



# Public granaries as a source of proxy data on grain harvests and weather extremes for historical climatology

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**Abstract.** Public granaries served as key infrastructure to improve food security in agrarian societies. Their history dates to the oldest complex societies, but they experienced a boom period during the 18th and early 19th centuries in Europe. In Bohemia and Moravia (modern-day Czech Republic), numerous granaries were established by decree in 1788 to provide serfs with grain for sowing in the face of fluctuating weather. Here, we analyse granary data from 15 out of a total of 17 considered domains in the Sušice region (southwestern Bohemia) from 1789 to 1849 CE. We use the documented annual values of grain borrowed by serfs, their grain depositions, total grain storage, and the total debt of serfs at the end of the year as proxies for harvest quality and size. Based on the series of these four variables, we calculate weighted grain indices, considering the balance between borrowed and returned grain: a weighted bad harvest index (WBHI), a weighted good harvest index (WGHI), a weighted stored grain index (WSGI: WSGI<sup>-</sup>, more borrowed than returned; WSGI<sup>+</sup>, more returned than borrowed), and a weighted serf debt index (WSDI: WSDI<sup>+</sup>, more borrowed than returned grain; WSDI<sup>-</sup>, more returned than borrowed grain). WBHI, WSGI<sup>-</sup>, and WSDI<sup>+</sup> were used to select years of extremely bad harvests, while WGHI, WSGI<sup>+</sup>, and WSDI<sup>-</sup> were used to identify years of extremely good harvests. We tested selected extreme harvest years against documentary weather data and reconstructed temperature, precipitation, and drought series from the Czech

Lands. We discuss the uncertainty in the data and the broader context of the results obtained. The findings document the potential of this new methodology using widely available public granary data as proxies for historical climatological research.

## 1 Introduction

Past agrarian societies were vulnerable to weather and climatic patterns that influenced the annual agricultural cycle (Brázdil et al., 2019b), as reflected in the quantity and quality of agricultural production (e.g. Jones, 1964; Brunt, 2015; White et al., 2018a; Skoglund, 2023; Martínez-González, 2025). The production of grain, the main source of caloric energy in Europe, was particularly crucial for food security. Any deficit in grain production had substantial knock-on effects on the wider economy (e.g. Wrigley, 1989; Edvinsson, 2012; Esper et al., 2017; Rácz, 2020). Due to limitations in trade and transport, the impacts of harvest fluctuations were often local and regional. In combination with economic, societal, and political stress, shortfalls could potentially result in social unrest or even famines (e.g. Campbell, 2009; Campbell and Ó Gráda, 2011; Brázdil et al., 2018; Huhtamaa, 2018). Adverse weather and its extremes could affect the entire cereal growing cycle from sowing to harvest (e.g. Petr, 1987; Brázdil et al., 2019b; Trnka et al., 2023; Skoglund,

2024). Extended wet or dry periods during autumn could negatively influence the sowing of winter crops (wheat, rye), extreme winter and late spring frosts could cause frost damage, and mild and overly wet conditions could lead to rotting crops. Spring crops (barley, oats) were vulnerable to prolonged snow cover, frost, and cold temperatures. Both overly wet or dry conditions could complicate their sowing, growing, blossoming, and ripening. Furthermore, wet conditions during the grain harvest could impede and delay fieldwork while also increasing potential losses during storage (e.g. Petr, 1987; Eitzinger et al., 2013).

The quantity and quality of grain harvests were especially reflected in fluctuations in grain prices, despite many other socio-economic and political factors influencing their final value (e.g. Petráň, 1977; Scott et al., 1998; Ljungqvist and Seim, 2024). Generally, good grain harvests were followed by lower prices and poor harvests by higher prices. The complex relationship between weather and climate, harvests, and grain prices has long been studied, primarily in local, regional, or national settings (e.g. Pfister, 1988; Hildebrandt and Gudd, 1991; Bauernfeind and Woitek, 1999; Brázdil and Durd'áková, 2000; Holopainen et al., 2012; Camenisch, 2015; Huhtamaa et al., 2015; Yin et al., 2015; Pribyl, 2017; Skoglund, 2022; Brázdil et al., 2024a). In recent years, several studies have explored this connection on a broader territorial scale. These studies investigated European cases, examining environmental drivers of fluctuations in historical grain prices (Esper et al., 2017), climate variability and grain prices (Ljungqvist et al., 2022), and climatic signatures in grain harvest yields (Ljungqvist et al., 2023). Moreover, the latter study emphasized the importance of research analysing the relationships between grain quantity and quality, their links to climate, and the subsequent effects on grain prices in historical contexts.

As reduced or failed harvests affected large parts of society, measures to avoid shortages and famine became a crucial part of administrative planning. The establishment of granaries had been a popular instrument for safeguarding against fluctuations since antiquity (e.g. Gast and Sigaut, 1979; Morales et al., 2014; Salido Domínguez, 2016). In the early modern period, this security infrastructure expanded in line with the ambitions of administrations. They not only addressed food security issues but also supplied the military and growing cities while providing governments with some control over the crucial food market. As such, they linked ecological factors with military, economic, and social concerns (Collet, 2010). Some polities, such as the Inca Empire, early modern China, or 18th-century Prussia, can be understood as veritable “granary states” centred around staple economies (e.g. Liu and Fei, 1978; Will and Wong, 1991; Polanyi, 2018; Shiue, 2024). In Europe, public granaries rose in prominence throughout the 18th century (see, e.g. Franko, 1907, for the former region of Galicia – now part of Poland and western Ukraine; Černý, 1932, for the Czech Lands; Kaplan, 1977, and Meuvret, 1977, 1987, 1988, for France;

Teerijoki, 1993, for Finland; Berg, 2007, for Sweden; Collet, 2010, for Prussia; Seppel, 2019, for Russia; and Løvdal, 2020, for Norway). Eventually, improved transportation during the late 19th and early 20th centuries allowed grain storage to be moved out of cities, dispersed, and gradually privatized (Collet, 2010).

So far, public granaries in Europe have been studied from historical, socio-economic, technological, and political perspectives. This paper, however, focuses on the use of granary records as proxies for the study of poor and abundant grain harvests and their relationships to weather and climatic factors. Based on public granary data from southwestern Bohemia (in the modern-day Czech Republic) for the period 1789–1849 CE, we argue that such widely available data provide a valuable new source of information for historical climatological research.

## 2 Data

### 2.1 The regional setting

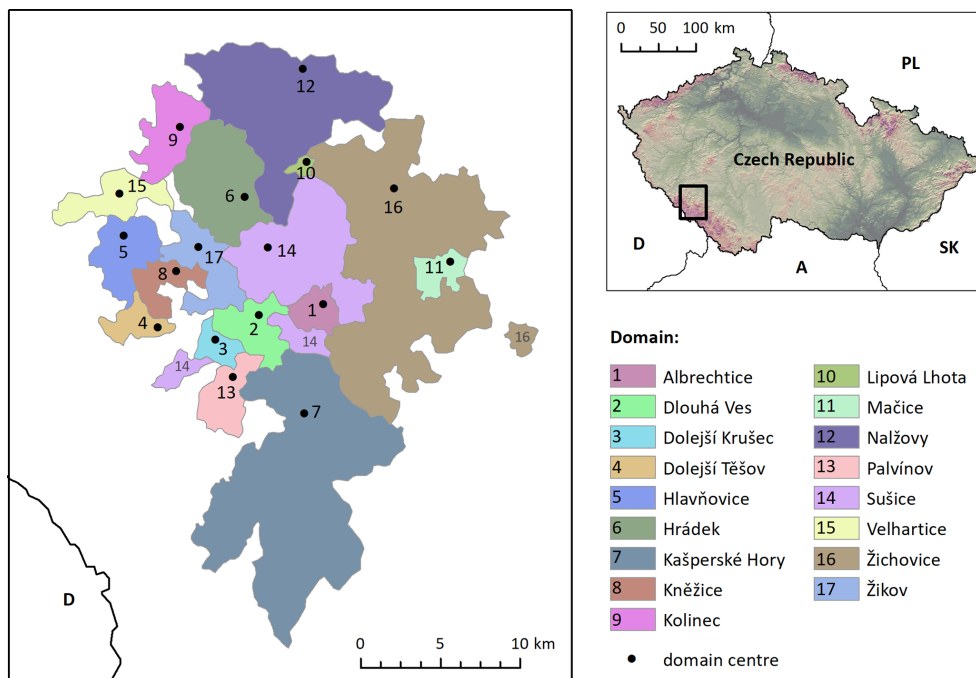
The town of Sušice in southwestern Bohemia was used for a detailed analysis of the relationships between grain prices and weather and climate effects during the period 1725–1824 CE by Brázdil et al. (2024a). Due to the rich regional record of historical and documentary weather and climate evidence, a broader area around this town was selected as the target region for analysing grain data from public granaries (Fig. 1). The excerpted data from the granaries pertain to a total of 17 domains (Table 1), representing 168 settlements or their parts and 30 305 inhabitants, covering an area of approximately 448.87 km<sup>2</sup> (the smallest being 1.44 km<sup>2</sup> for Lipová Lhota and the largest 101.31 km<sup>2</sup> for Žichovice). This region lies within the broader foothills of the Šumava mountains, spanning a wide altitudinal range from ca. 440–1140 m a.s.l. According to the Köppen climatic classification, this region falls under the Cfb type, i.e. temperate broadleaf deciduous forest, with mean annual temperatures ca. 6–8 °C and mean annual precipitation totals of ca. 550–700 mm (Tolasz et al., 2007). In terms of grain production, the main cereals grown in the studied area and period were rye and oats, while barley and particularly wheat were cultivated to a lesser extent.

### 2.2 Public granary data

Although public granaries (*kontribuční sýpky*) already existed in the Czech Lands (Vodnařík, 1886; Krofta, 1949), their systematic establishment in the Kingdom of Bohemia and the Moravian Margraviate followed the official patent no. 241 issued by Emperor Joseph II on 9 June 1788 (Kalousek, 1910; Fig. 2a). This decree was part of a broader European discussion on this infrastructure, which emerged in response to the climatic shocks of the 1770s and 1780s and connected to the Emperor's “grand plan” to reform agriculture (Pfister

**Table 1.** Basic information about the analysed domains in the Sušice region of southwestern Bohemia from the 1830s according to Sommer (1839, 1840). The altitude range represents the altitudinal interval of the corresponding villages in each domain. The number of villages also includes their parts when a village belonged to two domains. An “x” is used to indicate that the grain fund of the domain was not created.

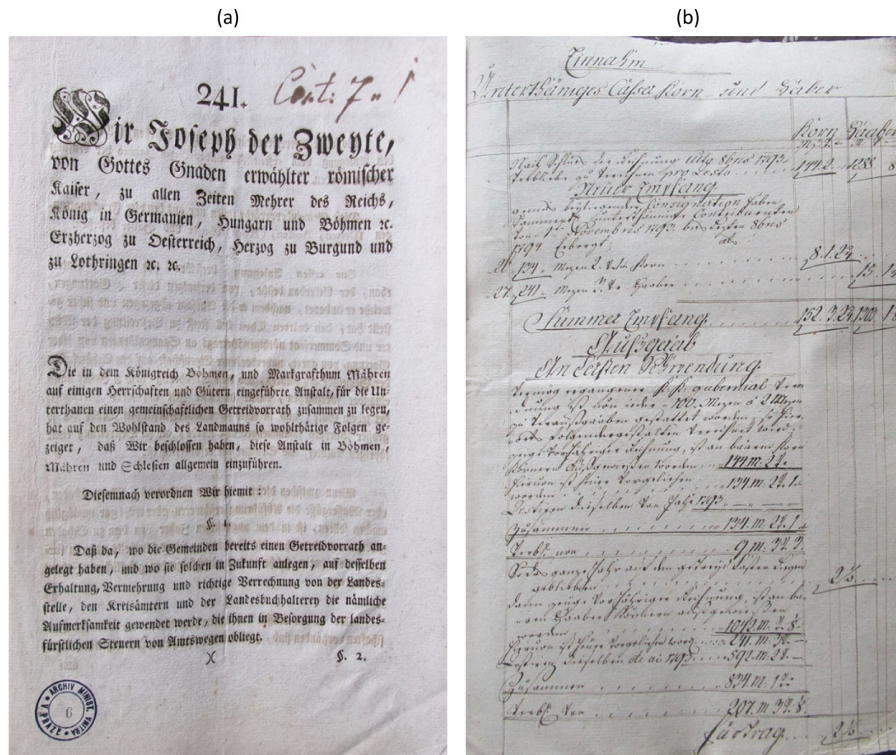
Name	Area (km <sup>2</sup> )	Altitude range (m)	Number of villages	Number of inhabitants	Granary records	Archival source
Albrechtice	6.58	504–714	5	393	1794–1845	AS8
Dlouhá Ves	8.42	512–600	3	904	1792–1849	AS13
Dolejší Krušec	3.52	621–657	4	404	x	AS19
Dolejší Těšov	4.89	737–876	4	316	1808–1839	AS20
Hlavňovice	12.12	610–790	10	871	1792–1848	AS10
Hrádek	27.53	485–793	10	989	1789–1849	AS11
Kašperské Hory	97.32	563–1144	26	4593	1810–1849	AS9
Kněžice	7.43	547–820	6	612	1805–1849	AS12
Kolinec	17.74	545–737	5	1472	1789–1849	AS7
Lipová Lhota	1.44	555	1	74	x	AS14
Mačice	6.80	567–652	3	583	1794–1849	AS15
Nalžovy	68.14	458–584	20	4941	1789–1848	AS6
Palvínov	12.44	520–770	10	954	1792–1849	AS16
Sušice	46.18	465–778	14	3327	1786–1844	AS18
Velhartice	12.24	622–705	4	651	1791–1849	AS21
Žichovice	101.31	442–1014	30	8185	1789–1845	AS17
Žikov	14.77	504–737	13	1036	1816–1845	AS22



**Figure 1.** The investigated Sušice region in southwestern Bohemia, consisting of 17 individual domains with available public granary data and its position within the Czech Republic. Abbreviations are as follows: A is Austria, D is Germany, PL is Poland, and SK is Slovakia.

and Brázdil, 2006; Collet, 2019). However, the main purpose of these new granaries was no longer general food security or supplying the military. Instead, they specifically aimed to secure seed grain for serfs, a focus that significantly reduced the impact of political interference. The emperor drew

upon existing voluntary systems in some domains to mandate the establishment of obligatory so-called crop funds in each domain from 1 November 1788. This support for serfs was driven more by concerns for the stability of the empire’s tax base than by humanitarian goals (Černý, 1932).



**Figure 2.** (a) Title page of patent no. 241 issued by Emperor Joseph II for the establishment of public granaries in the Czech Lands (Národní archiv, České gubernium – contributionale, karton č. 1580) and (b) an example of granary records from the Hrádek domain (AS11, karton č. 1586).

In theory, each peasant was annually required to transfer an amount equal to one-third of the seed grain needed for each type of cereal. In case of damage caused by a natural disaster, peasants could borrow grain from the crop fund created by these deposits, with the obligation to return it after the next harvest along with an interest rate of 12.5%. These transactions were documented in special accounts attached to the regular granary reports for each domain. These reports were sent to the regional office and then to the Czech government (*Gubernium*), where they have usually been preserved to the present day.

