



Linking European building activity with plague history

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ABSTRACT

Variations in building activity reflect demographic, economic and social change during history. Tens of thousands of wooden constructions in Europe have been dendrochronologically dated in recent decades. We use the annually precise evidence from a unique dataset of 49 640 tree felling dates of historical constructions to reconstruct temporal changes in building activity between 1250 and 1699 CE across a large part of western and central Europe largely corresponding to the former Holy Roman Empire of the German Nation. Comparison with annual records of 9772 plague outbreaks shows that construction activity was significantly negatively correlated to the number of plague outbreaks, with the greatest decrease in construction following the larger outbreaks by three to four years after the start of the epidemics. Preceding the Black Death (1346–1353 CE) by five decades and the Great Famine (1315–1322 CE) by two decades, a significant decline in construction activity at c. 1300 CE is indicative of a societal crisis, associated with population stagnation or decline. Another dramatic decline in building activity coincides with the Thirty Years' War (1618–1648 CE) and confirms the devastating nature of this conflict. While construction activity was significantly lower during periods of high grain prices, no statistically robust relationship between the number of felling dates and past temperature or hydroclimate variations is found. This study demonstrates the value of dendrochronological felling dates as an indicator for times of crisis and prosperity during periods when documentary evidence is limited.

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1. Introduction

Plague is a rapidly progressing zoonotic disease, caused by the bacterium *Yersinia pestis*, that can spill over into human populations and is capable of having major and long-lasting demographic consequences. Environmental factors, including climate, influence its epidemiological behavior in space and time (Stenseth et al., 2006, 2008; Kausrud et al., 2007; Walløe, 2008; Xu et al., 2011, 2014; Schmid et al., 2015; Tian et al., 2017; Yue and Lee, 2018). Plague is infamous for having caused tens of millions of deaths in large historic pandemics, most notably in Europe during the late medieval Black Death (1346–1353 CE) (Benedictow, 2004).

Europe's economic and demographic down-turn during the fourteenth and fifteenth centuries, the so-called Late Medieval Crisis, has to a large extent been attributed by most researchers to the Black Death and the following recurrent plague outbreaks (Russell, 1972; Sandnes, 1977; Gissel et al., 1981; Herlihy, 1997; Harrison, 2000; Cohn, 2002; Benedictow, 2004, 2016; Myrdal, 2009). However, it has also been acknowledged that the crisis, in some respects, predated the Black Death and was triggered by a combination of political and religious upheavals, as well as declining average living standards, and an increasing frequency and severity of famines (Postan, 1972; Anderson, 1974; Parry, 1978; Bois, 1984; Herlihy, 1989; Bartlett, 1993; Aberth, 2001; Dybdahl, 2010, 2012; DeWitte, 2015; Ljungqvist, 2017a; Campbell, 2018).

Direct and indirect contributions of climate change to the crisis, e.g. negative impacts on agricultural productivity with the climatic cooling of the Little Ice Age (Büntgen and Hellmann, 2014), have long been suspected (see Steensberg (1951) for an early example). Following recent advancements in high-resolution paleoclimatic reconstructions for medieval Europe (Büntgen et al., 2010, 2011; 2013, 2016; Cook et al., 2015; Luterbacher et al., 2016), this view has become increasingly popular (e.g. Aberth, 2013; Campbell, 2016). Special attention has been paid to the Great Famine 1315–1322 CE (Lucas, 1930; Kershaw, 1973; Jordan, 1996, 2010; Campbell, 1991, 2009; Slavín, 2014, 2018; Geens, 2018) caused by harvest failures due to an excessive precipitation during the growing seasons of 1314–1316 CE in combination with a

highly lethal and large-scale outbreak of cattle disease 1315–1325 CE (Newfield, 2009; Slavín, 2012). The Great Famine was the most mortal, largest and longest lasting recorded subsistence crisis in European history north of the Alps, not only during the fourteenth century but for the whole past millennium, with a population decline of around 10%. The relative roles of plague and climate in relation to the Late Medieval Crisis have been hard to quantify and results are ambiguous. However, it is clear that by the late fourteenth century, the population of Europe had been heavily reduced (Campbell, 2016). Widespread desertions of farmland and villages (Abel, 1980), and even substantial reforestation of sizable portions of Europe (Kaplan et al., 2009) followed in the wake of the population collapse (Biraben, 1979).

