafinski, 1891). Some of the writers pointed out that harvesting should be done in dry and sunny weather, but they also warned against harvesting during the rain (Gostomski, 1951; Rostafinski, 1891).

Manuring of the fields was also important in the cultivation of the cereals. Writers of the studied period treated manuring as a matter of fact and at the same time as a necessity, which is evidenced by numerous pieces of advice concerning methods of increasing the amount of manure (e.g. mixing the manure with rotten weeds or sheaves of old ploughing), methods of its storage, time and technique of soil manuring. What is more, they were well aware of the existence of relations not only between manuring and improvement of soil quality, but they also made the sowing of particular plant species dependent on soil types (Gostomski, 1951; Piprek, 1954; Legatowicz, 1823). However, there are indications suggesting that the world of farming in the Middle Ages and early modern period suffered from a chronic shortage of manure (Newman and Harvey, 1997). Hence, cereals requiring less organic material were probably grown on Polish soils (as a result of the shortage of manure and the condition of the soil). Nevertheless, it is extremely interesting that the authors of agrarian textbooks more often paid attention to excessive soil moisture than to drought (Piprek, 1954). Observations made on the basis of agrarian textbooks therefore show that wet periods were far more of an issue for the agriculture of the time than dry ones.

2.1 Data derived from tax registers and inventories of land estates

The beginning of the modern era was associated with the vast development of bureaucracy and written documentation both at the level of state institutions and of a society engaged in an increasingly commercialized economy. Prominent, among the surviving materials, are tax records maintained and economic inventories conducted at the time by both ecclesiastical and royal estates. Unfortunately, the materials relating to the estates of the gentry survived in a fragmentary and very dispersed form, and for this very reason they were not taken into account in our work (Leskiewiczowa, 1953; Maciejew ska, 1959). In order to observe the economic consequences of droughts, one should focus on looking for any disturbances related to factors such as the size of the cultivated agricultural area or, finally, the prices of agricultural products. In analysing the economic factor, we assumed that any significant fluctuation in the number of cultivated fields, number of water mills or yields could potentially indicate the occurrence of a climatic extreme – in this case drought. However, time is an important factor here. The longer a decline in crop yields, uncultivated land etc. is observed, the more likely we are to be dealing with the real effects of climate action.

2.1.1 Tax registers

During the 16th century the treasury apparatus in the Kingdom of Poland witnessed a period of intensive modernization (Boroda and Guzowski, 2016). One of its features was the increase in revenue coming from taxes, and one of the most important sources of money was taxation of the area of land cultivated by the peasants (Boroda, 2007). The source materials exhibit a different degree of preservation. Some confirm only the amount of money collected in the country in a given year, others give an idea of the taxed land area in the region, and some make it possible to reconstruct the level of agriculture in each locality. From the perspective of the central state finances, it can be noted that at the beginning of the 16th century taxes yielded on average only about 10,000 florins per year; with the reforms, more revenue was achieved, reaching 55,000–60,000 florins per year (1514, 1520), and the exceptionally dry decade did not change this trend. In 1533, more than 70,000 florins were collected, which is as much as was also collected in 1552–1553 (Rutkowski, 1909; Wyczani ski, 1952; Weyman, 1956). The surviving fiscal materials produced by the central government apparatus thus make it possible to compare, within certain regions, key economic information such as the size of the taxed agricultural acreage or the scale of the milling industry. The number of cultivated fields shows general economic trends in this context. On the other hand the number of water mills can be taken as a indicator related not only to the overall condition of the economy, but also to water levels, which may have been related to the climate changes and weather conditions.

In this study we have focused on Płock, Brześć, Dobrzyń and Sochaczew lands (Fig. 1), which should be considered particularly economically important in Poland. They were located on the Vistula river and therefore had to actively participate in trans-regional trade (Żaboklicka, 1958). The summaries allow us to obtain a variety of valuable economic information:

a. the acreage of cultivated land where the amount of land cultivated by peasants (lani kethonum), village representatives (lani scultetorum) and land cultivated directly by local gentry (aratura sua) were counted together;

b. the number of water mills divided by ownership structure into mills inherited by miller families (molendina hereditaria) and those leased under temporary contracts (molendina annualia).