The reality often looked somewhat different. Granaries were dynamic institutions where a range of interests overlapped and competed. The establishment of the crop funds often took several years to implement. The serfs had to cover the building costs, some estate owners were slow to respond to the decree, and the required amounts of surplus grain were hard to come by (Prasek, 1904). In addition, the intended volume of annual deposits and the level of interest proved unrealistic. Already in 1793 CE, deposits were reduced to one-twentieth of the required seed grain, and the interest for loans was dropped to 6.25% (in Moravia, interest was decreased to the same level as late as 1812). This was in response to the corn funds remaining incomplete for years, being loaned out in full, or only existing on paper in the first place. The

hardship brought by the Napoleonic Wars exacerbated this problem. The Czech *Gubernium* intensified oversight and reminded overseers to require the prompt return of loans to avoid desperate serfs falling into spiraling debt. Later, it emphasized lending grain only to dependable applicants and requested constant updates on the movement of crop funds. It also asked for relief on interest payments to be documented individually at the level of individual domains. Not least, the fluid agricultural ecology often corresponded imperfectly with administrative requirements, as late harvests and threshing dates into November could jeopardize annual deposits (for example, in Albrechtice – archival source AS8).

Cereal cultivation and record keeping often remained mismatched. Rye and oats dominated the granary records in southwestern Bohemia, barley was reported for six domains, and wheat was only reported for the Mačice domain and partly for the Žichovice domain. Granary accounts for these crops were kept according to the military year (from 1 November of the preceding year until 31 October of the current year), and measurements were recorded in Lower Austrian units: *měřice* (1 *měřice* = 61.49 L), *věrtel* (1 *věrtel* = 15.37 L), and *měřička* (1 *měřička* = 3.84 L). During this time, interest was added to borrowed grain, while annual storage losses (due to pests, humidity, technical faults at the granary, etc.) were subtracted. The resulting quantities of



borrowed and returned grain were recorded in account supplements, which listed the total loans and interest due from serfs. Together with the quantity of grain present in the granary, these figures were entered into the accounts as the value of cereal at the end of the military year. In hindsight, it is precisely because rather than in spite of these practical challenges that the granary records are so rich and valuable today.

### 2.3 Weather, climate, and harvest data

Weather and its extremes were taken from the internal historical–climatological database of the Institute of Geography, Masaryk University, Brno, with a particular focus on records from southwestern Bohemia, and further complemented by other local documentary evidence such as chronicles from the studied area and regular reports from the I. R. Patriotic Economic Society of Bohemia between 1822–1847 CE (Resultate, 1828; Neue Schriften, 1830–1847; Verhandlungen und Mitteilungen, 1849, 1850). These records also contain annual information related to agriculture and grain yields for some selected domains or locations.

Climatic patterns in the region, analysed for 1789–1849 CE, were based on long-term series reconstructed for three basic climatic variables for the territory of the Czech Lands since 1501 CE:

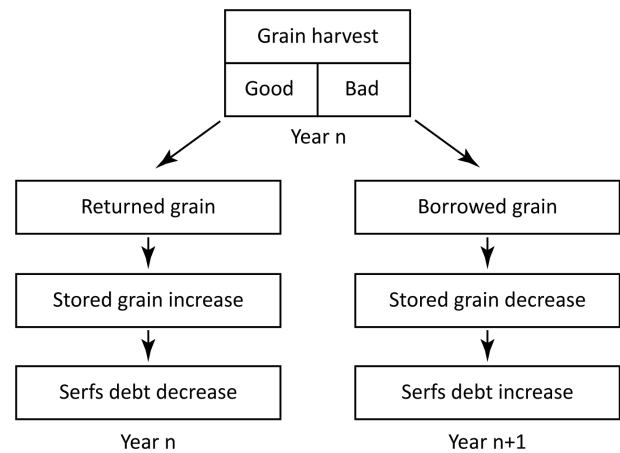
- i. the temperature series of central Europe, reconstructed from documentary-based temperature indices of Germany, Switzerland, and the Czech Lands (1500–1854 CE) and mean temperatures from 11 central European stations (from 1760 CE onwards) by Dobrovolný et al. (2010), which is fully representative of the Czech territory (see Brázdil et al., 2022);
- ii. the precipitation series of the Czech Lands, reconstructed from documentary-based precipitation indices (1501–1854 CE) and mean areal precipitation totals (from 1804 CE onwards) by Dobrovolný et al. (2015);
- iii. the self-calibrated Palmer drought severity index (scPDSI) of the Czech Lands calculated by Brázdil et al. (2016a) from temperature (Dobrovolný et al., 2010) and precipitation (Dobrovolný et al., 2015) reconstructions.

## 3 Methods

For the purposes of this study, the following four annual grain variables collected from domain granary records (Sect. 2.2) were selected.

### (i) Quantity of borrowed grain

The quantity of borrowed grain for sowing in the current year primarily reflected a poor grain harvest or its failure in



**Figure 3.** Scheme of relationships between the four grain variables from the granary records.

the preceding year. However, it could also include grain borrowed for new spring sowing when winter cereals had perished due to an unfavourable winter.

### (ii) Quantity of returned grain

The quantity of returned grain indicated a good harvest in the current year.

### (iii) Quantity of grain stored in the granary at the end of the year

The quantity of grain stored in the granary at the end of the current year represented a balance between the quantities of borrowed and returned grain. An increase in the annual grain quantity indicated a good harvest in the current year and vice versa.

### (iv) Total debt of serfs at the end of the year

The debt of serfs at the end of the current year reflected not only the balance between the quantities of borrowed and returned grain in that year but also the cumulative debt from preceding years.

The simplified relationships between the four variables (i)–(iv) are shown in Fig. 3. A poor harvest in year  $n$  forced serfs to borrow grain for sowing in year  $n + 1$ . If the harvest in year  $n + 1$  did not allow them to return the same quantity or more, it was reflected in a reduced quantity of grain stored, which also contributed to an increased debt for the serfs. On the other hand, a good harvest in year  $n + 1$  could lead to an increase in stored grain and a reduction in serf debt. Similarly, a good harvest in given year  $n$  would result in an increased quantity of returned grain in the same year, contributing to more grain stored in the granary and a decreased debt for the serfs.

Only 15 out of a total of 17 considered domains that had available data on grain variables (i)–(iv) for a sequence of years were selected for further analyses. To select years of extreme harvests, the series of four variables for each corresponding domain were detrended using a high-pass filter. The overall arithmetic mean and standard deviation of these detrended series were then used to select years with extreme grain harvests for each domain, applying thresholds defined by the mean plus multiples of the standard deviation, ranging from 0.5 to 5.0 in 0.5 steps for the corresponding variables (i)–(iv). Since individual domain records were not preserved for each year of the 1789–1849 CE period, the harvest extremeness of years for all 15 domains together was described by involving different weighted grain indices. These indices were calculated as the sum of the highest multiples of the standard deviation (from 0.5) achieved during a particular year across all domains, divided by the number of domains that had any related (non-missing) data for that year. By applying this method to the four grain variables, the following four types of weighted grain indices were obtained:

- i. weighted bad harvest index (WBHI),
- ii. weighted good harvest index (WGHI),
- iii. weighted stored grain index (WSGI: WSGI–, more grain borrowed than returned; WSGI+, more grain returned than borrowed),
- iv. weighted serf debt index (WSDI: WSDI+, more grain borrowed than returned; WSDI–, more grain returned than borrowed).

Combining the above indices allowed for the identification of years corresponding to bad or good harvests. These years were then cross-referenced with available documentary evidence on weather and harvest conditions related to the Sušice region in southwestern Bohemia or other more distant areas in Bohemia. Three climatic variables during bad and good harvest years were used as causal factors in a composite analysis (von Storch and Zwiers, 1999; Li and Dolman, 2023). This analysis was applied to groups of selected bad and good harvest years, with the associated seasonal temperature, precipitation, and scPDSI patterns for rye, barley, and oats presented in box plots (including the median, upper and lower quartiles, maximum, and minimum). To demonstrate statistically significant differences between the climate variables in bad and good harvest years, a *t* test for means, a median test, and a *F* test for variances were all applied (Higgins, 2004).

## 4 Results

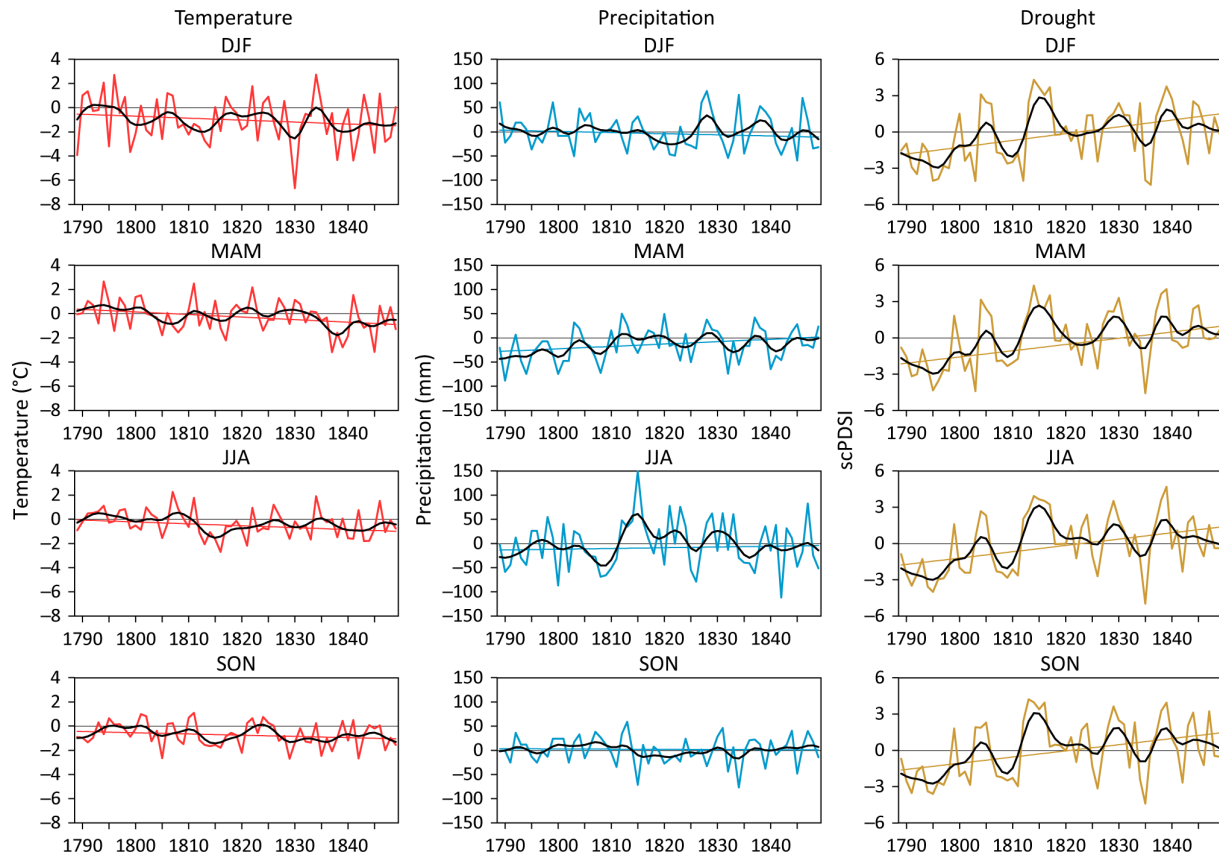
### 4.1 Climatic patterns in 1789–1849

Temperature, precipitation, and drought (expressed by scPDSI) series for the Czech Lands during the 1789–1849 CE period were used to describe the climatological

background of grain production. These three climate variables were analysed for all seasons due to the impact of weather patterns on both winter and spring crops throughout the growing cycle, from sowing to harvest. Their seasonal fluctuations, along with linear trends, are shown in Fig. 4. Linear trends were calculated using the non-parametric Theil–Sen method, which is generally robust against outliers in time series (Sen, 1968; Theil, 1992). To determine the presence of statistically significant linear trends, the non-parametric Mann–Kendall test was applied (Mann, 1945; Kendall, 1975). Despite substantial inter-annual variability in the seasonal climate series, the identified linear trends were not uniform. Temperature series showed a cooling tendency (decreasing trends) for all seasons, but these trends were statistically significant only for spring (MAM;  $-0.21\text{ °C}/10\text{ years}$ ,  $p < 0.05$ ) and summer (JJA;  $-0.16\text{ °C}/10\text{ years}$ ,  $p < 0.10$ ). For precipitation totals, winter (DJF) and autumn (SON) showed small decreasing trends, while MAM and JJA showed increasing trends (with the MAM increase being significant:  $4.9\text{ mm}/10\text{ years}$ ,  $p < 0.05$ ). Despite these mixed trends, all seasons showed statistically significant increases in wetness, as expressed by the scPDSI, even with significance at the  $p < 0.01$  level. The fluctuations in these three climate variables indicated a shift from generally warmer and drier conditions to cooler and wetter patterns around 1810 CE.

### 4.2 Grain harvest proxies in 1789–1849

Because the quantities of borrowed, returned, and stored grain in granaries, along with the debt of serfs (see Sect. 3), for individual domains typically covered different numbers of years during the 1789–1849 period, Fig. 5 shows the annual number of domains for which related data were available. Of the 17 considered domains (see Table 1), no granary data were available for Dolejší Krušec and Lipová Lhota. The slow increase in the number of domains with available data reflects the initial challenges in implementing the executive instructions for granary creation following the publication of the emperor's patent on 9 June 1788. This gradual increase in data availability varied in duration; for example, data on borrowed grain became consistently available for at least 10 domains by 1809 CE (Fig. 5a), while debt owed by serfs had reached this threshold by 1810 CE (Fig. 5d). In contrast, data on returned grain remained scarce for up to five domains until 1823 CE (Fig. 5b). The best-covered period for both borrowed and returned grain occurred between 1832 and 1845 CE, with data available for 10 or more domains. Records of stored grain were well covered from 1825 to 1845 CE (Fig. 5c), and records of serf debt were consistently available between 1810 and 1848 CE (Fig. 5d). However, data for the final years of the period, 1846–1849 CE, again became scarce. The trends described primarily concern data on rye and oats, the two dominant cereals. Only fragmentary data were recorded for barley, with records from



**Figure 4.** Fluctuations and linear trends in mean winter (DJF), spring (MAM), summer (JJA), and autumn (SON) temperatures; precipitation totals; and scPDSI in the Czech Lands during the 1789–1849 CE period. The values are presented as deviations relative to the 1961–1990 reference period and smoothed using a 10-year Gaussian filter.