A compilation of dendrochronological felling dates from historical construction timbers from southeastern Sweden, together with local pollen data, recently supported the view that the depopulation started with the Black Death (Lagerås et al., 2016). By contrast, Thun and Svarva (2018) showed, by felling dates alone, that Norway experienced an almost complete cessation of construction activities preceding the Black Death by some decades. The contrasting results suggest an existence of geographical variations in the timing of the onset of the crisis even within a relatively small region such as Scandinavia.

Absolutely dated tree felling dates from well-preserved historical construction timbers constitute a promising source for constraining the timing of societal crises and estimating demographic declines (e.g. Baillie, 1982, 1995; Schweingruber, 1988; Nicolussi, 2002; Eckstein, 2007), especially during periods when documentary evidence is of insufficient quantity and quality. Tree felling dates have, for example, been used to reconstruct demographic trends among the Ancestral Puebloans in the southwestern United States (e.g. Douglass, 1921, 1929; Dean, 1969; Eighmy, 1979; Berry, 1982; Berry and Benson, 2010; Bocinsky et al., 2016) as well as the settlement history in parts of the Swiss Alps (Büntgen et al., 2006), northwestern Carpathian arc (Büntgen et al., 2013), north-eastern France (Tegel et al., 2016) and in parts of medieval Scandinavia (Lagerås et al., 2016; Thun and Svarva, 2018). However, no attempts have hitherto been made to use annually resolved and absolutely dated felling dates to reconstruct past settlement and demographic dynamics on larger spatiotemporal scales in