It should be noted that the summaries that we have used prevent an analysis of the specific and detailed economic structure of a given region. However, they can be considered
a significant support in building a general economic portrait of each region, which is important in the context of the lack of adequate treasury sources from the first half of the 16th century. We believe that it was the time of dynamic agricultural growth. In the case of the Brześc Kujawski Land the acreage of arable land increased from 1928 mansi in 1489 to 2505.5 in 1533 (Senkowski, 1961). In the Sochaczew Land the growth was even more spectacular – from 752 mansi in 1496 to 2002.25 in 1533 (Archival sources AS 5). It is likely that in the remaining two regions, for which the data are not available, the situation was similar.

The 1530s and 1540s were characterized by relative stability in terms of the acreage of arable land, although a slight downward trend was visible in most regions.

It can be inferred from the tax source data that the highest decrease in arable land (comparing the first and the last summary) was observed in the Brześc Land (8.04 %); in the Dobrzyń Land it was 6.22 % and in the Sochaczew Land 2.88 % (Fig. 2). This gradual decrease in cultivated land could be interpreted as an effect of land degradation and settlement processes related to the three-field system economy (Newman and Harvey, 1997). The only increase in land acreage took place in the Płock Land and amounted to 1.68 %, which should be interpreted as a modest attempt to acquire new land, probably at the expense of the forest network (Gidaszewski et al., 2013). Unfortunately, the summaries from the areas discussed here did not include any information on deserted fields. The lack of this information prevents us from fully confirming these observations. Statistics related to the number of water mills in each of the mentioned lands can also be an important tool (Fig. 2). The variation in the number of water mills was usually closely related to the amount of acreage under cultivation (Związek, 2014). In the Brześc and Płock lands, an increase in the number of water mills was

Figure 1. Distribution of areas analysed in the text in the spatial context of Vistula river exports in the 16th century (before the Union of Lublin of 1569). Map made by Tomasz Panecki based on data collected while writing the article and files from http://www.atlasfontium.pl website (last access: 24 June 2022).
observed, ranging from 4 % to 8 %; in the Dobrzyń Land, the increase was the most spectacular and amounted to 100 % (from 44 to 88 mills). Only in the Sochaczew Land the number of water mills decreased by about 4 %. Additionally, data from the summaries provide us with information showing the ongoing reconstruction of the economic structure of water mill ownership from hereditary to leased (in the Brześć, Dobrzyń, and Płock lands) and from leased to hereditary in the Sochaczew Land. With the present state of our knowledge, it should be assumed that the system based on temporary leases was more advantageous from the point of view of land ownership (Kaczmarczyk, 1910; Trawkowski, 1960; Guzowski, 2020). It enabled better management and adaptation to various fluctuations – probably including economic ones resulting from climate change during the Little Ice Age. However, this issue requires further and more detailed research.

2.1.2 Great estate inventories

The 16th century was a period of development of manorial economy in estates belonging to large landowners in the Polish Kingdom (Cerman, 2012; Słoń, 2014). Data concerning inventories of landed estates from the first half of the 16th century can be divided into three main types. First, there is information concerning the economic status of the Malbork Royal Economy (MRE), for which the longest and most complete series of data has been preserved (Szpak, 1971). These data were supplemented by eight series of inventories of manors that were part of the royal estates (Wawrzyńczyk, 1974). We also used two series of data on the inventories of the bishops of Włocławek from the early 1530s (Żytkowski, 1962).

Most of the estates used in our analyses were located in the basin of the Vistula river, which was then the most important navigable trade route. We presented our data in the form of sets expressed in so-called kopy, and using the grain yield ratio (GYR). The GYR gives us an idea of the economic level of the goods concerned and, on a broader scale, of the overall level of agricultural production in the period in question. It also gave us the possibility to compare the cereal production between particular regions (Wawrzyńczyk, 1960; Wyczanski, 1968). All data under scrutiny were also placed in a wider time context. Therefore, we used all information from before and after the studied decade from 1531 to 1540 to track the changes within the economy of kings’ and ecclesiastical estates. In this view, all later inventories from the mid-1560s have been treated as reference points in our analysis. However, we were forced to omit the Red Ruthenian lands and partially Greater Poland, whose level of description at the time was far from perfect (Wawrzyńczyk, 1974).