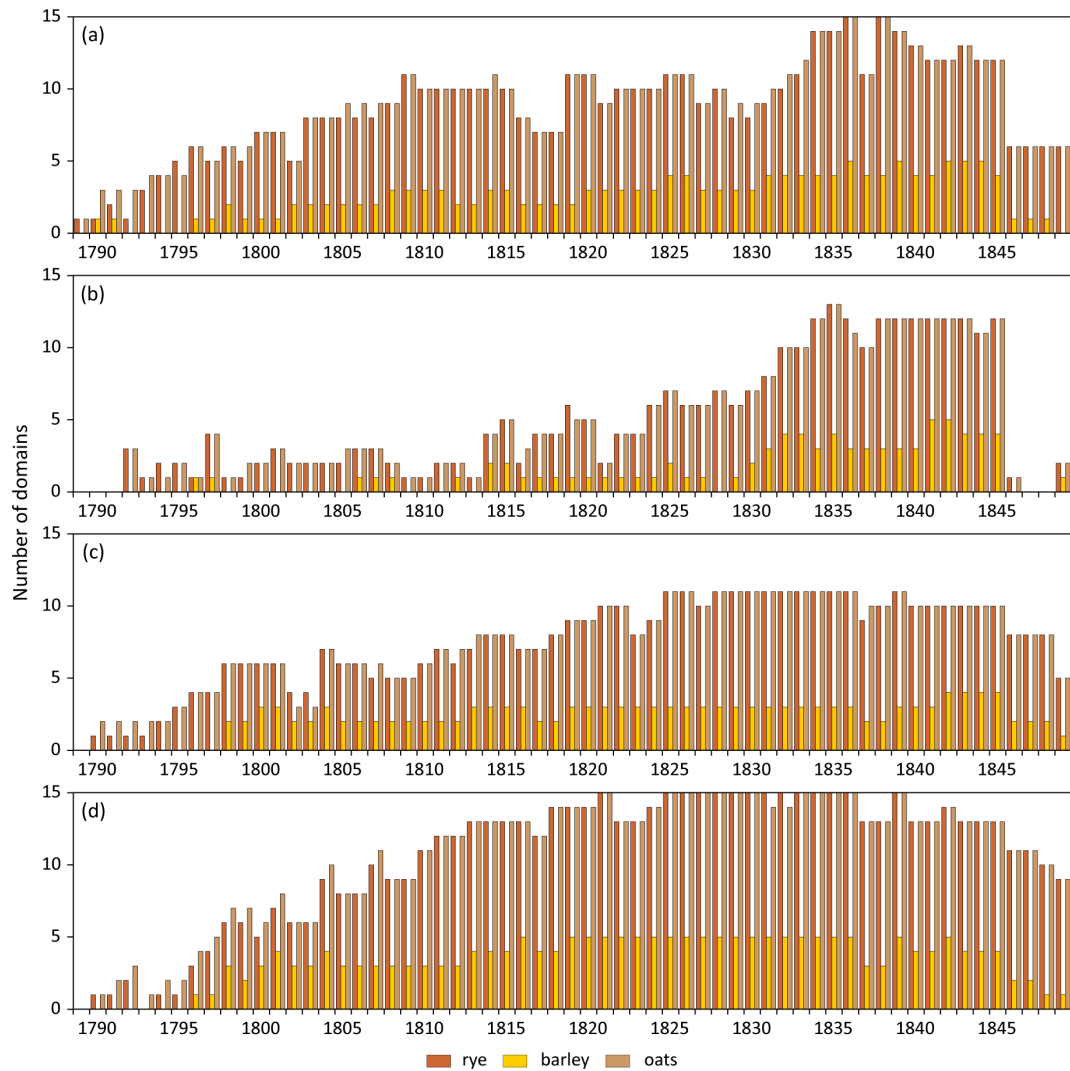
either none or fewer than five domains. Continuous data for five domains related to barley were available only for serf debt between 1819 and 1836 CE (Fig. 5d).

### 4.3 Selection of extreme harvest years

To select years of extreme grain harvests in the entire Sušice region during the 1789–1849 CE period, different annual weighted grain indices for each of the four selected grain variables were calculated based on the methodology described in Sect. 3. Bad or failed grain harvests were indicated by the weighted bad harvest index (WBHI), a decrease in the weighted stored grain index (WSGI–, i.e. more grain borrowed than returned), and an increase in the weighted serf debt index (WSDI+, i.e. more grain borrowed than returned). Figure 6 shows significant inter-annual variability in the three indices of bad harvests, with varying degrees of overlap between their local peaks. Missing or zero values appeared particularly often in the early years following the establishment of public granaries, and this trend is most evident for barley, which is represented by data from only six domains. Table 2 presents, for all three indices ( $\geq 0.5$ ), the individual years indicating poor grain harvests, along with the number of do-

main for which data were available in the given year. While some extreme years were reflected in all three indices, others were expressed via two indices (often WSGI– and WSDI+), while many were indicated by only one index. Years identified from a higher number of domains indicate greater regional representativeness of poor harvests compared to those derived from a smaller number of domains, which may reflect more localized prominence.

The overview of bad grain harvest years in Table 2 can, in some cases, be complemented by short notes from granary records that report bad harvests in connection with the effects of adverse weather. For example, records from the Albrechtice domain for 1796 CE mentioned that “oats were burned due to great heat” (AS8). The following short remarks concerned grain returns to the granary of the Hlavňovice domain: “No grain was returned due to weather damage.” (1797 CE); “Nothing returned due to low yield and many in-kind batches.” (1799 CE); “Nothing returned due to poor [grain] growth and bad harvest.” (1801 CE) (AS10). A similar report was noted in the Kolinec domain in 1797 CE (AS7): “Serfs returned nothing this year due to bad weather.” In 1802, serfs in the Velhartice domain were affected by



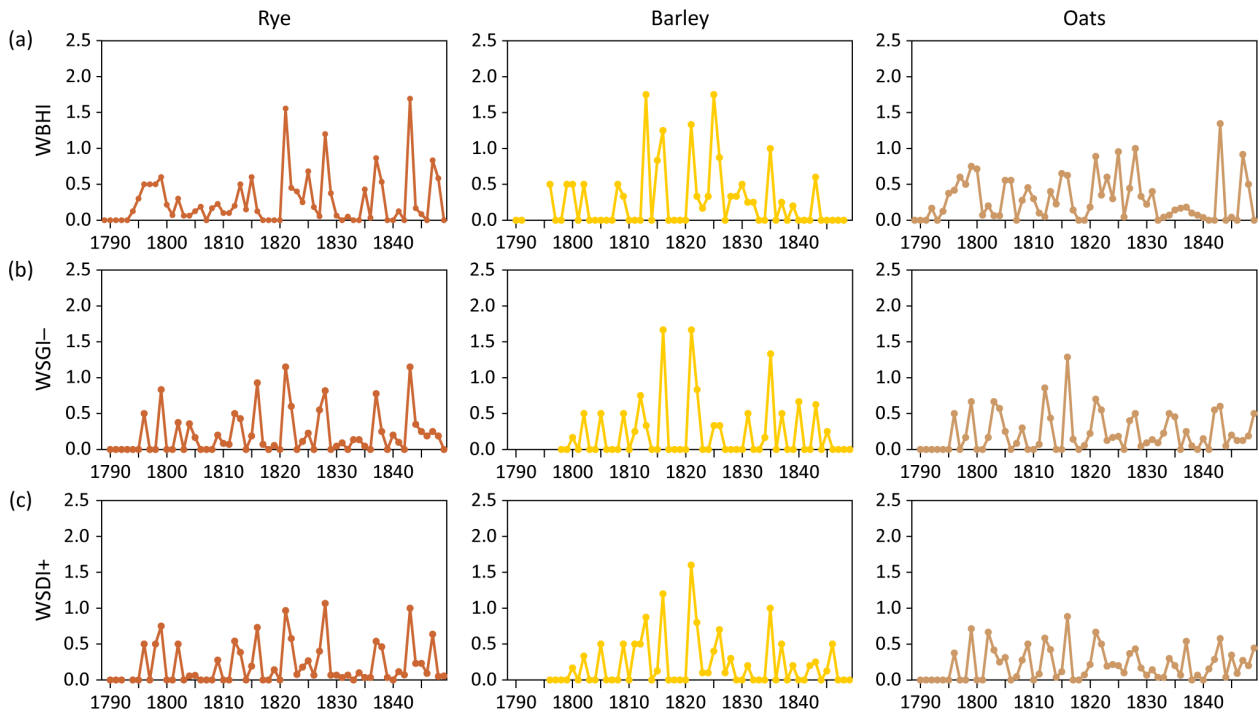
**Figure 5.** Annual numbers of individual domains with available granary data, structured according to individual cereals (rye, barley, oats) in the Sušice region during the 1789–1849 CE period: **(a)** borrowed grain, **(b)** returned grain, **(c)** stored grain, and **(d)** debt of serfs.

strong hail (*Wetterschlag*) and returned no grain to the granary (AS21). The granary records from the Žichovice domain reported four instances of “damage due to weather” – from hailstorms: in 1803, on 21 August 1806, on 16 August 1808, and in 1812 (AS17). A bad grain harvest was also mentioned in the granary notes of the Dlouhá Ves domain for 1828 CE (AS13): “Bad harvest this year, serfs could not return grain borrowed in the spring, and after autumn sowing, they had only a minimum to eat; oats went bad due to wet weather.” In 1844 CE, in the Albrechtice domain “the harvest was very bad, accompanied by wet weather, so that serfs were not able to cover their own needs from their yields and had to buy grain” (AS8). A bad harvest also occurred in the following year in 1845 when “serfs had to buy grain at high prices to cover [their] grain debt” (AS8).

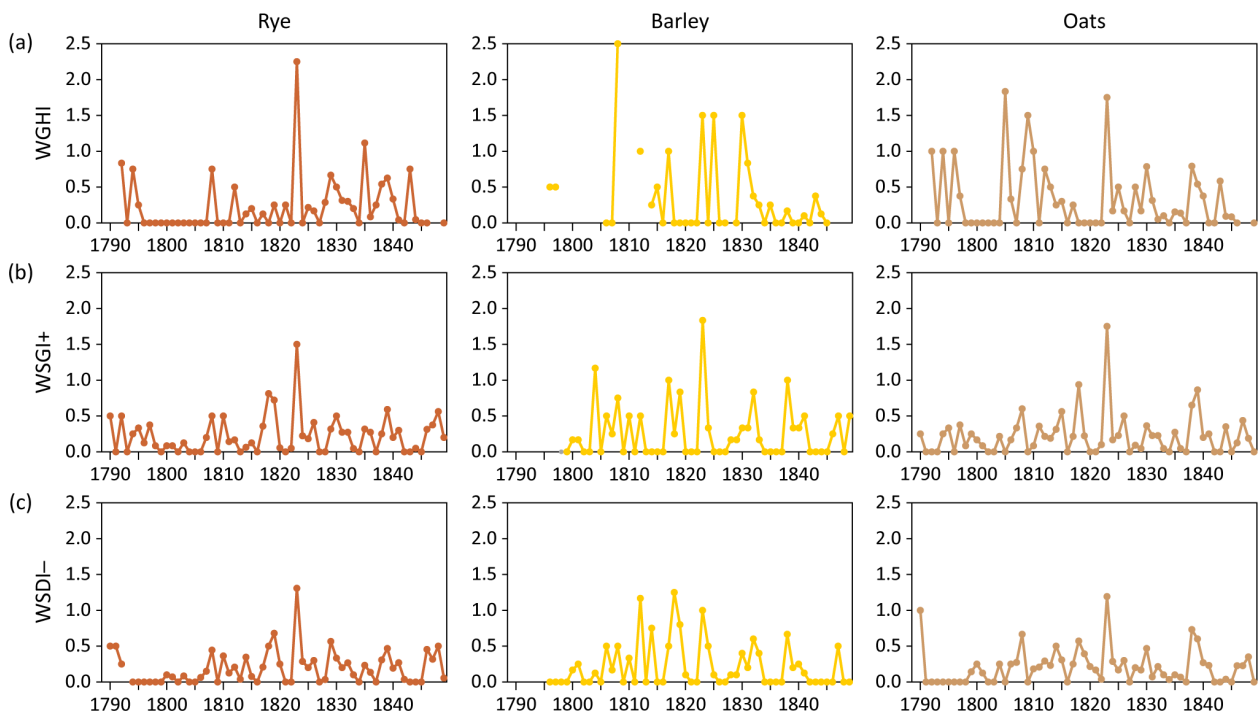
As for the years of a good grain harvest, they were indicated by the weighted good harvest index (WGHI),

an increase in the weighted stored grain index (WSGI+; more grain returned than borrowed), and a decrease in the weighted serf debt index (WSDI–; more grain returned than borrowed) (Fig. 7, Table 3). The features described above for the three grain indices of bad harvests were generally valid for those indicating good harvests as well. However, notable differences appeared in the WGHI compared to the WBHI for rye, with a long period of zero values from 1796 to 1807 CE and one dominant peak in 1823, which was also well expressed in WSGI+ and WSDI–. Similarly, the WGHI for barley suffered from only sporadic data until 1814 CE, with an outlier of 2.5 in 1808 for the Mačice domain.





**Figure 6.** Fluctuations in annual weighted grain indices in the Sušice region indicating bad harvests for rye, barley, and oats during the 1789–1849 CE period: (a) WBHI is the weighted bad harvest index, (b) WSGI– is the weighted stored grain index (decrease), and (c) WSDI+ is the weighted serf debt index (increase).



**Figure 7.** Fluctuations in annual weighted grain indices indicating good harvests for rye, barley, and oats in the Sušice region during the 1789–1849 CE period: (a) WGHI is the weighted good harvest index, (b) WSGI+ is the weighted stored grain index (increase), and (c) WSDI– is the weighted serf debt index (decrease).

**Table 2.** Bad grain harvest years ordered according to values of weighted grain indices  $\geq 0.5$  ( $\geq 1.0$  in italics) derived from data from contribution granaries of 15 domains in the Sušice region during the 1789–1849 CE period: WBHI is the weighted bad harvest index, WSGI– is the weighted stored grain index (decrease), WSDI+ is the weighted serf debt index (increase), and “No.” indicates number of domains with data available. The real year of a bad grain harvest  $n$  is indicated by WBHI for the year  $n + 1$ .

Rye						Barley					
WBHI		WSGI–		WSDI+		WBHI		WSGI–		WSDI+	
Year	No.	Year	No.	Year	No.	Year	No.	Year	No.	Year	No.
<i>1843</i>	<i>13</i>	<i>1821</i>	<i>10</i>	<i>1828</i>	<i>15</i>	<i>1813</i>	<i>2</i>	<i>1816</i>	<i>3</i>	<i>1821</i>	<i>5</i>
<i>1821</i>	<i>9</i>	<i>1843</i>	<i>10</i>	<i>1843</i>	<i>13</i>	<i>1825</i>	<i>4</i>	<i>1821</i>	<i>3</i>	<i>1816</i>	<i>5</i>
<i>1828</i>	<i>10</i>	1816	7	1821	15	<i>1821</i>	<i>3</i>	<i>1835</i>	<i>3</i>	<i>1835</i>	<i>5</i>
1837	11	1799	6	1799	6	<i>1816</i>	<i>2</i>	1822	3	1813	4
1847	6	1828	11	1816	13	<i>1835</i>	<i>4</i>	1812	2	1822	5
1825	11	1837	9	1847	11	1826	4	1840	3	1826	5
1799	5	1822	10	1822	13	1815	3	1843	4	1805	3
1815	10	1827	10	1812	12	1843	5	1802	2	1809	3
1848	6	1796	4	1837	13	1796	1	1805	2	1811	3
1838	15	1812	6	1796	3	1799	1	1809	2	1812	3
1796	6			1798	6	1800	1	1831	3	1837	3
1797	5			1802	6	1802	2	1837	2	1846	2
1798	6					1808	3				
1813	10					1830	3				

Oats					
WBHI		WSGI–		WSDI+	
Year	No.	Year	No.	Year	No.
<i>1843</i>	<i>13</i>	<i>1816</i>	<i>7</i>	1816	13
<i>1828</i>	<i>10</i>	1812	7	1799	7
<i>1825</i>	<i>11</i>	1821	10	1802	6
1847	6	1799	6	1821	15
1821	9	1803	3	1812	12
1799	6	1843	10	1843	13
1800	7	1804	7	1837	13
1815	10	1822	10	1809	9
1816	8	1842	10	1822	13
1797	5	1796	4		
1823	10	1828	11		
1805	9	1834	11		
1806	9	1849	5		
1798	6	1816	7		
1848	6				
1843	13				

4.4 Extreme harvest years, weather, and climate

4.4.1 Extreme harvest years and documentary data

A total of 10 years of extremely bad and 7 years of extremely good harvests of rye, barley, and oats (or at least two of them) were selected for comparison with documentary data on weather and related phenomena from the Sušice region and its surroundings. This analysis combines information from the weighted grain indices shown in Figs. 6 and 7 and Tables 2 and 3, along with their logical evaluation and remarks in granary records. Due to the substantial amount of

documentary data, we present here only a representative selection of corresponding records that confirm the character of especially extreme years (for the locations of further cited places, see Fig. A1).