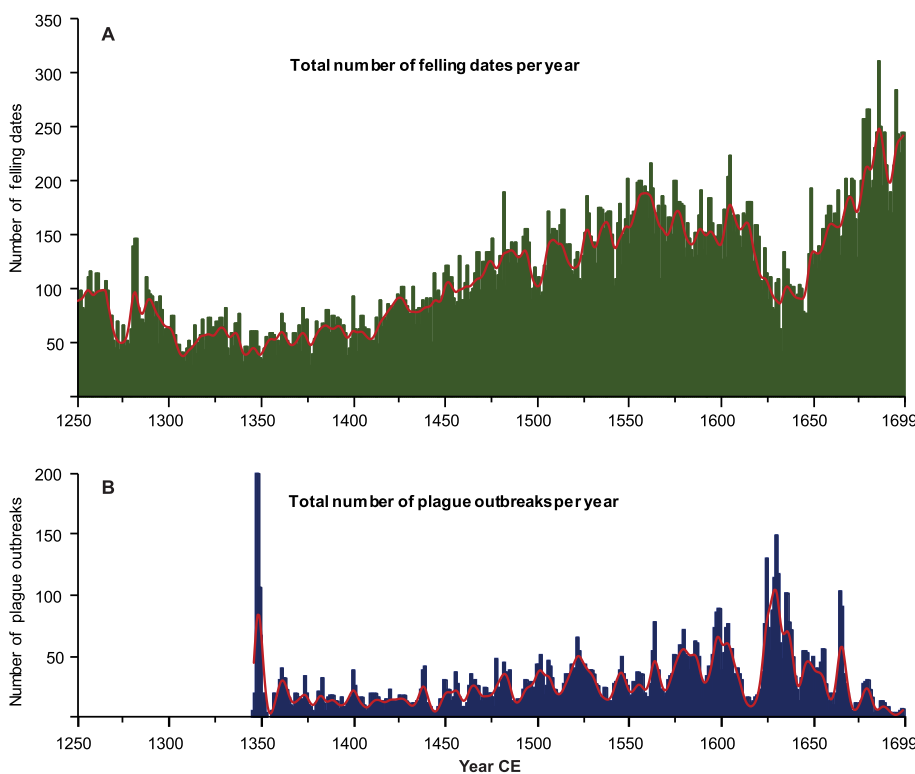


Fig. 1. (A) The 49 640 felling dates averaged across western and central Europe from 1250 to 1699 CE. (B) The 9772 recorded plague outbreaks averaged across the whole of Europe from 1346 to 1699 CE. A 10-year low-pass filter (red lines) is applied to the annually resolved values (vertical bars). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Europe. Here, we analyze 49 640 felling dates from across a large part of western and especially central Europe over the period 1250–1699 CE and explore their potential and limitations for reconstructing past societal and demographic changes. Particular attention is paid to the detection of: (1) effects of large plague outbreaks, (2) the onset and duration of the Late Medieval Crisis, (3) the fingerprints of high grain prices and short-term climatic extremes, and (4) impacts of the Thirty Years' War (1618–1648 CE).

2. Materials and methods

2.1. Felling dates

Here we present the largest collection of felling dates so far from historical construction timbers from much of western and central Europe (Fig. 1a), primarily the German- and French-speaking parts of the former Holy Roman Empire of the German Nation. Comprised of 49 640 entries, this dataset is the product of decades of dendrochronological dating work in Austria, Belgium, the Czech Republic, France, Germany, and Switzerland (Table 1; Fig. 2a). The tree-ring sequences used for this study contain only series where the terminal ring of the last year of tree growth is present, the so-called waney edge. Hence, we can determine the exact felling year of the used trees.

The dendrochronological dating was primarily initiated for the following three reasons: (a) inventory of historical buildings for protection and historical research, (b) accompanying documentation in context of renovation, restoration, re-use and demolition of architectural monuments, and (c) various academic research projects. The vast majority of all studied timbers are from towns, typically small ones in rural settings that in many cases have lost their importance in modern times. Under such conditions old buildings were most likely to survive despite the destruction caused by later wars and nineteenth and twentieth century urban renewal. Rural farm buildings pre-dating the seventeenth century are rarely preserved and are therefore only represented to a limited extent in our dataset.

Most of the felling dates come from roof trusses, ceiling joists, buttresses and basement pillars (Fig. 2b). The majority of the wood survived under largely dry conditions in buildings that are in many cases still intact. Only a small proportion of archaeological timbers from hydraulic structures and mining activities (Tegel and Hakelberg, 2008; Straßburger and Tegel, 2009) are represented in the older part of this collection. The most preferred broadleaf species for timber in western and central Europe was oak (*Quercus* spp.), due to its favorable technological properties and durability (Haneca et al., 2009; Tegel et al.,

2010; Büntgen et al., 2011). For wooden constructions in buildings, coniferous species comprising fir (*Abies alba*), spruce (*Picea abies*) and pine (*Pinus sylvestris*) were also frequently used due to their favorable weight to strength ratio (Straßburger and Tegel, 2009).

2.2. Plague outbreaks

To analyze the relationship between construction activity and plague frequency, we used 9772 annually dated plague outbreaks that occurred between 1346 and 1699 CE (Fig. 1b). It should be noted that the digitized and georeferenced plague evidence by Büntgen et al. (2012), used for this study, only represents a subset of the original inventory by Biraben (1975–1976). The plague dataset of Biraben (1975–1976) is most likely biased towards France (see Section 4.1 for details), and prone to methodological errors (e.g., Roosen and Curtis, 2018), with a lack of information about how plague outbreaks are retrospectively diagnosed.

To test whether the unequal coverage of both the plague and tree felling datasets would affect the results, we performed an initial experiment with a subset of 3305 plague outbreaks from Germany and north-eastern France, where the bulk of the felling dates are concentrated. After finding a highly significant correlation ($r = 0.75$) between the number of outbreaks in the full and partial dataset, we continued working only with the full dataset including 9772 plague outbreaks with the understanding that: (a) the German and north-eastern France subset does not exactly overlap with the spatial domain of our felling dates, (b) pan-European epidemics did not only affect local communities but had far-reaching consequences, and (c) the full dataset can be expected to more accurately capture the major epidemics across the continent.