Malbork Royal Economy (MRE) and other royal estates

The first area for which we have an extant and abundant set of inventory sources is the area of MRE covering a large part of Vistula Fens (Fig. 3, Pol. Żuławy Wiślane) surrounding the former capital of the Teutonic State – Marienburg (Pol. Malbork). As a result of intensive German colonization in this region between the late 13th and the late 14th centuries, this area underwent intensive landscape changes involving adaptation of the site for agricultural purposes. Protected from floods by dikes constructed before the end of the 14th century, it was abundant in water and rich in river silts, which were ideally suited to arable farming and animal husbandry (Bertram et al., 1923); this is confirmed by rather laconic references in sources describing the land there as “good” or “comely” (Hoszowski, 1961). High profits obtained by royal administrators from fields and pastures situated mainly between the Vistula and Nogat rivers were one of most important reasons for establishing the royal economy in that area in 1511. Its agricultural potential was effectively used in subsequent decades, especially since the late 1550s, when the area became subject to intensive Hollander (Dutch-type) colonization and, consequently, turned to a technical revolution, which involved the construction of drainage canals in the Vistula Fens and subjecting the water flows to strict control (Ludwig, 1961).

Comparing the state of preservation of source materials with other areas of the Crown at that time, the source information on the economic condition of the MRE is extremely rich (Szpak, 1971). It should be noted, however, that in the estate, unlike in other parts of the Crown, rye did not play the main role in agricultural production. Wheat and barley were definitely in the lead. Szpak (1972) claimed that it was probably a direct result of a deliberate policy of the estate management based on environmental experiments. The researcher pointed out that the administrators of manor estates were to a large extent guided by the natural fertility of particular soils, and adjusted the appropriate share of particular crops to their quality. Wheat and barley grew mainly on bet-
ter soils, whereas rye and oats grew on weaker ones. The agricultural potential of this area was supported by the occurrence of fertile soils like Dystric and Eutric Fluvisols and Cambisols (Dobrzański et al., 1974; IUSS Working Group WRB, 2015).

Our data on crop yields from the MRE concern basic crops and peas. They show that the decade from 1531 to 1540 was a time of exceptionally abundant wheat, barley, rye and oat harvests, much more abundant than in the early 16th century as well as in the following decades (Fig. 4). Pea harvests were growing consistently over the first half of the 16th century, including the “drought decade” and the ensuing one.

The increase in agricultural productivity can also be seen in the growing volume of cereal harvests. In the period from 1531 to 1540 they were significantly more abundant than at the beginning of the century. Despite some decline at the beginning of the 1540s, at the end of this decade they were also better than in the years preceding the “drought decade” (Fig. 5). The increase took place in spite of reductions in the acreage of arable land. In the years 1521–1530 the acreage fell to 97% of the area from the beginning of the century,

Figure 3. Vistula Fens settlement. Map made by Tomasz Panecki based on data collected while writing the article and files from https://atlasfontium.pl/ website (last access: 24 June 2022).
and in the decade from 1531 to 1540 to 85.7 %, with a gradual increase in the amount of land lying fallow (Szpak, 1971).

Unfortunately, our data from other royal estates are less complete than the ones cited above. Some fragmentary information comes from eight estates which were owned by Polish monarchs at the time (Wawrzyńczyk, 1974). What is available does not permit any conclusive estimates of harvests before the “drought decade”. The data do show that the 1530s were characterized by lower harvests than the consecutive decades of the 16th century. However, this does not necessarily have to be the result of dry weather but may simply reflect a lower level of development of manorial farms and less advanced manuring than in the 1560s (Fig. 6).

**Estates of Włocławek bishops**

The last series of inventory data is information on sowing and yields on the estates of the bishops of Włocławek in two complexes located in Kuyavia (Raciążek, Włocławek, see Fig. 7). These data, together with a basic historical and economic analysis, come from a compilation published many years ago by Żytkowski (1962). When describing the inventories of the estates of the bishops of Włocławek, Żytkowski paid special attention to the source context. For the 1530s, very detailed accounts concerning grain from the manors of various estates have been preserved (*Regestra rationis factae de frumentis praediorum*). According to this researcher, they can be treated as a firm source concerning the ways in which the bishops of Włocławek managed their estates. This naturally reflects on the degree of reliability of our analysis. In the present work we have used all the data preserved and published by Żytkowski from the 1530s and subsequent years (1565, 1566 and 1582).