Bad grain harvests

Selected years of poor grain harvests were characterized by different reports from documentary sources as follows.

**Table 3.** Good grain harvest years ordered according to values of weighted grain indices  $\geq 0.5$  ( $\geq 1.0$  in italics) derived from data from contribution granaries of 15 domains in the Sušice region during the 1789–1849 CE period: WGHI is the weighted good harvest index, WSGI+ is the weighted stored grain index (increase), WSDI– is the weighted serf debt index (decrease), and “No.” indicates the number of domains with data available.

Rye						Barley					
WGHI		WSGI+		WSDI–		WGHI		WSGI+		WSDI–	
Year	No.	Year	No.	Year	No.	Year	No.	Year	No.	Year	No.
<i>1823</i>	<i>4</i>	<i>1823</i>	<i>8</i>	<i>1823</i>	<i>13</i>	<i>1808</i>	<i>1</i>	<i>1823</i>	<i>3</i>	<i>1818</i>	<i>4</i>
<i>1835</i>	<i>13</i>	1818	8	1819	14	<i>1823</i>	<i>1</i>	<i>1804</i>	<i>3</i>	<i>1812</i>	<i>3</i>
1792	3	1819	9	1829	15	<i>1825</i>	<i>2</i>	<i>1817</i>	<i>2</i>	<i>1823</i>	<i>5</i>
1794	2	1839	11	1790	1	<i>1830</i>	<i>2</i>	<i>1838</i>	<i>2</i>	1819	5
1808	2	1848	8	1791	1	<i>1812</i>	<i>1</i>	1819	3	1814	4
1843	12	1790	1	1818	14	<i>1817</i>	<i>1</i>	1832	3	1838	3
1829	6	1792	1	1848	10	1831	3	1808	2	1832	5
1839	12	1808	5			1796	1	1806	2	1806	3
1838	12	1810	6			1797	1	1810	2	1808	3
1812	2	1830	11			1815	2	1812	2	1817	4
1830	7							1841	3	1824	5
								1847	2	1847	2
								1849	1		

Oats					
WGHI		WSGI+		WSDI–	
Year	No.	Year	No.	Year	No.
<i>1805</i>	<i>3</i>	<i>1823</i>	<i>8</i>	<i>1823</i>	<i>13</i>
<i>1823</i>	<i>4</i>	1818	8	<i>1790</i>	<i>1</i>
<i>1809</i>	<i>1</i>	1839	11	1838	13
<i>1792</i>	<i>3</i>	1838	10	1808	9
<i>1794</i>	<i>1</i>	1808	5	1839	15
<i>1796</i>	<i>1</i>	1815	8	1818	14
<i>1810</i>	<i>1</i>	1826	11	1814	13
1838	12				
1830	7				
1808	2				
1812	2				
1843	12				
1839	12				
1813	1				
1825	7				
1828	7				

## (i) 1795

The reeve in Milčice (central Bohemia), František Jan Vavák, mentioned frequent rainy days in summer, leading many farmers to harvest grain that was moist and wet. The harvest was better for rye than in the preceding year (1794), good for barley and oats, and poor for wheat (Skopec, 1916). The rainy weather in summer was confirmed by records from Bělá nad Radbuzou, where on 24–26 July parishioners prayed for nice weather (AS25). Poor winter cereals and good spring cereals were harvested in Klášter Hradiště nad Jizerou (Šimon, 1927).

## (ii) 1798

A note in the granary records of the Kolinec domain for the year 1798 mentioned “Accounting of tax reduction for damage caused by weather” (AS7). A source from Skuhrov nad Bělou reported a very cold and rainy spring and summer, with only about 2 weeks of warm and sunny weather. At higher elevations, much of the grain went bad (Robek, 1976). Reports from Milčice indicated less straw from rye and barley but good grain quality, along with a lower-than-usual oat harvest at higher elevations (Skopec, 1918). A scant harvest

and rising grain prices during the harvest were reported in *Noviny pod Ralskem* (AS24).

### (iii) 1811

Dry conditions from May to June and warm weather from May to July in the Czech Lands contributed to an earlier onset of the grain harvest, which was very poor, as documented by many sources throughout the country (see Brázdil and Trnka, 2015). While the granary records of the Velhartice domain noted only a “bad harvest” for 1811 without specifying the cause (AS21), other sources from central Bohemia linked the bad harvest to dryness. For instance, in Dřínov cereals dried out immediately after blossoming, while in Hostín only a small amount of rye was reported (Robek, 1974). The parson in Žitenice, František Jindřich Jakub Kreybich, reported very sparse rye and wheat that was short in stature and spring cereals (AS3). František Jan Vavák noted in his records from Milčice that “rye and wheat are short, barley sparse, and everything of a small ear” (Jonášová, 2009, p. 93).

### (iv) 1812

Potential grain yields in 1812 were reduced by hail damage, as reported in seven villages of the Žichovice domain (AS17). Similarly, hail damage was noted in the Nalžovy domain (AS6): “Part of [the annual] debt [of serfs] was remitted to villages damaged by “*Wetterschlag*” [hailstorm].” František Jan Vavák recorded for Milčice that rye lay on the ground overgrown with grass due to frequent rains and that some fields were infested with beetles eating the grain (Jonášová, 2009). A poorer grain harvest was also reported in Ouholice (Neruda, 1862). In Budenice, the grain harvest was prolonged due to cold weather until September (Komárek, 1911), while adverse weather prevented grain harvesting altogether in Hora Svatého Šebestiána, leaving no grain for the next sowing (Binterová, 2000).

### (v) 1815

Georg Mayer in Fleky reported a cold and wet year with a poor grain harvest and a large number of mice (Blau, 1908). Josef Schück, in his records from Litoměřice, mentioned a very scant harvest across all of Bohemia due to incessant wet weather (Bachmann, 1911). František Jan Vavák from Milčice noted a long period of frost, followed by dry weather, which was then replaced by continuous rain. This caused many rye ears to lack grain and barley to have short ears and small size, while overall “the grain harvest was woeful, and peasants carried wet grain to barns, making threshing difficult” (Jonášová, 2009, p. 388). The harvest failure of 1815 coincided with the large Tambora volcanic eruption in April, and the following year (1816) became known as “the year without a summer” (Luterbacher and Pfister, 2015; Brázdil et al., 2016b).

### (vi) 1820

The school chronicle of Bukovník mentioned a severe thunderstorm with torrential rain and hail on 23 May that heavily damaged fields and which was followed by great drought (AS29). A very dry summer was also reported for Bělá nad Radbuzou (AS25).

### (vii) 1821

The poor grain harvest of 1821 was reflected in the granary remarks of the Dlouhá Ves domain (AS13) for this year: “Half [the grain] went bad due to weather.” This is also reflected by the following statement from 1822: “Serfs returned only a small amount of grain due to the poor harvest of the previous year [1821] and the not much better harvest of this year [1822].” Augustin Kalach from Obora mentioned a late harvest, partly due to unripe grain and partly due to incessant rains (Robek, 1979). During the rainy August, a procession beseeching favourable weather for the grain harvest was organized on 19 August in Jablonné v Podještědí (AS24). The memories of Jan Chlebeček from Chrudim cited a cold, wet, and rainy year, with rains during the August harvest that negatively impacted rye (AS23).

### (viii) 1827

The school chronicle of Bukovník reported a “bad harvest due to great drought” (AS29). Records from Řeňče mentioned delayed spring sowing (end of April to early May) due to excessive wetness and generally average yields, although “barley was bad everywhere” (Urban, 1999, pp. 45–46). A great drought also contributed to a poor grain harvest in Hostín (Robek, 1974). The harvest in Hřivice was poor in grain, leading to rising prices by August (Robek, 1979). According to a report by the I. R. Patriotic Economic Society of Bohemia, grain yields were negatively influenced by a rainy March and April, which delayed spring sowing, followed by rainy weather in June during rye and wheat blossoming and very hot and dry weather in the subsequent 2 months (Neue Schriften, 1830).

### (ix) 1836

The chronicle from Lhovice reported a dry year with less wheat, average rye (more straw and less grain), and average barley and oats (AS27). The municipal chronicle of Poleň mentioned a cold spring lasting until May, followed by warmer weather with some rain, and then a summer drought, which resulted in rye with good straw but weak grain, average wheat, and very poor barley and oats (AS26). In neighbouring Poleňka, the wheat harvest was also very poor (AS28). At Hřivice, grain dried up, with very bad rye and slightly better barley (Robek, 1979). A report from the I. R. Patriotic Economic Society of Bohemia described this year as generally characterized by higher temperatures and



lighter rains, especially in summer; for example, in Lito-měřice rye was sparse, wheat was short, and barley and oats varied in growth (Neue Schriften, 1838).

#### (x) 1842

The very bad harvest of 1842 in the Czech Lands was related to the extremely dry conditions from April to September, as documented by many sources (see Brázdil and Trnka, 2015). This drought extended beyond the Czech Lands to a broader European region (Brázdil et al., 2019a). The granary records of the Albrechtice domain mentioned “a bad harvest [*Mis-sernte*] in the region” in this year (AS8). A severe drought with almost no rain in Lhovice after spring sowing led to a very scant harvest, with nearly no oats (AS27). Similarly, in Budětice, the absence of rain since spring caused poor cereal growth and a meager harvest with no oats at all (AS30). The chronicle of Bukovník also reported particularly poor barley and oats due to the severe drought (AS29), while in Poleň rye was average (but very short) and bad harvests for the other three cereals are recorded (AS26).

#### Good grain harvests

The selected years of good grain harvests were characterized by different reports from documentary sources as follows.

#### (i) 1808

Although Czech meteorological data indicated dry conditions in March, May, and July–August (Brázdil and Trnka, 2015), the grain harvest was affected in different ways. František Jan Vavák in Milčice mentioned that the dry and warm weather caused fast ripening of cereals, resulting in their drying out with only a little grain (Skopec, 1938). However, František Jindřich Jakub Kreybich in Žitenice described the year as good and fruitful for cereals, with good harvests of winter crops like rye and wheat, although spring crops like barley fared worse (AS1). A very good harvest was noted in Dřínov in central Bohemia (Robek, 1974).

#### (ii) 1810

František Jindřich Jakub Kreybich characterized the harvest in lowlands as average, but at higher altitudes (“mountains”) both winter and spring crops, especially rye and oats, were very good (AS2). An average grain harvest was also reported for Dřínov (Robek, 1974).

#### (iii) 1819

The parish chronicle from Srní reported a plentiful year with cheaper rye (AS4). The school chronicle of Bukovník cited “a great cheapness in grain” (AS29). A plentiful year was also reported in the chronicles from Bělá nad Radbuzou (AS25) and Zhůří (AS32).

#### (iv) 1823

A good grain harvest was reported by Georg Mayer in Fleky (Blau, 1908). Václav Jan Mašek from Řenče noted that 1823 brought “[...] nice times and also fertile rain. From it followed God’s blessing on fields in the harvest during the whole summer, but God sent us a scourge of hail in mid-harvest [8 August]. Not too much damage was done, only to some oats [...]” (Urban, 1999, p. 42). Records from Jablonné v Podještědí cited an abundant grain harvest due to favourable weather (AS24). The agricultural summary of the I. R. Patriotic Economic Society of Bohemia for 1823 mentioned a good autumn sowing (in 1822), followed by a severe winter that delayed spring sowing until late April in mountainous regions, resulting in a very good grain harvest by the second part of August (Resultate, 1828).

#### (v) 1830

An average harvest was reported in the chronicle from Bukovník (AS29) that was similar to that of Srní, where the fertility of this year was evaluated generally as average (AS4). The parish chronicle from Železná Ruda reported high summer temperatures leading to thunderstorms, but they did not occur in the surrounding area, and the grain harvest was identified as good (AS33). According to reports from the I. R. Patriotic Economic Society of Bohemia, the rye harvest turned out to be better than expected after poor autumn sowing (1829) and a very severe winter in 1829/1830. Yields of barley and oats were evaluated as good (Neue Schriften, 1833).

#### (vi) 1838

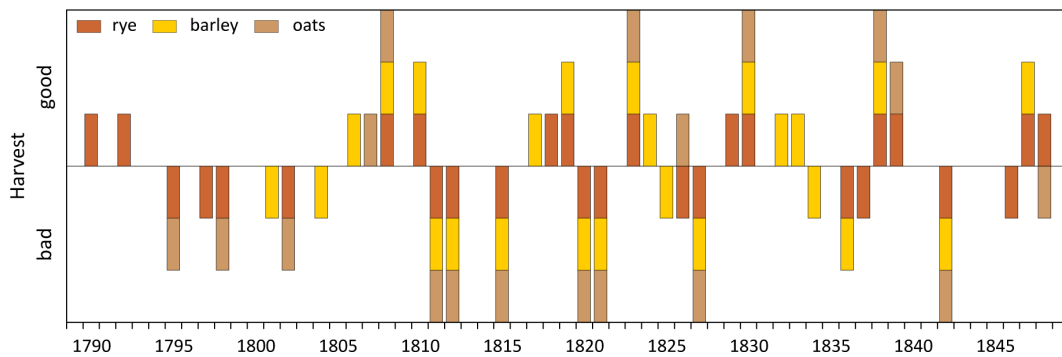
The local chronicle of Lhovice reported “such an abundant harvest as not remembered for many years, both in grain and straw” (AS27). An abundant harvest was also noted in Hojsova Stráž (AS31). The parish chronicle of Kašperské Hory cited average rye but excellent oats (AS5). A good harvest of all four cereals was reported in the chronicle from Poleň (AS26), and a similar report is given for Poleňka, where the chronicler added “such a good harvest [of grain] had not been recorded for many years” (AS28). The I. R. Patriotic Economic Society summarized reports of harvests from 12 different locations in Bohemia as follows: wheat was good for both grain and straw; rye was rather average; barley was partly very good and partly below average; and oats were good, particularly for grain (Neue Schriften, 1840).

#### (vii) 1839

According to records from Hojsova Stráž, severe winter conditions affected meadows and fields, but favourable spring and summer weather contributed to a good grain harvest (AS31). A source from Lhovice cited a good harvest with abundant straw but less grain (AS27). The chronicle from

**Table 4.** Years of bad and good harvests of rye, barley, and oats in the Sušice region during the 1789–1849 CE period.