2.3. Grain price and climate data

To compare the number of felling dates with grain prices, we used the average European grain price record by Esper et al. (2017) from 1348 CE onwards when at least two series per year are available. The underlying historical grain price dataset consists of nineteen records from central and northern Europe, covering different periods between the fourteenth and eighteenth centuries. All records span the period 1546–1660 CE, and their average length is 295 years. The maximum individual record length is 445 years (Exeter, 1316–1800 CE), with a minimum of 178 years (Leiden, 1480–1660 CE). The inter-series correlation is high, with the exception of those records from peripheral locations, suggesting that all records can be combined into one

Table 1

List of data contributors for the felling dates, their main affiliation, contribution size, and the geographical origin of their samples. All data contributors are included as co-authors to the article.

Data contributor	Affiliation	Nr of dates	Region/country
1. Hanns Hubert Leuschner	University of Göttingen, Germany	6096	Northern and central Germany
2. Karl-Uwe Heussner	German Archaeological Institute, Germany	11 369	North-eastern Germany
3. Thorsten Westphal	Curt-Engelhorn-Zentrum Archäometrie gGmbH, Germany	714	Central Germany
4. Kristof Haneca	Flanders Heritage Agency, Belgium	8	Flanders, Belgium
5. David Houbrechts	Association du Patrimoine Artistique, Belgium	1998	Wallonia, Belgium
6. Willy Tegel	University of Freiburg, Germany	541	North-eastern France
7. Jutta Hofmann	Jahrlinglabor Hofmann, Germany	10 438	Southern Germany
8. Friederike M. Gschwind	Büro für Dendrochronologie, Germany	403	Bavaria, Germany
9. Franz Herzig	Bavarian State Office for Monument Protection, Germany	559	Bavaria, Germany
10. Tomáš Kyncl	CzechGlobe, Czech Republic	4064	Bohemia, Czech Republic
11. Christophe Perrault	Lab. CEDRE, France	2691	Central France
12. Martin Schmidhalter	Dendrosuisse, Switzerland	1412	South-western Switzerland
13. Raymond Kontic	Lab. DENDRON, Switzerland	3760	Northern Switzerland
14. Felix Walder	City of Zürich, Switzerland	2320	Northern Switzerland
15. Mathias Seifert	Amt für Kultur, Switzerland	1751	North-eastern Switzerland
16. Kurt Nicolussi	University of Innsbruck, Austria	761	Western Austria
17. Klaus Pfeifer	Labor für Dendrochronologie, Austria	755	Western Austria