The analyses conducted by Żytkowski show a relatively high proportion of manorial farms in relation to peasant holdings, especially in the Włocławek and Raciążek estates. This is probably directly related to the fact that these estates were located close to the Vistula river, which was the main export artery at the time.

Żytkowski also pointed out that in the estates of the bishops of Włocławek the most frequently cultivated cereals were rye and oats, which (depending on the period) constituted 85 %—89 % of all production. He explains such a structure of cultivation mainly by two factors: (1) the permanent shortage of manure and (2) the relatively poor soils, which became sterile very quickly. The main soil types in this area are the sandy Brunic Arenosols and Podzols, the more fertile Luvisols, and the locally encountered Gleyic and Stagnic Phaeozems or Gleyic and Stagnic Chernozems (IUSS Working Group WRB, 2015). It can be inferred from the yields obtained in both estates of the bishops of Włocławek that they were the lowest in comparison with royal estates at that time, which was also pointed out by Żytkowski. Perhaps this was the reason why they were leased out in 1584, when the econ-
Figure 5. Volume of grain harvests in Malbork Royal Economy (calculated in coreti; 1 coretus = 55 kg). Sources: Szpak (1971).

2.2 Data on fires in cities and towns

Recently, it has been argued that there is a strong causal correlation between extreme droughts and occurrence of fires in cities and towns of the pre-industrial era (Mauelshagen, 2010; Parker, 2013; Nowosad and Olifinski, 2020). To verify this hypothesis, we have collected data on urban fires (Fig. 8) from the reign of Sigismund the Old (1507–1548) using the so-called Crown Metric (Pol. Metryka Koronna, hereinafter CM); i.e. the royal chancery registers recording charters, privileges, acts, letters and other documents issued in the name of the king by royal officials (Sułkowska, 1961; Sułkowska-Kurasiowa, 1966). As by the 16th century, it had become mandatory to record all the issued documents in the CM, it is assumed that its volumes from that time contain the vast majority of royal grants. We have focused on tax exemptions and concessions given to towns affected by fires as they were awarded on request (made mostly by town councils but in some cases also by town owners or individual burghers). Assuming that almost all urban centres impacted by a fire applied for such a privilege, we argue that this type of data provides the most consistent (both temporally and geographically) and reliable evidence for the quantitative analysis. Moreover, a comparison of the length of exemption periods allows us to evaluate, to some extent, the severity of a particular incident. Some inconsistencies might be caused by the initial lack of tax exemptions for towns of the Duchy of Mazovia, which until its incorporation into the Crown of Poland in 1526 had a different administrative, fiscal and economic system (Senkowski, 1965).

In most cases, the documents contain no extensive direct information about the fires. Only incidentally do they describe the area of a town that was damaged or provide an exact date of the incident. Nonetheless, common expressions such as “nuper” – “recently” (e.g. CM 31: 230–231, CM 48: 80–81), “non pridem” – “not long ago” (e.g. CM 48: 61–62; CM 70: 562), “novissima ignis voragine” – “the newest blaze” (CM 50: 400–402) and relative efficiency of the official apparatus lead to the conclusion that the privileges were granted soon after a fire occurred. For instance, when a part of Kraków burnt down on 24 April 1528, the relevant exemption was issued on 28 May by the king, who was then in Vilnius (630 km in a straight line from Kraków) (Piekosiński, 1885). Similarly, the concession for Wschowa, which was destroyed with its suburbs by a conflagration on 6 June of the next year, was granted about a month later, also in Vilnius (ca. 670 km away from the town) (CM 44: 387–389).

Between 1507 and 1548, we identified 226 individual instances of urban fires which resulted in the granting of a tax
exemption. The number of documents relating to them was higher as some privileges were repeated or recorded more than once, different concessions were given by more than one deed, or the time of exemption was later extended by another act. In four cases there is no information about the length of the liberty period (CM 47: 408; CM 35: 746–747; CM 70: 223–223a). Formulae of the exemption clause varied from quite general (“liberty from a contribution called schoss for 6 years”, CM 51: 216, transl. from Latin) to very detailed (“liberty from all rents, charges, contributions and levies which for us or the commonwealth were constituted or in future will be constituted”, CM 23: 215, transl. from Latin). They commonly consisted of more than one stipulation, often with a different free period for particular provisions: “liberty from the rents that they pay for their dwelling plots or houses as well as from the civil levies, commonly called schoss, and from all the other public levies and contributions that were constituted or will be constituted for 10 years; from the rents paid for fields for 4 years; from civic transport duties for three years; from the liquor tax (Pol. czopowe) for two-quarters of a year” (CM 36: 165–166, transl. from Latin).