Cereal	Year of bad harvest
Rye	1795, 1797, 1798, 1802, 1811, 1812, 1815, 1820, 1821, 1826, 1827, 1836, 1837, 1842, 1846
Barley	1801, 1804, 1811, 1812, 1815, 1820, 1821, 1825, 1827, 1834, 1836, 1842
Oats	1795, 1798, 1802, 1811, 1812, 1815, 1820, 1821, 1827, 1842, 1848
Cereal	Year of good harvest
Rye	1790, 1792, 1808, 1810, 1818, 1819, 1823, 1829, 1830, 1838, 1839, 1847, 1848
Barley	1806, 1808, 1810, 1817, 1819, 1823, 1824, 1830, 1832, 1833, 1838, 1847
Oats	1807, 1808, 1823, 1826, 1830, 1838, 1839

**Figure 8.** Fluctuations in good and bad harvest years for rye, barley, and oats in the Sušice region during the 1789–1849 CE period.

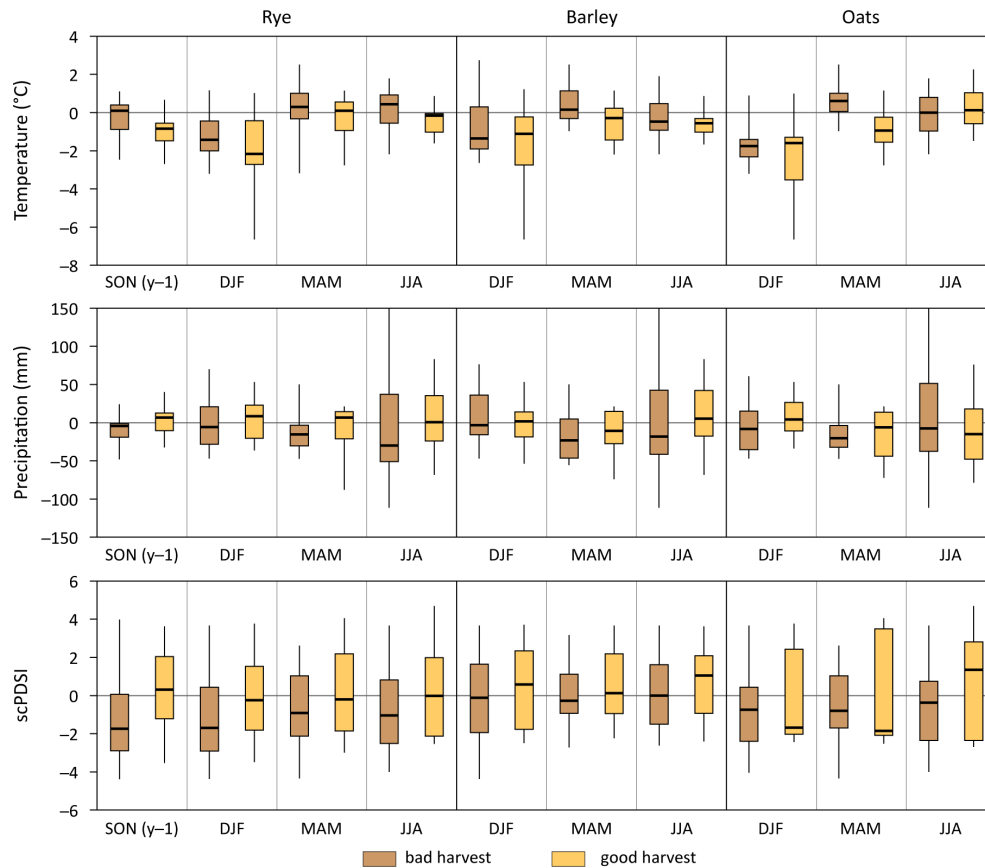
Poleň reported average yields for rye, wheat, and barley, but a good harvest of oats (AS26). Information on grain harvests from 17 different locations in Bohemia was summarized in the report of the I. R. Patriotic Economic Society as follows: wheat was good for both grain and straw; rye was regionally variable, from very good to poor; barley was good but better for grain than straw; and oats were good (Neue Schriften, 1841).

#### 4.4.2 Climate and extreme harvest years

Table 4 lists the bad and good harvest years separately for rye, barley, and oats in the Sušice region, with this data being derived from the calculated weighted grain indices in Tables 2 and 3. The number of bad harvest years was higher than good harvest years for rye (15 vs. 13) and oats (11 vs. 7), while for barley both datasets were represented by 12 years. Figure 8 shows some alternation of bad and good harvest years during the study period, lasting no longer than 3 consecutive years (1806–1808 and 1817–1819 for good harvests and 1825–1827 for the bad harvest). All three considered cereals experienced concurrently good harvests in 4 years (1808, 1823, 1830, 1838) and bad harvests in 7 years (1811, 1812, 1815, 1820, 1821, 1827, 1842). Two cereals had good or bad harvests in 4 years each, but in 1826 a good harvest of oats and a bad harvest of rye occurred, while in 1847 the situation was reversed. As for a single cereal, good har-

vests were detected in 10 years compared to 7 years with bad harvests.

The selected years of bad and good harvests were further used in composite analyses to examine their relationships to temperature, precipitation, and drought (scPDSI) patterns, represented by seasonal box plots of related climate variables (Fig. 9). Climatic patterns from the previous SON to the JJA of the harvest year were considered for rye, while for barley and oats the analysis was limited to the period from DJF to JJA. For rye, years of bad harvests compared to good harvests were characterized by relatively high temperatures and low precipitation totals from SON to JJA. This was particularly well expressed in the scPDSI deviations, which showed much drier patterns for years of bad harvests. However, the high variation range in JJA precipitation totals suggests that bad harvests could be influenced by either extremely high or extremely low precipitation totals. In contrast, spring crops like barley and oats showed more ambiguous relationships. After a colder DJF in good harvest years, MAM temperatures were higher in bad harvest years and similar to JJA for barley. For oats, JJA temperatures were comparable between the two datasets. MAM and JJA precipitation totals were lower in years of bad barley harvests, while for oats this was only observed for MAM. Regarding the scPDSI, drier conditions characterized bad barley harvests from DJF to JJA, while for oats this pattern was observed only in JJA. Interestingly, lower median values for DJF and MAM scPDSI in years of good oat harvests compared to bad harvests were



**Figure 9.** Composite analysis represented by box plots (median, upper and lower quartiles, maximum, and minimum) of seasonal (DJF – winter, MAM – spring, JJA – summer, SON (y–1) – autumn of the preceding year) mean temperatures, precipitation totals, and scPDSI for the Czech Lands during years of bad and good harvests of rye, barley, and oats in the Sušice region from 1789–1849 CE. Climate variables are expressed as deviations relative to the 1961–1990 reference period.

accompanied by larger interquartile ranges, favouring wetter conditions. A question remains as to what extent this differing relationship for oats results from the limited sample size of only 7 good harvest years compared to 11 bad harvest years. Testing the statistical significance of the differences in climate variables between years of bad and good harvests showed significant results in only a few cases. Significant differences were found in the means of MAM temperatures ( $p < 0.10$  for barley and  $p < 0.05$  for oats) and SON scPDSI for rye ( $p < 0.10$ ), in the median for MAM temperatures for oats ( $p < 0.05$ ), and in variability for DJF temperatures ( $p < 0.10$  for rye and  $p < 0.05$  for oats) and JJA temperatures ( $p < 0.05$  for barley).

## 5 Discussion

### 5.1 Data uncertainties

Various types of uncertainties are present in the granary data due to the multiple and sometimes competing purposes and interests associated with them and their connection to a dy-

namic agricultural ecology. These factors contribute to some data gaps during the period analysed. For instance, when no grain was available in the granary, it was impossible to borrow grain, and no grain circulation would be recorded, even in the case of a severe grain failure. For example, in 1799 no grain was returned to the granary in the Velhartice domain due to a bad harvest (AS21). Similarly, in the 2 subsequent years, serfs did not return any grain to the granary, as it was supplied to armies instead (AS21). A comparable situation occurred in 1802, when the grain was damaged by a severe hailstorm (AS21). In the Mačice domain in 1813, serfs used all available grain for “army depots, transports, fresh draught horses [*Vorspann*], and faraway cartloads [*weite Fuhren*]”, leaving nothing to be delivered as debt payment (AS15).

A sudden decrease in grain in the granary could result not only from loans but also from grain sales authorized by the corresponding officers. For example, a sale of 80.5 *měrice* (4950 L) of rye and 27.3 *měrice* (1679 L) of oats was reported in the Kněžice domain in 1838 (AS12), and 150 *měrice* (9224 L) of rye was sold from the Dlouhá Ves domain in 1839 (AS13). In the Nalžovy domain, nearly every

year starting from 1793 CE, 34 *měřice* (2091 L) of oats were given to the surgeon, and from 1839 CE this was increased to 52 *měřice* (3198 L) of oats (AS6). In 1843 and 1844, 42 *měřice* (2583 L) of rye was provided to serfs affected by fire (ibid.). In the Kašperské Hory domain, 479 *měřice* (29 454 L) of rye from the granary was distributed free of interest starting in 1837 CE among serfs for 3 years due to the danger of worms in the granary (AS9). Loss of grain in the granary could also have been related to thefts, as was the case in the Hrádek domain in 1812 (8 *měřice* of rye and 5 *měřice* of oats, i.e. 492 and 307 L, respectively) or in 1828 (58 *měřice* of oats, i.e. 3566 L) (AS11). In 1817 CE, in the Žikov domain the regional office decided that the preceding amount of grain was not sufficient for sowing the serfs' fields and requested 436 *měřice* 5 1/16 *měřička* (26 829 L) of rye and 523 *měřice* 10 5/16 *měřička* (32 199 L) of oats from the serfs (AS22). Due to the lack of a public granary building, in 1827 CE all of the grain in the granary was divided among the serfs, and their debt was decreased accordingly, while in the following years half of the grain always had to be delivered back to the granary (AS22).

The speculative sale of granary grain on the free market was legislatively excluded. According to section 14 of the patent issued in 1788 (Kalousek, 1910), only surplus granary grain beyond the annual sowing reserve from stored grain could be sold. This was possible only with the agreement of the state administration (district offices), and the obtained money was saved in dedicated contribution (tax) cash desks or used for granary building. Later it was recommended to sell long-stored grain and to buy new grain from the corresponding income with the aim of ensuring grain quality. Granary records never report other reasons that led serfs to borrow grain (only the need for food or seed corn was ever mentioned). Due to this, the associated costs, and the fact that granaries never achieved the needed annual sowing reserve, it is unlikely that serfs might have also borrowed grain as a form of speculation instead of coping with actual dearth. In addition, it appears that the local granary accountants had very good knowledge about the real situation of the serfs.

The selling of grain from granaries was considered in the analysis of the quantity of grain stored in the granary at the end of the year. Before the calculation of WSGI, the quantity of grain sold in year  $n$  was added back to this year for comparison with the quantity of the preceding year ( $n - 1$ ). However, it was not considered in comparing the grain quantities in year  $n$  with the following year ( $n + 1$ ).

Some domains experienced territorial changes throughout the entire 1789–1849 CE period due to the sale of small parts of their land. Nevertheless, these had only a minor impact on both the number of active peasants and the extent of arable land. The results of these changes were unsubstantial, affecting only a few peasants, and the incorporation of new areas often failed to influence the original accounting if crop fund administrations already existed. For example, Kolinec, which became part of the Nalžov domain in 1837, remained a

self-contained entity afterward. The same occurred in Dolejší Těšov, which joined the Kunderatice domain in 1802. Sometimes, the borrowing of grain from crop funds in justified cases remained open to serfs from other domains, even when the borders of a particular domain were not changed.

The integrity of collected grain data was also partly influenced by issues already criticized by contemporary state administration, such as the complete lending out of the crop fund and the procrastination of repayments, which could last several years. This meant that grain existed only in the accounts, and in crisis years it was not possible to use the funds for their intended purpose, as was the case in the Žikov domain (AS22). To avoid distorting the data, it was necessary to account for all individual corrections in grain accounting (such as remission of interest), involving in-kind salaries for patrimonial medical and clerical staff or reductions in stored grain due to official misappropriation or pests (e.g. insects, mice). Year after year, 1 % of stored grain in each granary was subtracted due to pests and storage manipulation. In case of a greater damage to grain, the state administration (district office) assigned purchases of grain at the most favourable market price and from such money to procure fresh grain immediately. Whenever such purchases were recorded in granary records, they were differentiated expressly from borrowed grain due to weather. Substantial loss due to pests and insect attacks was reported in 1796 at the Albrechtice domain (“A worm spoiled part of stored grain.” – AS8) or in 1837 at the Kašperské Hory domain (“473 *měřice* [i.e. 29 085 L] of rye from the granary was distributed interest-free among serfs due to a worm danger.” – AS9).

Regarding the weather and climate datasets used, some biases for their use in this study must be noted. The studied region is in the marginal part of Bohemia, at middle and higher altitudes, which may result in different weather and climate effects on grain harvests compared to lowland or generally lower-altitude areas. This may apply to documentary reports from more distant locations from the Sušice region, where the impacts of colder and wetter patterns on grain harvests could differ. Moreover, the reconstructions of temperature, precipitation, and scPDSI represent average patterns rather than specific values for the entire territory of the Czech Lands, which may vary to some extent in the Sušice region. This underscores the importance of using documentary data directly connected to this region or its nearby surroundings.

## 5.2 Broader context

European interest in maintaining public granaries reached its peak at the end of the 18th century. Repeated harvest failures, increased demographic pressure, and new economic ideas converged in a veritable granary mania. Journals all over the continent debated their potential and drawbacks, expanding from modest establishments geared at stocking seed grain or army supplies to major institutions able to balance market prices and feeding whole populations (Collet, 2019). Some



**Table 5.** Spearman rank correlation coefficients between series of weighted grain indices used for the delimitation of bad and good harvest years for rye, barley, and oats in the Sušice region during the 1789–1849 CE period. The statistical significance of coefficients is as follows: \*  $p < 0.10$ , \*\*  $p < 0.05$ , and \*\*\*  $p < 0.01$ . Abbreviations of weighted grain indices are as follows: A is WBHI, B is WSGI–, C is WSDI+, D is WGHI, E is WSGI+, and F is WSDI–.

Cereal	Bad harvest			Good harvest		
	A–B	A–C	B–C	D–E	D–F	E–F
Rye	0.51***	0.60***	0.78***	0.51***	0.45***	0.74***
Barley	0.58***	0.62***	0.80***	0.45***	0.37**	0.82***
Oats	0.23*	0.34***	0.78***	0.26**	0.23*	0.71***

academies even hosted European competitions for the best papers on the pitfalls and potentials of granaries (Reimarus, 1772). A minority of discussants saw them as an expensive challenge to free trade that would de-incentivize private merchants. Many more envisioned them as a vital infrastructure against increasingly frequent weather shocks; a tool to curb profiteering; and, crucially, as a tool to strengthen administrative control of the grain market, which was a key sector of pre-industrial economies. Their form, organization, and dispersion, however, responded to local constellations and needs (see the Supplement for information about Prussia and northern Europe).

Concerning the Czech Lands, different grain data from public granaries of 15 domains in the Sušice region in southwestern Bohemia during the 1789–1849 CE period allowed for the calculation of six different weighted grain indices, which were then combined to identify years of bad or good harvests of rye, barley, and oats (see Sect. 3). To assess the explanatory ability of these indices in representing the same harvest characteristics, Spearman rank correlation coefficients were calculated between the indices used for delimiting bad and good grain harvests (Table 5). All correlation coefficients were statistically significant, at least at the  $p < 0.10$  level, and they were generally higher between bad harvest indices than between good harvest indices. Although the lowest correlations were observed for oats, those for barley were higher than for rye in the case of bad harvests, while the opposite was true for good harvests (except for correlation E–F between WSGI+ and WSDI–). As expected, the strongest correlation appeared between stored grain and serf debts (B–C and E–F), as demonstrated by the highest correlations.