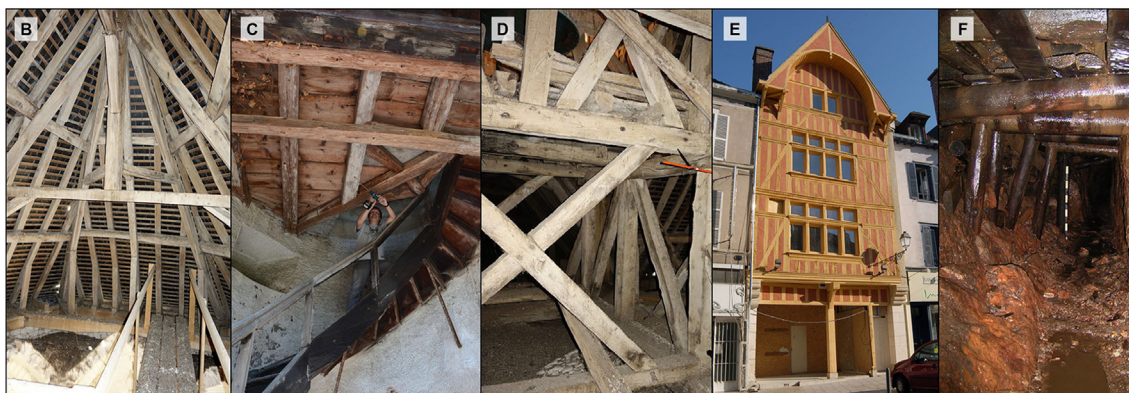
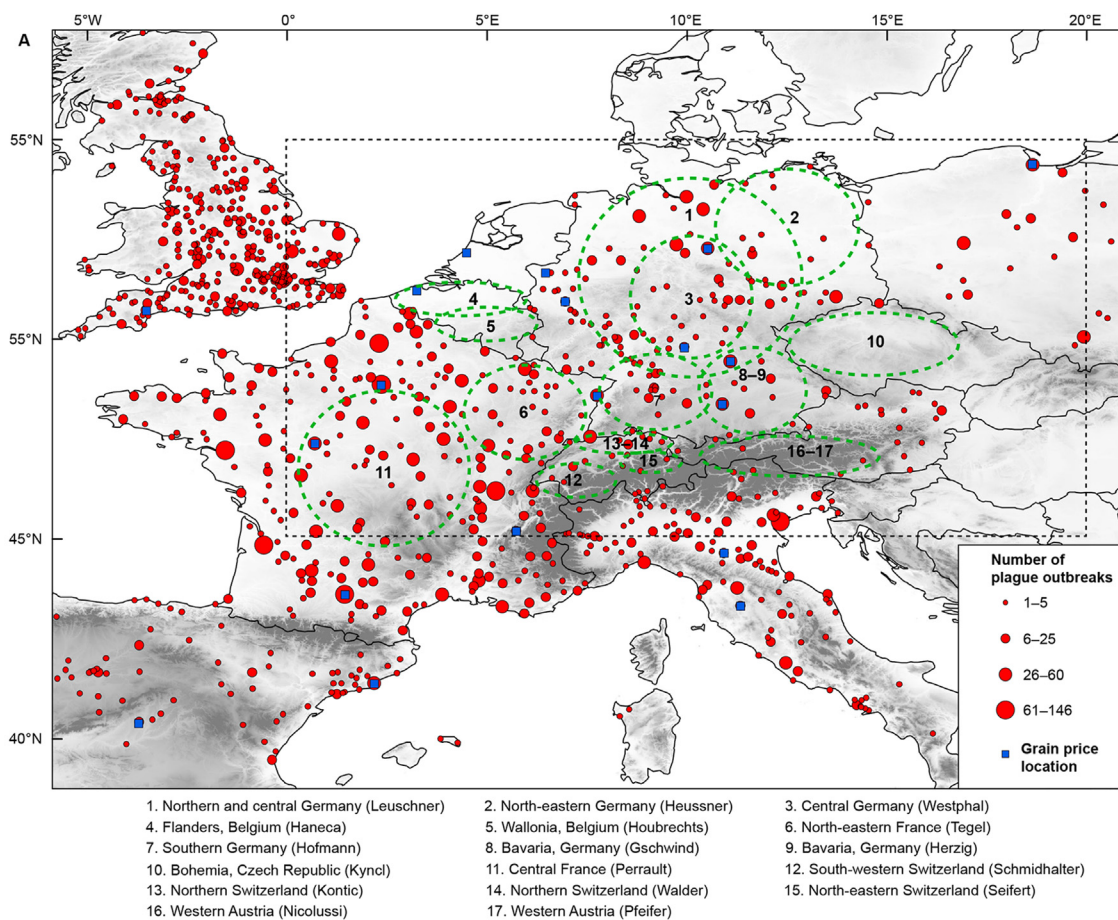


Fig. 2. (A) Map showing the approximate locations from where the felling dates of the historical construction timber in our dataset originate. Dashed green circles indicate the approximate locations of felling dates contributed from each of the different data contributors (Table 1). Filled red circles show the locations of recorded plague outbreaks 1346–1699 CE (larger size signifies more recorded outbreaks) digitized and georeferenced by Büntgen et al. (2012) from the inventory of Biraben (1975–1976). The blue squares mark the locations of the cities from where our grain price data originate. The dashed black box denotes the geographic delimitations of our temperature and hydroclimate datasets. (B–F) Figures showing examples of constructions that our dendroarchaeological felling dates originate from. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

normalized index series (Esper et al., 2017).