The number of tax exemptions connected with fires between 1531 and 1540 was greater than in the earlier and later periods, although the growth by 30% was not alarming. Moreover, data show that the single year with the largest number of fires in the first half of the 16th century was not any year in the “drought decade” but 1522. Meanwhile, in

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**Figure 6.** Grain yield ratio of main crops in the royal estates. Sources: Wawrzyńczyk (1974).

**Figure 7.** Grain yield ratio in the estates of Bishops of Włocławek. Source: Żytkowski (1962).
1540, which was seen as exceptionally dry, there were only five tax exemptions related to damage caused by fire.

For the comparative analysis, we used the highest number of years of liberty granted for each incident, regardless of the concession type. In the vast majority of cases, however, the longest liberty period was granted for schoss, which was the basic tax (wealth tax) paid by burghers in Poland. Moreover, the longer the primary exemption period, the more of various stipulations were typically included. Although some municipal authorities or town owners were probably able to obtain a longer exemption or a greater number of concessions owing to better relations with the royal apparatus, it seems that those variations were not extreme and not common. Therefore, the length of the principal liberty is a good indicator of the fire severity, as it was mainly determined by the destruction caused by each incident. Using that measure, we have divided the recorded fires into three fire severity categories (FSCs) (Fig. 9). The year range of each category was related to dealing with fire, and often with the open one. It is reflected in the substantial share of municipal regulations relating to fires of the pre-industrial period with climate factors. Even short spells of extremely high temperatures, droughts and wind are described as critical causes of conflagrations in medieval and early urban centres (Mauelschagen, 2010). We argue, however, that our analyses show that there is little or no correlation between dry and hot periods of weather and the occurrence of urban fires (Fig. 11). These climate factors were not the source of conflagrations.

There were instances in which a blaze was started by a natural phenomenon, i.e. a lightning strike (e.g. Biała in 1518, CM 31: 329; Stężyca 1540, CM 57: 291); yet, fires cannot be linked with the direct influence of the climate change. In most cases, a fire was directly caused by human activity and negligence. In the CM, there are safe-conduct documents issued for burghers who were accused of starting a blaze or in whose property a fire originated (e.g. CM 37: 453v–454, CM 23: 523, CM 31: 499). Involuntary conflagrations were very common, especially as daily home activities (e.g. cooking) as well as the majority of crafts (e.g. baking, brewing, smithing, textile and leather production) were related to dealing with fire, and often with the open one. It can be concluded that in spite of a larger number of fire outbreaks, their severity was lesser than in the preceding and following decades (cf. with Fig. 10).

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As pointed out in the previous chapter, it became common to associate fires of the pre-industrial period with climate factors. Even short spells of extremely high temperatures, droughts and wind are described as critical causes of conflagrations in medieval and early urban centres (Mauelschagen, 2010). We argue, however, that our analyses show that there is little or no correlation between dry and hot periods of weather and the occurrence of urban fires (Fig. 11). These climate factors were not the source of conflagrations.