The granary records were more representative when expressing bad harvests than good harvests (see Tables 2 and 3), which was reflected in the higher number of years with weighted grain indices  $\geq 0.5$  (36 to 28 for rye, 38 to 35 for barley, and 37 to 30 for oats). Moreover, high proportions of indices for good harvests compared to bad harvests were derived from only one or two domains (25.0% to none for rye, 51.4% to 31.6% for barley, and 26.7% to none for oats). The presented results can be explained by a greater need for serfs to borrow grain from granaries rather than an obligation

to return it. However, it needs to be acknowledged that barley in our region was cultivated less than rye and oats, which were considered the main cereals.

The final selection of extreme years identified 10 years with bad harvests and 7 years with good harvests for at least two of the three cereals considered, as clearly confirmed by documentary data from the analysed region and other locations in Bohemia (see Sect. 4.4.1). However, considering grain data availability (see Fig. 5), their spatial coverage by a variable number of domains (Tables 2 and 3), and the uncertainty in granary data (see Sect. 5.1), some extreme years with both bad and good grain harvests could remain unnoticed, as they are not well captured in the available granary records. A potential spatiotemporal incompleteness of such anthropogenic data is a typical feature of documentary data in historical climatological research (e.g. Brázdil et al., 2005; White et al., 2018b; Pfister and Wanner, 2021). When years of bad and good harvests were studied separately for each cereal, higher temperatures, lower precipitation totals, and intense droughts expressed by the scPDSI from SON of the preceding year to JJA of the given year characterized bad rye harvests. The same processes applied to MAM and JJA variables in the case of barley harvests. Less unambiguous patterns, like those for barley, characterize MAM and JJA climate variables in the case of oats (see Sect. 4.4.2). Statistically significant differences in mean seasonal temperatures between years of bad and good harvests were found for MAM (barley, oats) and in temperature variability for DJF (rye, oats) and JJA (barley). However, climate–harvest yield associations can be regionally variable, as documented by Ljungqvist et al. (2023), who identified positive significant signals in JJA soil moisture for Sweden and warmer and drier DJF patterns for Switzerland but negative signals in MAM and annual mean temperatures for Spain. Rácz (2023) attributed poor winter wheat harvests in the Carpathian Basin during the first half of the 19th century to cold and wet October, cold March, dry May, dry and hot or wet June, and wet July and August months. The significance of MAM and JJA temperatures identified in southwestern Bohemian grain harvests coincides well, for example, with their impacts on grain prices in the Burgundian Low Countries during the 15th cen-

tury (Camenisch, 2015) and on 56 analysed grain price series in early modern Europe (Ljungqvist et al., 2022).

In the evaluation of general patterns during the 1789–1849 CE period, other important non-climatic factors must also be mentioned, particularly the time of the Napoleonic Wars in Europe between 1803 and 1815 CE. These wars were represented by a series of conflicts in which Great Britain, Russia, Prussia, and the Austrian Empire were the principal adversaries, with battles often occurring on or near their territories. The Czech Kingdom, as part of the Austrian Empire, significantly supported the Austrian and, to some extent, the coalition armies. French troops moved through Czech territory in 1805, 1809, and 1813 (e.g. Šedivý, 2001; Gates, 2003; Esdaile, 2019). Some response to military conflict is apparent in the granary records of the Hrádek domain, where in 1813, 410 *měřice* (25 211 L) of oats was distributed among serfs due to the danger of war (AS11). However, despite some oats being sold to the army as early as 1790–1792 CE in the Nalžovy domain (AS6), other information indicating support for armies in the study region is missing. This is notably different from Prussia, where military interests were instrumental in establishing public granaries (cf. Collet, 2010). The increasing importance of potato growing was another factor influencing cereal production in the target area during the period analysed. Potatoes, which found broad use in the less fertile foothills of the Šumava Mountains, disrupted the monopoly of cereals because they could fulfil the role of the main foodstuff instead.

Despite several studies addressing different historical, socio-economic, and political aspects of grain granaries in Europe (e.g. Franko, 1907; Černý, 1932; Kaplan, 1977; Teerijoki, 1993; Meuvret, 1977, 1987, 1988; Berg, 2007; Collet, 2010; Seppel, 2019; Løvdal, 2020), our paper is the first to attempt using granary data for historical–climatological research. Specifically, it identifies bad or good grain harvests in relation to weather and climate patterns, situating them within the broader context of the Czech Lands in the late 18th and the first half of the 19th century. Additionally, it presents a methodology that can be used to analyse the large number of extant granary accounts available throughout Europe, which share the same or similar structures of record-keeping.

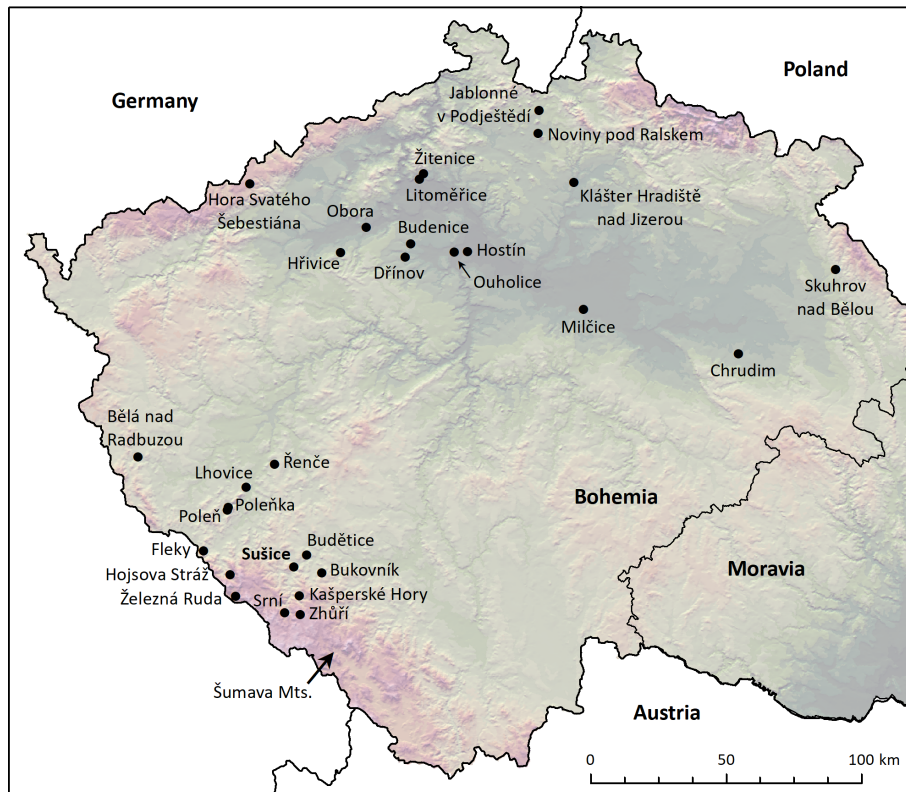
Although grain data mining from archival documentation of individual domain granaries is an extremely time-consuming process, the potential of such data is very high, especially if the data are combined comparatively across wider areas. The data can also be used to distinguish the effects of broader weather and climate anomalies from more local or regional meteorological effects, such as frosts in specific geographic locations, downpours with subsequent field inundation, or hailstorms. The case study in this paper demonstrates how granary data can serve as proxies for grain harvest in relation to weather and climate patterns. This could motivate further researchers to examine and potentially use granaries in other European countries as proxies for similar historical–climatological studies.

## 6 Conclusions

The analysis of grain records from public granaries of 17 individual domains in southwestern Bohemia during the 1789–1849 CE period can be summarized as follows.

- i. Data recorded by public granaries documenting the quantity of borrowed seed grain, deposits after harvest, overall storage quantity, and the level of serfs' debt represent important proxy indicators of grain production, allowing the selection of years with bad and good yields.
- ii. The use of these four basic types of grain data enabled the calculation of six different weighted grain harvest indices, allowing for the identification of years with bad and good grain harvests. Despite incomplete granary data and their relatively high uncertainty, the new methodology contributed to obtaining a sufficiently robust selection of years with bad and good harvests.
- iii. A total 10 selected years of extremely bad harvests and 7 years of extremely good harvests, involving at least two of the three cereals considered (rye, barley, oats), were clearly confirmed and complemented by other documentary data of weather and related phenomena from the Czech Lands.
- iv. The number of identified years with bad harvests was higher than those with good harvests. Higher temperatures, lower precipitation totals, and intense droughts from SON to JJA distinguished bad rye harvests from good ones. A similar correlation characterized MAM and JJA patterns for barley, while MAM and JJA patterns for oats were less clear. Differences in climate variables between years of bad and good harvests were predominantly statistically non-significant.
- v. Grain records from public granaries may be used as important proxies for evaluating grain harvests in relation to weather and climatic patterns. Extending the territorial scope of the analysis, together with the new methodology, opens up new research directions and offers great data and research potential for historical climatology. Given the ubiquity of such records in the 18th and 19th centuries, the approach developed here is applicable to a range of similar cases throughout Europe.

## Appendix A



**Figure A1.** Location of places across the Czech Republic cited in Sect. 4.4.1.

## Archival sources

- AS1: Archiv Akademie věd České republiky, inv. č. 775 (stará sign. VI C 8, č. 10), Meteorologische Beobachtungen vom Jahre 1808 in Schüttenitz nahe bei Leitmeritz gemacht von Fr. Jac. H. Kreybich.
- AS2: Archiv Akademie věd České republiky, inv. č. 777 (stará sign. VI C 8, č. 12), Meteorologische Beobachtungen vom Jahre 1810 in Schüttenitz nahe bei Leitmeritz gemacht von Fr. Jac. H. Kreybich.
- AS3: Archiv Akademie věd České republiky, inv. č. 778 (stará sign. VI C 8, č. 13), Meteorologische Beobachtungen vom Jahre 1811 in Schüttenitz nahe bei Leitmeritz gemacht von Fr. Jac. H. Kreybich.
- AS4: Arciděkanství farní úřad Kašperské Hory, Farní kronika Srní 1836–1952.
- AS5: Arciděkanství farní úřad Kašperské Hory, Pamětní kniha farnosti Kašperské Hory 1726–1959.
- AS6: Národní archiv, fond Kontribučenské fondy, inv. č. 571, karton č. 1065–1066; inv. č. 875, karton č. 1574–1575 (Nalžovy).
- AS7: Národní archiv, fond Kontribučenské fondy, inv. č. 586, karton č. 1090–1091 (Kolinec).
- AS8: Národní archiv, fond Kontribučenské fondy, inv. č. 854, karton č. 1534 (Albrechtice u Sušice).
- AS9: Národní archiv, fond Kontribučenské fondy, inv. č. 857, karton č. 1540–1541 (Kašperské Hory).
- AS10: Národní archiv, fond Kontribučenské fondy, inv. č. 880, karton č. 1578 (Hlavňovice).
- AS11: Národní archiv, fond Kontribučenské fondy, inv. č. 884, karton č. 1586–1587 (Hrádek u Sušice).
- AS12: Národní archiv, fond Kontribučenské fondy, inv. č. 890, karton č. 1594 (Kněžice).
- AS13: Národní archiv, fond Kontribučenské fondy, inv. č. 895, karton č. 1601–1602 (Dlouhá Ves).

- AS14: Národní archiv, fond Kontribučenské fondy, inv. č. 898, karton č. 1606 (Lipová Lhota).
- AS15: Národní archiv, fond Kontribučenské fondy, inv. č. 902, karton č. 1610 (Mačice).
- AS16: Národní archiv, fond Kontribučenské fondy, inv. č. 913, karton č. 1622 (Palvínov).
- AS17: Národní archiv, fond Kontribučenské fondy, inv. č. 921, karton č. 1643–1646 (Žichovice).
- AS18: Národní archiv, fond Kontribučenské fondy, inv. č. 924, karton č. 1652–1653 (Sušice).
- AS19: Národní archiv, fond Kontribučenské fondy, inv. č. 938, karton č. 1674 (Dolejší Krušec).
- AS20: Národní archiv, fond Kontribučenské fondy, inv. č. 940, karton č. 1676 (Dolejší Těšov).
- AS21: Národní archiv, fond Kontribučenské fondy, inv. č. 947, karton č. 1687–1688 (Velhartice).
- AS22: Národní archiv, fond Kontribučenské fondy, inv. č. 955, karton č. 1703 (Žikov).
- AS23: Státní okresní archiv Chrudim, fond Sběrka rukopisů, inv. č. 6: Jan Chlebeček – paměti (před 1849).
- AS24: Státní okresní archiv Česká Lípa, fond Sběrka rukopisů, sign. 13/3: Witterungs-Geschichte. Auszug aus den Titl: Lesenswürdige Sammlungen der hinterlegten Jahrgängen. Von Anton Lehmann Lehrer in Neuland. Abgeschrieben durch Joseph Meißner.
- AS25: Státní okresní archiv Domažlice, fond Farní úřad Bělá nad Radbuzou, inv. č. 1, sign. K 1, Pamětní kniha 1786–1938.
- AS26: Státní okresní archiv Klatovy, fond Archiv města Poleň (nezpracovaný fond), Kronika obce 1835–1848.
- AS27: Státní okresní archiv Klatovy, fond Archiv obce Lhovice, inv. č. 6, sign. K 6, Pamětní kniha 1836–1849.
- AS28: Státní okresní archiv Klatovy, fond Archiv obce Poleňka (nezpracovaný fond), Kronika obce 1834–1925.
- AS29: Státní okresní archiv Klatovy, fond Farní škola Bukovník, inv. č. 25, sign. K 25, Pamětní kniha 1815–1869.
- AS30: Státní okresní archiv Klatovy, fond Farní úřad Budětice (nezpracovaný fond), Pamětní kniha 1649–1981.
- AS31: Státní okresní archiv Klatovy, fond Farní úřad Hojsova Stráž (nezpracovaný fond), Pamětní kniha 1820–1946.
- AS32: Státní okresní archiv Klatovy, fond Farní úřad Zhůří (nezpracovaný fond), Pamětní kniha 1763–1946.
- AS33: Státní okresní archiv Klatovy, fond Farní úřad Železná Ruda (nezpracovaný fond), Pamětní kniha 1787–1933.

**Data availability.** The datasets and series used in this article are available from <https://doi.org/10.5281/zenodo.13918307> (Brázdil et al., 2024b).

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**Author contributions.** RB designed and wrote the paper with contributions from all co-authors. JL collected all of the public granary data, interpreted them, and contributed to the paper's writing with historical knowledge. KC performed the basic calculations concerning grain harvests and climate series and finalized all figures. DC contributed expertise on the function of granaries and added to the paper's overall conclusions and approach. PD contributed to the methodology and analysis of the relationship between grain harvests and climate variables. HeH contributed to the methodology and provided knowledge of public granaries in northern Europe. All authors have read and commented on the latest version of the paper.