To assess possible relationships between the number of felling dates and climate conditions, we used two annually resolved spatial climate reconstructions for the past millennium across Europe: the June–August temperature “atlas” of Luterbacher et al. (2016), and the June–August self-calibrating Palmer Drought Severity Index (scPDSI; van der Schrier et al., 2013) from the Old World Drought Atlas (OWDA) of Cook et al. (2015). The temperature reconstruction is derived from tree-ring records (both ring width and maximum latewood density), as well as historical documentary data, interpolated on a 5° × 5° grid and calibrated to instrumental temperature anomalies with regard to the

1961–1990 CE mean. The OWDA is developed from a tree-ring network of 106 sites, calibrated to instrumental observations of scPDSI, and interpolated on a 0.5° × 0.5° grid. We computed the average temperature and scPDSI for all grid cells within the domain 0–20°E and 45–55°N from both datasets.

2.4. Statistical analyses

A sizable proportion of the long-term trends in both the felling dataset and plague dataset most likely are biased due to decreasing preservation rates of constructions back in time and because a larger

proportion of small plague outbreaks in the earliest centuries went unrecorded (Section 4.1). To address these time-dependent constraints, we removed the long-term trends in both the felling dates and plague outbreaks by calculating ratios between the raw values and 300-year cubic smoothing splines (Cook and Peters, 1981) (Fig. 3) using a custom developed F77-Fortran spline program. As a sensitivity test, we performed all analyses on different frequency filtered transformations of both felling and plague data. After filtering, the data were transformed to standard normal deviates having a mean of zero and a standard deviation of one. Since long-term trends in the temperature and hydroclimatic records contain useful information, they remain unfiltered. For the correlation statistics all datasets are, besides using the annual values, smoothed using 10-year splines as well as 10-year, non-overlapping, box-car filters.

The superposed epoch analysis (SEA; Chree, 1913, 1914) method is used to identify statistically significant departures in the number of felling dates associated with the timing of plague outbreaks, high grain prices, and climatic extremes. In our implementation of the SEA, using a custom developed program for the purpose written in F77-Fortran, a 95% confidence interval is estimated by 1000 randomizations, testing the effect of the key year selections in the determination of the outcome. We present the median values from the SEA, but conducted the same experiments using the Gaussian and the bi-weight robust means (Hoaglin et al., 1983). We calculated the total number of recorded plague occurrences for each year (Fig. 2B) to define key years with the 10 and 20 most severe plague outbreaks, respectively, for the SEA. For plague outbreaks that spanned several years we selected the first year when the outbreak exceeded one standard deviation. If another less severe plague outbreak exceeded one standard deviation but occurred within two years on either side of the most severe outbreak, we excluded that outbreak in our key year list. As a sensitivity test, alternative lists of plague outbreak years were created, allowing for clusters

of plague years, requiring three years instead of two years to pass between outbreaks, and including all plague years exceeding either one standard deviation or half a standard deviation.

We used the sequential algorithm of Rodionov (2004) in a Matlab environment to detect years when significant ($p < 0.05$) regime shifts occurred, i.e. we identified the start year of a decreasing or increasing trend in the number of felling dates using both a 30- and 50-year cut-off length on both the unfiltered and 300-year filtered datasets. The Rodionov (2004) regime shift test searches for multiple, significant, change-points based on the F-test.

3. Results

By applying the regime shift algorithm to the felling date data, we detected the center year of significant shifts in the number of felling dates (Table 2). The Late Medieval Crisis, occurring c. 1300–1415 CE based on the felling dates, appears as a prominent feature. A step-wise increase in felling dates is seen afterwards until c. 1580 CE. The effect of the Thirty Years' War (1618–1648 CE) is clearly evident from the sharp decrease of felling dates. In the following sections, we focus on the impact of plague outbreaks on the number of felling dates, then on the Late Medieval Crisis, and finally the Thirty Years' War.