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High temperatures, low humidity and prolonged lack of rain were not among the major factors contributing to fire spread and acceleration. Weather could impact fire conditions to some extent. Garrioch points out that in northern and central Europe, raging fires broke out during winter months, when it was cold and wet (Garrioch, 2019). In his examples of Stockholm and Vienna, however, the disparity in the number and severity of fires should be attributed to a snow cover acting as a natural insulation layer rather than to simply wet conditions. Nonetheless, we, as did Garrioch, argue that the dominant element affecting the flammability of towns was the characteristic of the urban built environment. Medieval and early modern towns, especially the larger ones, were often densely built up, with the majority of urban fabric consisting of timber buildings (with wooden shingles and thatching as the most common roofing) (Shofield and Vince, 2005; Samsonowicz and Bogucka, 1986; Karpiński and Nowosiela, 2021) and large quantities of combustible materials stored on each dwelling plot (e.g. firewood, hay). Even the Polish royal capital city of Kraków is considered to be predominantly built of timber in the 16th century – houses on the plots adjacent to the main square were constructed with stones or bricks, but the greater the distance from the city centre, the more dominant wood became (Follprecht and Noga, 2014). Moreover, masonry structures commonly occupied only the front parts of the dwelling plots of European urban cen-
 tres, while their rear areas were often covered with wooden sheds; storage buildings; fences; and facilities such as kilns, hearths and ovens (Schofield and Vince, 2005; Karpiński and Nowosiela, 2021). The main role of the building materials in the combustibility of the urban fabric was recognized by municipal authorities in their ordinances. They obliged burghers to construct firewalls and prohibited storing of highly flammable materials in the towns. They also stipulated that each property had to be furnished with leather buckets and pike poles used for knocking the burning structures down to prevent the further spread of a fire as well as compelling town inhabitants to participate in firefighting (Sowina, 2002; Modrzyński, 2017; Karpiński and Nowosiela, 2021). The importance of improving the building materials was also underlined in the royal tax exemptions, with substantial extension of the liberty period for burghers willing to rebuild their property in stone or brick (e.g. Oświęcim 1519, CM 31: 501–503; Poznań 1536, CM 51: 237v–238; respectively, from 14 to 18 years and from 10 to 20 years). It should be stressed that although droughts and high temperatures may affect the flammability of timber structures, their impact on acceleration and spreading of flames is marginal – buildings and whole towns could have easily burnt down during thunderstorms accompanied by heavy rain. The only weather factor that played a critical role in the acceleration and spreading of flames was wind.

2.3 Product prices

Data on grain and beer prices in the largest Polish cities compiled by historians reflect the market situation prevailing in them. In the case of the Kingdom of Poland, the grain market, which was also the basis for beer production – the basic drink of society at the time – was a free market in which all social groups could participate. In the first half of the 16th century the Polish grain market became increasingly integrated with the European market, but in the years under review the economic base of Gdańsk (and its exports) was mainly Pomerania and its immediate neighbours: Cuyavia and Mazovia, connected to the largest Polish port by a waterway, the Vistula river (Mielczarski, 1962; Guzowski, 2011). First of all, the prices of oats and rye were taken into account (Fig. 12), i.e. the most important cereals on the Polish market, being the basic feed cereal (oats) and the main element of the human diet (rye). Oats were produced and sold on local markets, so their prices reflect the situation undisturbed by export impulses. Rye was exported to a greater extent (wheat as well), although it can be concluded that external demand in the period under review influenced only prices in Gdańsk, while prices in Kraków and Lviv represent a regional situation. In the case of the three large cities for which data are available, we can assume that the market situation in the period from 1520 to 1550 was enduring. The hottest decade is not distinguished by an exceptional rise in the prices of either rye or oats, but rather a gentle upward trend can be observed throughout the period which can be linked to an increase in demand due to population growth.

However, quarterly prices are more important for determining the seasonal fluctuations of agricultural production. For the purposes of our research, we have analysed how the value of agricultural products changed in the fourth quarter relative to the average price in the preceding quarters. An in-
crease in the prices after the harvest, when most of the crop was coming to market, would indicate a poor harvest and a definite excess of demand over supply. The data shown in the graph usually indicate the opposite situation, where prices tend to fall, with the exception of years with extraordinary increases. It should be noted at this point that in the decade from 1531 to 1540 there were no more such seasons than in the preceding and following decade; moreover, if a certain decline in production should be referred to, it occurred in different years for different regions, which means that in the case of a potential crisis in production, regional variations must be taken into account. As regards the grain prices in the case of Kraków (because the gathered prices made it possible only there), an observation was added on the price trend of pea, characterized by different weather requirements than for grain (Fig. 13). In order for pea to yield well, they had to be sown in the spring into moist, undrained soil. The prices of pea in Kraków point to a potentially successful harvest of this crop. The years 1532 and 1533 (market in Kraków, rye prices) and 1549–1550 (market in Kraków and Lviv, pea, rye, oats) are considered less fertile years.