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## References

- Bachmann, J.: Aufzeichnungen eines Alt-Leitmeritzers, *Mitteilungen des Vereines für Geschichte der Deutschen in Böhmen*, 50, 254–281, 1911.
- Bauernfeind, W. and Woitek, U.: The influence of climatic change on price fluctuations in Germany during the 16th century price revolution, *Clim. Change*, 43, 303–321, <https://doi.org/10.1023/A:1005502518695>, 1999.
- Berg, B. Å.: Volatility, Integration and Grain Banks: Studies in Harvests, Rye Prices and Institutional Development of the Parish Magazines in Sweden in the 18th and 19th Centuries, Stockholm School of Economics, Stockholm, Sweden, 216 pp., ISBN 9789172587229, 2007.
- Binterová, Z.: Od Kalku po Boleboř a Blatno (From Kalek to Boleboř and Blatno), Okresní museum, Chomutov, Czech Republic, 127 pp., ISBN 80-238-6410-6, 2000.
- Blau, J.: Ein Kapitel vom Getreidepreis, *Mitteilungen des Vereines für die Geschichte der Deutschen in Böhmen*, 47, 277–283, 1908.
- Brázdil, R. and Durd'áková, M.: The effect of weather factors on fluctuations of grain prices in the Czech Lands in the 16th–18th centuries, *Prace Geograficne*, 108, 19–25, 2000.
- Brázdil, R. and Trnka, M. (Eds.): Sucho v českých zemích: minulost, současnost, budoucnost (Droughts in the Czech Lands: Past, Present and Future), Centrum výzkumu globální změny Akademie věd České republiky, v.v.i., Brno, Czech Republic, 400 pp., ISBN 978-80-87902-11-0, 2015.
- Brázdil, R., Pfister, C., Wanner, H., von Storch, H., and Luterbacher, J.: Historical climatology in Europe – the state of the art, *Clim. Change*, 70, 363–430, <https://doi.org/10.1007/s10584-005-5924-1>, 2005.
- Brázdil, R., Dobrovolný, P., Trnka, M., Büntgen, U., Řezníčková, L., Kotyza, O., Valášek, H., and Štěpánek, P.: Documentary and instrumental-based drought indices for the Czech Lands back to AD 1501, *Clim. Res.*, 70, 103–117, <https://doi.org/10.3354/cr01380>, 2016a.
- Brázdil, R., Řezníčková, L., Valášek, H., Dolák, L., and Kotyza, O.: Climatic effects and impacts of the 1815 eruption of Mount Tambora in the Czech Lands, *Clim. Past*, 12, 1361–1374, <https://doi.org/10.5194/cp-12-1361-2016>, 2016b.
- Brázdil, R., Kotyza, O., and Bauch, M.: Climate and famines in the Czech Lands prior to AD 1500: Possible interconnections in a European context, in: *Famines during the “Little Ice Age” (1300–1800)*, edited by: Collet, D. and Schuh, M., Springer, Berlin/Heidelberg, Germany, 91–114, ISBN 978-3-319-54341-3, [https://doi.org/10.1007/978-3-319-54337-6\\_5](https://doi.org/10.1007/978-3-319-54337-6_5), 2018.
- Brázdil, R., Demarée, G. R., Kiss, A., Dobrovolný, P., Chromá, K., Trnka, M., Dolák, L., Řezníčková, L., Zahradníček, P., Limanowka, D., and Jourdain, S.: The extreme drought of 1842 in Europe as described by both documentary data and instrumental measurements, *Clim. Past*, 15, 1861–1884, <https://doi.org/10.5194/cp-15-1861-2019>, 2019a.
- Brázdil, R., Možný, M., Klír, T., Řezníčková, L., Trnka, M., Dobrovolný, P., and Kotyza, O.: Climate variability and changes in the agricultural cycle in the Czech Lands from the sixteenth century to the present, *Theor. Appl. Climatol.*, 136, 553–573, <https://doi.org/10.1007/s00704-018-2508-3>, 2019b.
- Brázdil, R., Dobrovolný, P., Mikšovský, J., Pišoft, P., Trnka, M., Možný, M., and Balek, J.: Documentary-based climate reconstructions in the Czech Lands 1501–2020 CE and their European context, *Clim. Past*, 18, 935–959, <https://doi.org/10.5194/cp-18-935-2022>, 2022.
- Brázdil, R., Lhoták, J., Chromá, K., and Dobrovolný, P.: Effects of weather and climate on fluctuations of grain prices in southwestern Bohemia, 1725–1824 CE, *Clim. Past*, 20, 1017–1037, <https://doi.org/10.5194/cp-20-1017-2024>, 2024a.
- Brázdil, R., Lhoták, J., Chromá, K., and Dobrovolný, P.: Data from public granaries as a source of proxy data on grain harvests and weather extremes (Sušice region, Czech Republic), Zenodo [data set], <https://doi.org/10.5281/zenodo.13918307>, 2024b.
- Brunt, L.: Weather shocks and English wheat yields, 1690–1871, *Explor. Econ. Hist.*, 57, 50–58, <https://doi.org/10.1016/j.eeh.2014.12.001>, 2015.
- Camenisch, C.: Endlose Kälte. Witterungsverlauf und Getreidepreise in den Burgundischen Niederlanden im 15. Jahrhundert, Schwabe, Basel, Switzerland, 523 pp., ISBN 3796534686, 2015.
- Campbell, B. M. and Ó Gráda, C.: Harvest shortfalls, grain prices, and famines in preindustrial England, *J. Econ. Hist.*, 71, 859–886, <https://doi.org/10.1017/S0022050711002178>, 2011.
- Campbell, B. M. S.: Four famines and a pestilence: harvest, price, and wage variations in England, 13th to 19th centuries, in: *Agrarhistoria på många sätt*, edited by: Liljewall, B., Flygare, I. A., Lange, U., Ljunggren, L., and Söderberg, J., KSLAB, Stockholm, Sweden, 23–56, 2009.
- Collet, D.: Storage and starvation: public granaries as agents of food security in early modern Europe, *Hist. Soc. Res.*, 35, 234–252, <https://doi.org/10.12759/hsr.35.2010.4.234-252>, 2010.
- Collet, D.: Die doppelte Katastrophe. Klima und Kultur in der europäischen Hungerkrise 1770–1772, Vandenhoeck & Ruprecht, Göttingen, Germany, 466 pp., ISBN 978-3-525-35592-3, 2019.
- Černý, V.: Kontribučenské fondy obilní (Contribution grain funds), in: *Okresní záložny hospodářské 1882–1932, Almanach vydaný na paměť padesátiletého jejich trvání (Regional economic credit unions 1882–1932. Anthology published at 50-years of their duration)*, Svaz okresních záložen hospodářských, Praha, Czechoslovakia, 7–33, 1932.
- Dobrovolný, P., Moberg, A., Brázdil, R., Pfister, C., Glaser, R., Wilson, R., van Engelen, A., Limanowka, D., Kiss, A., Halíčková, M., Macková, J., Riemann, D., Luterbacher, J., and Böhm, R.: Monthly and seasonal temperature reconstructions for Central Europe derived from documentary evidence and instrumental records since AD 1500, *Clim. Change*, 101, 69–107, <https://doi.org/10.1007/s10584-009-9724-x>, 2010.
- Dobrovolný, P., Brázdil, R., Trnka, M., Kotyza, O., and Valášek, H.: Precipitation reconstruction for the Czech Lands, AD 1501–2010, *Int. J. Climatol.*, 35, 1–14, <https://doi.org/10.1002/joc.3957>, 2015.
- Edvinsson, R.: Harvests and grain prices in Sweden, 1665–1870, *Agr. Hist. Rev.*, 60, 1–18, <https://www.jstor.org/stable/23317128> (last access: 19 May 2024), 2012.
- Eitzinger, J., Trnka, M., Semerádová, D., Thaler, S., Svobodová, E., Hlavinka, P., Šiška, B., Takáč, J., Malatinová, L., Nováková, M., Dubrovský, M., and Žalud, Z.: Regional climate change impacts on agricultural crop produc-

- tion in Central and Eastern Europe – hotspots, regional differences and common trends, *J. Agr. Sci.*, 151, 787–812, <https://doi.org/10.1017/S0021859612000767>, 2013.
- Esdaile, C. J.: *The Wars of Napoleon*, Taylor & Francis Ltd., London, New York, UK, USA, 628 pp., ISBN 9781138324145, 2019.
- Esper, J., Büntgen, U., Denzer, S., Krusic, P. J., Luterbacher, J., Schäfer, R., Schreg, R., and Werner, J.: Environmental drivers of historical grain price variations in Europe, *Clim. Res.*, 72, 39–52, <https://doi.org/10.3354/cr01449>, 2017.
- Franko, I.: *Gromadski shpichliri v Galičini 1784–1840 r. (Communal Granaries in Galicia, 1784–1840)*, *Ukrainsko-Ruskiy Archiv II*, Lwov, Galicia, LXXXIV and 168 pp., 1907.
- Gast, M. and Sigaut, F.: *Les techniques de conservation des grains à long terme. Leur rôle dans la dynamique des systèmes de cultures et des sociétés*, Editions du Centre national de la recherche scientifique, Paris, France, 232 pp., ISBN 978-2-222-02507-8, 1979.
- Gates, D.: *Napoleonic Wars 1803–1815*, Pimlico, London, UK, 304 pp., ISBN 9780712607193, 2003.
- Higgins, J. J.: *An Introduction to Modern Nonparametric Statistics*, Thomson Brooks/Cole, Pacific Grove, USA, 366 pp., ISBN 9780534387754, 2004.
- Hildebrandt, H. and Gudd, M.: *Getreidebau, Missernten und Witterung in südwestlichen Vogelsberg und dem angrenzenden Vorland während des 16. und frühen 17. Jahrhunderts*, *Archiv für hessische Geschichte und Altertumskunde*, 49, 85–146, 1991.
- Holopainen, J., Rickard, I. J., and Helama, S.: Climatic signatures in crops and grain prices in 19th-century Sweden, *Holocene*, 22, 939–945, <https://doi.org/10.1177/0959683611434220>, 2012.
- Huhtamaa, H.: Combining written and tree-ring evidence to trace past food crises: a case study from Finland, in: *Famines during the “Little Ice Age” (1300–1800)*, edited by: Collet, D. and Schuh, M., Springer, Berlin/Heidelberg, Germany, 43–66, [https://doi.org/10.1007/978-3-319-54337-6\\_3](https://doi.org/10.1007/978-3-319-54337-6_3), 2018.
- Huhtamaa, H., Helama, S., Holopainen, J., Rethorn, C., and Rohr, C.: Crop yield responses to temperature fluctuations in 19th century Finland: Provincial variation in relation to climate and tree-rings, *Boreal Environ. Res.*, 20, 707–723, 2015.
- Jonášová, S.: *Paměti Františka Jana Vaváka, souseda a rychtáře mlčického z let 1770–1816 (Memoirs of František J. Vavák, Inhabitant of the Neighbourhood and Reeve in Milčice for the Years 1770–1816)*, *Kniha VI–VII (1810–1816)*, Nakladatelství Karolinum, Praha, Czech Republic, 486 pp., ISBN 978-80-246-1482-3, 2009.
- Jones, E. L.: *Seasons and Prices. The Role of the Weather in English Agricultural History*, George Allen & Unwin, London, UK, 193 pp., 1964.
- Kalousek, J.: *Řády selské a instrukce hospodářské 1781–1850 (Peasantry Codes and Economic Instructions 1781–1850)*, *Archiv český* 25, Domestikální fond království Českého, Praha, Bohemia, 800 pp., 1910.
- Kaplan, S. L.: Lean years, fat years: The “community” granary system and the search for abundance in eighteenth-century Paris, *Fr. Hist. Stud.*, 10, 197–230, <https://doi.org/10.2307/286069>, 1977.
- Kendall, M. G.: *Rank Correlation Methods*, 4th ed., Charles Griffin, London, UK, 202 pp., ISBN 9780852641996, 1975.
- Komárek, F.: *Paměti panství a farní osady budenické (Memoirs of the Domain and Parish Settlement of Budenice)*, *Nákladem vlastním*, Praha, Bohemia, 171 pp., 1911.
- Krofta, K.: *Dějiny selského stavu (The History of Peasant Status)*, Jan Laichter, Praha, Czechoslovakia, 458 pp., 1949.
- Li, L. and Dolman, A. J.: On the reliability of composite analysis: an example of wet summers in North China, *Atmos. Res.*, 292, 106881, <https://doi.org/10.1016/j.atmosres.2023.106881>, 2023.
- Liu, T.-J. and Fei, J. C. H.: *The Public Granary Institution of the Ch’ing Dynasty, 1644–1911*, Center Discussion Paper No. 299, Yale University, Economic Growth Center, New Haven, USA, 46 pp., <https://www.econstor.eu/bitstream/10419/160226/1/cdp299.pdf> (last access: 19 May 2024), 1978.
- Ljungqvist, F. C. and Seim, A.: Reassessing grain price variability in early modern Europe (c. 1500–1800), *Eur. Econ. Rev.*, 170, 104852, <https://doi.org/10.1016/j.eurocorev.2024.104852>, 2024.
- Ljungqvist, F. C., Thejll, P., Christiansen, B., Seim, A., Hartl, C., and Esper, J.: The significance of climate variability on early modern European grain prices, *Climatologica*, 16, 29–77, <https://doi.org/10.1007/s11698-021-00224-7>, 2022.
- Ljungqvist, F. C., Christiansen, B., Esper, J., Huhtamaa, H., Leijonhufvud, L., Pfister, C., Seim, A., Skoglund, M. K., and Thejll, P.: Climatic signatures in early modern European grain harvest yields, *Clim. Past*, 19, 2463–2491, <https://doi.org/10.5194/cp-19-2463-2023>, 2023.
- Løvdal, Ø.: *Kornmagasin, klima og kriser En studie av kornmagasiner som håndtering av klimatiske kriser på 1700- og 1800-tallet i Norge (Granaries, Climate, and Crisis. A Study on Coping with Climatic Crises in the 18th and 19th Centuries)*, MA-thesis, University of Oslo, Norway, 88 pp., <http://urn.nb.no/URN:NBN:no-87397> (last access: 19 May 2024), 2020.
- Luterbacher, J. and Pfister, C.: The year without a summer, *Nat. Geosci.*, 8, 246–248, <https://doi.org/10.1038/ngeo2404>, 2015.
- Mann, H. B.: Non-parametric tests against trend, *Econometrica*, 13, 163–171, <https://doi.org/10.2307/1907187>, 1945.
- Martínez-González, J. L.: Assessing agricultural adaptation to changing climatic conditions during the English agricultural revolution (1645–1740), *Climatologica*, 19, 163–193, <https://doi.org/10.1007/s11698-024-00285-4>, 2025.
- Meuvret, J.: *Le problème des subsistances à l’époque de Louis XIV. Tome I: La production des céréales dans la France du XVIIIe et XVIIIe siècle*, Paris-La Haye et École des Hautes Études en Sciences Sociales, Paris, ISBN 978-2713200342, 224 pp., 1977.
- Meuvret, J.: *Le problème des subsistances à l’époque de Louis XIV. Tome II: La production des céréales et la société rurale*, École des Hautes Études en Sciences Sociales, Paris, ISBN 978-3110985658, 286 and 275 pp., 1987.
- Meuvret, J.: *Le problème des subsistances à l’époque de Louis XIV. Tome III: Le commerce des grains et la conjoncture*, Éditions de École des Hautes Études en Sciences Sociales, Paris, ISBN 978-2713208867, 191 and 162 pp., 1988.
- Morales, J., Rodríguez-Rodríguez, A., González-Marrero, M. del C., Martín-Rodríguez, E., Henríquez-Valido, P., and del-Pino-Curbelo, M.: The archaeobotany of long-term crop storage in northwest African communal granaries: a case study from pre-Hispanic Gran Canaria (cal. AD 1000–1500), *Veg. Hist. Archaeobot.*, 23, 789–804, <https://doi.org/10.1007/s00334-014-0444-4>, 2014.
- Neruda, J.: *Výjimky z kroniky selské (Excerpt from peasant chronicle)*, in: *Dílo Jana Nerudy XI, Drobné klepy*, Nakladatelé Kvasnička a Hanyl, Praha, Bohemia, 203–212, 1862.

- Neue Schriften: Neue Schriften der kais. königl. patriotisch-ökonomischen Gesellschaft im Königreiche Böhmen, Gottlieb Haase Söhne, Prag, Bohemia, 1830–1847.
- Neue Schriften: Neue Schriften der kais. königl. patriotisch-ökonomischen Gesellschaft im Königreiche Böhmen, Zweiten Bandes erstes Heft, Gottlieb Haase Söhne, Prag, Bohemia, 216 pp., 1830.
- Neue Schriften: Neue Schriften der kais. königl. patriotisch-ökonomischen Gesellschaft im Königreiche Böhmen, Dritten Bandes Erstes Heft, Gottlieb Haase Söhne, Prag, Bohemia, 179 pp., 1833.
- Neue Schriften: Neue Schriften der kaiserl. königl. patriotisch-ökonomischen Gesellschaft im Königreiche Böhmen, Sechsten Bandes Erstes Heft, Gottlieb Haase Söhne, Prag, Bohemia, 216 pp., 1838.
- Neue Schriften: Neue Schriften der kaiserl. königl. patriotisch-ökonomischen Gesellschaft im Königreiche Böhmen, Siebenten Bandes Erstes Heft, Gottlieb Haase Söhne, Prag, Bohemia, 215 pp., 1840.
- Neue Schriften: Neue Schriften der kaiserl. königl. patriotisch-ökonomischen Gesellschaft im Königreiche Böhmen, Siebenten Bandes Zweites Heft, Gottlieb Haase Söhne, Prag, Bohemia, 237 pp., 1841.
- Petr, J. (Ed.): Počasí a výnosy (Weather and yields), Státní zemědělské nakladatelství, Praha, Czechoslovakia, 368 pp., 1987.
- Petráň, J.: Ceny obilí a tržní okruhy v Čechách v 18. a počátkem 19. století (Grain prices and market cycles in Bohemia in the 18th century and at the beginning of the 19th century), *Acta Universitatis Carolinae, Philosophica et historica* 3, *Studia historica*, 17, 9–49, 1977.
- Pfister, C.: Fluctuations climatiques et prix céréalières en Europe du XVIIe au XXe siècle, *Ann. Hist. Sci. Soc.*, 43, 25–53, 1988.
- Pfister, C. and Brázdil, R.: Social vulnerability to climate in the "Little Ice Age": an example from Central Europe in the early 1770s, *Clim. Past*, 2, 115–129, <https://doi.org/10.5194/cp-2-115-2006>, 2006.
- Pfister, C. and Wanner, H.: *Climate and Society in Europe, The Last Thousand Years*, Verlag Paul Haupt, Bern, Switzerland, 400 pp., ISBN 9783258082349, 2021.
- Polanyi, K.: *The Great Transformation. The Political and Economic Origin of Our Time*, Beacon Press, Boston, USA, 360 pp., ISBN 9780807056431, 2018.
- Prasek, V.: Záložny kontribučenské jak vznikly (How originated taxation credit unions), *Selský archiv*, 3, 212–220, 1904.
- Pribyl, K.: Climate and the grain price, 1264–1431, in: *Farming, Famine and Plague: The Impact of Climate in Late Medieval England*, edited by: Pribyl, K., Springer, Berlin/Heidelberg, Germany, 187–198, [https://doi.org/10.1007/978-3-319-55953-7\\_9](https://doi.org/10.1007/978-3-319-55953-7_9), 2017.
- Rácz, L.: Carpathian Basin – the winner of the Little Ice Age climate changes: Long-term time-series analysis of grain, grape and hay harvests between 1500 and 1850, *Economic- and Ecohistory*, 16, 81–96, <https://hrcak.srce.hr/file/369363> (last access: 19 May 2024), 2020.
- Rácz, L.: The impact of the Little Ice Age on winter wheat yields in the Carpathian Basin in the first half of the 19th century, *Economic- and Ecohistory*, 19, 5–27, <https://hrcak.srce.hr/en/file/462752> (last access: 19 May 2024), 2023.
- Reimarus, J. A. H.: Preisschrift über die, von der K. Societät der Wissenschaften zu Göttingen aufgegebenen Frage: In wie fern und unter welchen Umständen die Anlegung beträchtlicher öffentlicher Kornmagazine dem Kornhandel und dem Lande überhaupt nachtheilig oder nützlich oder gleichgültig sey? Wie diese Magazine mit den wenigsten Kosten anzulegen und zu erhalten, auch dergestalt zu verwalten seyn, daß dem Lande daraus der meiste Nutzen zuwachse? Welche Folgen aus den öffentlichen Kornmagazinen in den Ländern, wo dergleichen befindlich sind, entstanden? und welche Folgen deren Mangel veranlassen habe, *Hannoversches Magazin*, 10, 1057–1070 and 1073–1082, 1772.
- Resultate: Resultate aus den Witterungsbeobachtungen von den Jahren 1822 bis einschliessig 1826, nebst Jahresberichten; als Fortsetzung der in der ersten und zweiten Lieferung dargestellten Witterungsbeobachtungen, Gottlieb Haase Söhne, Prag, Bohemia, 1828.
- Robek, A.: Lidové kronikářství na Kralupsku a Mělnicku. Edice lidových kronikářských textů (Folk Chronicle Writing of the Kralupy and Mělník Regions. Edition of the Texts of Folk Chronicles), Ústav pro etnografii a folkloristiku ČSAV, Praha, Czechoslovakia, 253 pp., 1974.
- Robek, A.: Městské lidové kronikářství na Rychnovsku I. Edice lidových kronikářských textů (Town Folk Chronicle Writing of the Rychnov Region I. Edition of the Texts of Folk Chronicles), Ústav pro etnografii a folkloristiku ČSAV, Praha, Czechoslovakia, 211 pp., 1976.
- Robek, A.: Lidové kronikářství na Lounsku. Prameny lidové provenience 3. Edice etnografických pramenů (Folk Chronicle Writing of the Louny Region, Sources of Folk Origin 3, Edition of the Ethnographic Sources), Ústav pro etnografii a folkloristiku ČSAV, Praha, Czechoslovakia, 161 pp., 1979.
- Salido Domínguez, J.: Supplying the Roman towns in Hispania. Granaries and warehouses, in: *Wirtschaftsbauten in der Antiken Stadt*, edited by: Fellmeth, U., Krüger, J., Ohr, K., and Rasch, J. J., KIT Scientific Publishing, Karlsruhe, Germany, 181–196, <https://books.openedition.org/ksp/5464> (last access: 20 May 2024), 2016.
- Scott, S., Duncan, S. R., and Duncan, C. J.: The origins, interactions and causes of the cycles in grain prices in England, 1450–1812, *Agr. Hist. Rev.*, 46, 1–14, <https://www.jstor.org/stable/40275190> (last access: 19 May 2024), 1998.
- Sen, P. K.: Estimates of the regression coefficient based on Kendall's tau, *J. Am. Stat. Assoc.*, 63, 1379–1389, <https://doi.org/10.1080/01621459.1968.10480934>, 1968.
- Seppel, M.: Communal granaries in the Russian Empire, *Jahrb. Gesch. Osteur.*, 67, 183–205, <https://www.jstor.org/stable/10.2307/26831808> (last access: 9 May 2024), 2019.
- Shiue, C.: Local granaries and central government disaster relief: Moral hazard and intergovernmental finance in eighteenth- and nineteenth-century China, *J. Econ. Hist.*, 64, 100–124, <https://doi.org/10.1017/S002205070400261X>, 2024.
- Skoglund, M. K.: Climate variability and grain production in Scania, 1702–1911, *Clim. Past*, 18, 405–433, <https://doi.org/10.5194/cp-18-405-2022>, 2022.
- Skoglund, M. K.: Farming at the margin: Climatic impacts on harvest yields and agricultural practices in Central Scandinavia, c. 1560–1920, *Agr. Hist. Rev.*, 71, 203–233, 2023.

- Skoglund, M. K.: The impact of drought on Northern European pre-industrial agriculture, *Holocene*, 34, 120–135, <https://doi.org/10.1177/09596836231200431>, 2024.
- Skopec, J.: Paměti Františka J. Vaváka, souseda a rychtáře milčického z let 1770–1816 (Memoirs of František J. Vavák, Inhabitant of the Neighbourhood and Reeve in Milčice for the Years 1770–1816), *Knihy třetí (Rok 1791–1801), Část II. (1795–1797)*, Nákładem “Dědictví sv. Jana Nepomuckého”, Praha, Bohemia, 111 pp., 1916.
- Skopec, J.: Paměti Františka J. Vaváka, souseda a rychtáře milčického z let 1770–1816 (Memoirs of František J. Vavák, Inhabitant of the Neighbourhood and Reeve in Milčice for the Years 1770–1816), *Knihy třetí (Rok 1791–1801), Část III. (1798–1800)*, Nákładem “Dědictví sv. Jana Nepomuckého”, Praha, Bohemia, 132 pp., 1918.
- Skopec, J.: Paměti Františka J. Vaváka, souseda a rychtáře milčického z let 1770–1816 (Memoirs of František J. Vavák, Inhabitant of the Neighbourhood and Reeve in Milčice for the Years 1770–1816), *Knihy pátá (Rok 1807–srpen 1810)*, Nákładem “Dědictví sv. Jana Nepomuckého”, Praha, Czechoslovakia, 232 pp., 1938.
- Sommer, J. G.: Das Königreich Böhmen; statistisch-topographisch dargestellt. Siebenter Band. Klattauer Kreis, J. G. Calve Buchhandlung, Prag, Bohemia, 284 pp., 1839.
- Sommer, J. G.: Das Königreich Böhmen; statistisch-topographisch dargestellt. Achter Band. Prachiner Kreis, J. G. Calve Buchhandlung, Prag, Bohemia, 448 pp., 1840.
- Šedivý, I.: Napoleonské války a české země (Napoleonic Wars and Czech Lands), *Nakladatelství Lidové noviny*, Praha, Czech Republic, 301 pp., ISBN 978807106467X, 2001.
- Šimon, A.: Záznamy přírodních zjevů na Hradištsku (Notes of natural phenomena in the Hradiště region), *Od Ještěda k Troskám*, 6, 56–60, 1927.
- Teerijoki, L.: Nälkävuosien turva? Pitäjänmakasiinit Suomessa 1700-luvulla (A Securite Measure for Famine Years? Parish Grain Storehouses in Finland during the 18th Century), *Suomen historiallinen seura*, Helsinki, Finland, 280 pp., ISBN 9518915776, 1993.
- Theil, H.: A rank-invariant method of linear and polynomial regression analysis, in: *Henri Theil's Contributions to Economics and Econometrics, Advanced Studies in Theoretical and Applied Econometrics* 23, edited by: Raj, B. and Koerts, J., Springer, Dordrecht, Netherlands, 345–381, [https://doi.org/10.1007/978-94-011-2546-8\\_20](https://doi.org/10.1007/978-94-011-2546-8_20), 1992.
- Tolasz, R., Míková, T., Valeriánová, A., and Voženílek, V.: *Atlas podnebí Česka (Climate Atlas of Czechia)*, Český hydrometeorologický ústav, Univerzita Palackého v Olomouci, Praha, Olomouc, Czech Republic, 255 pp., ISBN 9788086690261, 2007.
- Trnka, M., Brázdil, R., Brilli, L., von Czettritz und Neuhaus, H. C., Costafreda-Aumedes, S., Dobrovolný, P., Holub, P., Klem, K., Kuhnert, M., Leolini, L., Moriondo, M., Muntean, N., Olesen, J. E., Poděbradská, M., Potopová, V., Štěpánek, P., Urban, O., Zander, P., and Nendel, C.: Modelling the impact of climate change on agriculture in Europe, in: *Modelling climate change impacts on agricultural systems*, edited by: Nendel, C., Burleigh Dodds Science Publishing, Cambridge, UK, 361–408, ISBN 978 1 80146 174 0, <https://doi.org/10.19103/AS.2022.0115.14>, 2023.
- Urban, J. F.: *Písmák jižního Plzeňska Václav Jan Mašek (The chronicler of the south Plzeň region, Václav Jan Mašek)*, Granát, Horní Bříza, Czech Republic, 177 pp., ISBN 9788090221130, 1999.
- Verhandlungen und Mitteilungen: Verhandlungen und Mitteilungen der k. k. patriotisch-ökonomischen Gesellschaft im Königreiche Böhmen, und des mit ihr verbundenen Schafzüchter-, so wie des pomologischen Vereins. Erster Band, Friedrich Tempsky, Prag, Bohemia, 419 pp. + appendices, 1849.
- Verhandlungen und Mitteilungen: Verhandlungen und Mitteilungen der k. k. patriotisch-ökonomischen Gesellschaft im Königreiche Böhmen, und des mit ihr verbundenen pomologischen, so wie des Schafzüchter-Vereines. Zweiter Band, Friedrich Tempsky, Prag, Bohemia, 300 pp. + appendix, 1850.
- Vodnařík, E.: *Dějiny a statistika moravských kontribučních záložních ústavů (The History and Statistics of Moravian Taxation Credit Unions)*, Eduard Vodnařík, Brno, Moravia, 100 pp., 1886.
- von Storch, H. and Zwiers, F. W.: *Statistical Analysis in Climate Research*, Cambridge University Press, Cambridge, UK, 484 pp., ISBN 0-521-01230-9, 1999.
- White, S., Brooke, J., and Pfister, C.: Climate, weather, agriculture, and food, in: *The Palgrave Handbook of Climate History*, edited by: White, S., Pfister, C., and Mauelshagen, F., Palgrave Macmillan, London, UK, 331–353, ISBN 978-1-137-43019-9, [https://doi.org/10.1057/978-1-137-43020-5\\_27](https://doi.org/10.1057/978-1-137-43020-5_27), 2018a.
- White, S., Pfister, C., and Mauelshagen, F.: *The Palgrave Handbook of Climate History*, Palgrave Macmillan, London, UK, 656 pp., ISBN 978-1-137-43019-9, <https://doi.org/10.1057/978-1-137-43020-5>, 2018b.
- Will, P.-É. and Wong, R. B.: *Nourish the People. The State Civilian Granary System in China, 1650–1850*, University of Michigan Press, Ann Arbor, USA, 634 pp., ISBN 978-0-472-90182-1, <https://doi.org/10.3998/mpub.19044>, 1991.
- Wrigley, E.: Some reflections on corn yields and prices in pre-industrial economies, in: *Famine, disease and the social order in early modern society*, edited by: Walter, J. and Schofield, R., Cambridge University Press, Cambridge, UK, 235–278, ISBN 9780521259064, 1989.
- Yin, J., Su, Y., and Fang, X.: Relationships between temperature change and grain harvest fluctuations in China from 210 BC to 1910 AD, *Quatern. Int.*, 355, 153–163, <https://doi.org/10.1016/j.quaint.2014.09.037>, 2015.