Consequently, an upward trend in beer prices or at least a stable situation over the years 1521–1550 are by no means surprising; in Lviv, a decline can even be observed in the 1530s, although this conclusion may be distorted by the quality of data (prices recorded for only 2 years) (Fig. 12). More pronounced is the increase in the prices of wine imported to Poland from abroad (from Hungary and Germany), although even in this case, an upward trend characteristic of the entire period under consideration can be seen, in which the decade from 1531 to 1540 does not stand out (Fig. 14). On the contrary, a slight decline in prices on the large Wrocław market can be observed. At that time, the Wrocław market was dominated by the consumption of imported wine. From the mid-15th century, along with the change in Silesia’s affiliation to the monarchy of Matthias Corvinus, the share of Hungarian wines and small–medium wines imported via Hungary gradually increased, while the popularity of Alpine wines continued unabated (Myśliwski, 2009). To a small extent, domestic wines were present on the market, as most of the crops had already declined in the 15th century. Single vineyards (near Środa Śląska or near Wrocław) satisfied only liturgical needs, and most wine found its way to the tables of monasteries (Adamska, 2017). The decade from 1531 to 1540 also saw stable wine prices at a level not exceeding 2 grosze per 1 quart. What is more, a slight decline in prices in the years 1532–1536 can even be observed, along with an equally slight increase in subsequent years (Wolański, 1996).

2.4 Polish grain exports in Gdańsk

In the 16th century Gdańsk was a monopolist in the exports of Polish products to the west of Europe, participating successfully in international trade and maintaining close contacts with the main Dutch and English centres (Bogucka, 1970). The city benefited from the fact that Poland of the 16th century became the “granary of Europe”, which means that most of the grain arriving in Gdańsk down the Vis-
tula river was traded on the markets of western Europe (Batou and Szlajfer, 2010; Samsonowicz, 1956). Apart from grain (mainly rye), the Gdańsk market also exported industrially important raw materials (wood, ash, tar, pitch, wax and wool). Unfortunately, for the first half of the 16th century only rudimentary data are available on the volume of Polish grain exported by Gdańsk, although it seems that from the end of the Middle Ages there was an upward trend (Fig. 15).

Slightly more information on the development of trade contacts between the ports of the south-eastern Baltic is provided by the registers of the Sundtolls recording the number of ships from individual ports crossing the Danish straits (Ellinger and Korst, 1906) (Fig. 16). In the fourth decade of the 16th century, despite a visible slump in 1540 (and the following year), on average slightly more ships sailed annually from Gdańsk and Ducal Prussia than in the earlier and later periods. Thus, a decade-long crisis in trade cannot be referred to based largely on agricultural products, although the crisis years of 1540–1541 certainly stand out in a negative fashion. A similar trend is also evidenced by the registers of the water chamber in Włocławek, surviving from 1537. They too imply a decline in both the number of ships and their capacity after 1540 (Fig. 17).
3 Conclusions

Narrative texts, which have so far been used in many works on historical climatology, should not be used as the only indicator for studying the resilience of ancient societies to weather and climate change. By using different series of economic data we were able to show that the former economy of the Polish lands, based mainly on the production and exports of cereals, coped quite well with periods of drought in the decade from 1531 to 1540. The set of individual phenomena captured in the Brázdil et al. (2020), and coming from different places in Europe at the time, did not allow us to find the potentially fundamental economic changes that could have been triggered by the prolonged periods of drought at the time. In this dimension, the research presented here complements significantly the picture obtained by previous researchers and shows that a macroeconomic analysis of the available historical data can provide a slightly different perspective on the issues of the long-term consequences of climate extremes in the past. Written sources recording the condition of the core branch of the preindustrial Polish economy do not show signs of any particular agricultural crisis in the “drought decade”. It can be explained by the fact that the most commonly grown and consumed crops were rye and oats, which are resistant to difficult winter conditions and dry weather (winter rye in particular). Additionally, winter rye has a well-developed root system (up to 2.5 m), and its greatest demand for water occurs in April–May, when the soil usually has horizontal water reserves; therefore it is resistant to short-term droughts. Neither of the cereals requires good soils or much manure, either. This made it possible not only to obtain relatively high yields, but also to better manage the valuable manure, which could then be used to enrich wheat, barley or garden crops with nutrients.

The climate in the regional (mesoscale) or local scale, i.e. the one directly affecting human activity, can be significantly modified by many factors. Some of them are independent of humans, such as the proximity of water reservoirs, height above sea level or topography, while an important anthropogenic factor is human modification of land cover. In turn, the land cover significantly affects the local, regional and global water and energy balance at the land surface (Foken,
2008) and thus the surface and air temperature, the rate of evapotranspiration, and, indirectly, the amount of precipitation. For instance, according to model studies, deforestation in temperate regions amplifies the diurnal temperature variation and increases the mean and maximum air temperature and annual precipitation, and afforestation has the opposite effect (Alkama and Cescatti, 2016; Perugini et al., 2017). Also, undrained wetlands will have different thermal properties than drained and cultivated lands. Considering it, the type of land cover and the way it was used in regional scale may be of great importance in buffering or deepening meteorological drought, which is a very complex and difficult topic, and therefore underestimated. That the pre-industrial landscape had a buffer character is evidenced by numerous maps dating from the late 18th and early 19th centuries. The presence of large areas of species-diverse forests and numerous (and undisturbed) peatlands and wetlands resulted in water being retained in the environmental cycle. This probably made it easier for ancient societies to cope with the consequences of upcoming droughts.

Concerning the historical sources the system based mostly on lump-sum levies in individual tax categories was not too burdensome for peasants, gentry or clergy. It left quite a lot of money on the market, allowing the accumulated capital to be effectively used on local markets and providing a sufficiently large economic security in case of possible crises.

Our observations have also shown that the automatic linking of dry periods with urban fires present in the literature is a gross oversimplification of the situation at the time. Previous researchers writing on the subject have not taken into account several of the obvious issues with the functioning of cities and towns in the Middle Ages and early modern times in the context of the history of material culture, e.g. the type of construction material from which the buildings were made. Observations made on the basis of a series of detailed data preserved in the CM indicate that there was no relationship between droughts and the occurrence of town fires. But does this mean that droughts did not cause fires during dry periods? They did, but first of all, people were to blame for the outbreak of fires in urban centres, and next, nature could be blamed (e.g. the outbreak of fire in the city or town due to lightning). The weather conditions could have a much stronger impact on non-urban fires – forests, fields and meadows; yet, at this stage of the research into this topic, quantitative evidence is lacking.

It must also be added that the only crisis actually visible in the collected source material concerns the consequences related to the drought of 1540. In our opinion, this opens up completely new possibilities of interpretation related to this event, and potential new research questions should be asked about how the extreme weather events of 1540 affected the economic stability of Europe in the long term. Our research has also shown that in-depth economic analyses inspired by climatological studies make it possible to better understand the complex relationship between humans and the environment in the past.

Appendix A: Archival sources

| AS 1 | – Ratio facta cum omnibus exactoribus de omnibus et singulis actionibus publicis [1533] in AGAD, Archiwum Skarbu Koronnego I 35, ff. 202–255.
| AS 2 | – Ratio facta cum omnibus exactoribus de omnibus et singulis actionibus publicis [1535] in AGAD, Archiwum Skarbu Koronnego I 2, ff. 145–166.
| AS 3 | – Suscpcio racionum ab exactoribus Regni anni Domini 1543 in AGAD, Archiwum Skarbu Koronnego I 61, ff. 766–805.
| AS 4 | – Kings’ tax exemption privileges in AGAD, Metryka Koronna (Crown’s Metric), No. 23, 24, 25, 26, 28, 30, 31, 35, 36, 38, 39, 40, 42, 46, 47, 48, 49, 50, 51, 52, 61, 63, 70.
| AS 5 | – Sochaczew tax register from 1496 in AGAD, Archiwum Skarbu Koronnego I 48, ff. 49–53.

Data availability. The data collected during the preparation of the article are drawn from already published monographs or archival sources cited in this study. All data are stored by Tomasz Związek and Piotr Guzowski.

Author contributions. TZ and PG designed the study. RP provided the statistical analysis and prepared all statistical graphs. TZ, PG, MTR, MKS, MT and DA provided the historical analysis. TP prepared all cartographical figures. SS and BK supplemented the text with regard to the soil and climate context. All authors discussed the methods and results and commented on the paper.

Competing interests. The contact author has declared that neither they nor their co-authors have any competing interests.

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