3.1. Plague outbreaks and construction activity

We find a significantly negative relationship between the numbers of felling dates and plague outbreaks. Construction activity was lower during periods with many plague outbreaks ($r = -0.25$; $r = -0.43$ for 10-year smoothed data and $r = -0.47$ for 10-year box-car filtered data). Similar results are obtained using Pearson's correlation and Spearman's rank correlation (Table 3). Considering the strong impact of the Thirty Years' War (1618–1648 CE) (Section 3.4) on the number of

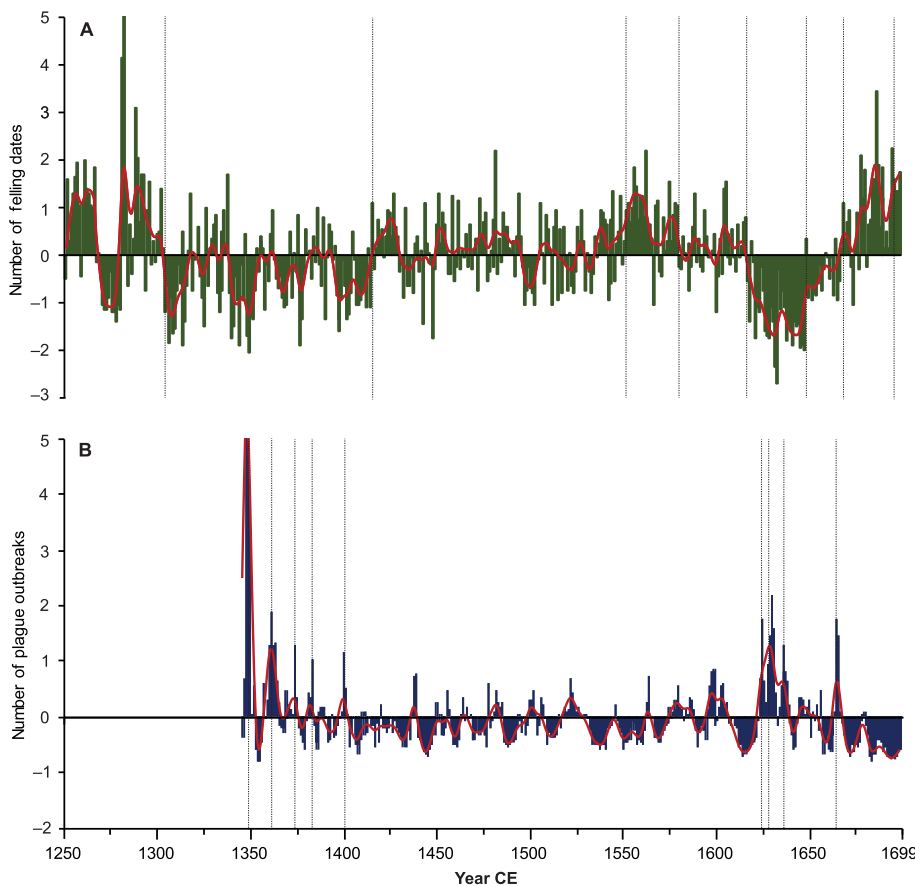


Fig. 3. (A) Number of felling dates and (B) number of plague outbreaks standardized using a 300-year filter, respectively. A 10-year low-pass filter (red lines) is applied to the annually resolved values (vertical bars). The dashed vertical lines in (A) show the onset years of significant regime shifts in the number of felling dates, using a 30-year cut-off length. The dashed vertical lines in (B) show the timing of the ten years with the most recorded plague outbreaks in Europe. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2

Years with significant (at a 95% level) regime shifts in the number of 300-year filtered and unfiltered felling dates using a 30- and 50-year cut-off length for the sequential algorithm of Rodionov (2004). A downward arrow marks the year shift towards a decreasing number and an upward arrow the year shift towards an increasing number of felling dates, respectively.

300-yr filtered		Unfiltered	
30-yr cut-off	50-yr cut-off	30-yr cut-off	50-yr cut-off
1304 ↓	1267 ↓	1304 ↓	1297 ↓
1415 ↓	1415 ↑	1415 ↑	1415 ↑
1552 ↑	1544 ↑	1552 ↑	1450 ↑
1580 ↓	1580 ↓	1450 ↑	1506 ↑
1617 ↓	1621 ↓	1473 ↑	1552 ↑
1648 ↑	1656 ↑	1526 ↑	1617 ↓
1668 ↑		1555 ↑	1648 ↑
1695 ↑		1580 ↓	1678 ↑
		1617 ↓	
		1648 ↑	
		1668 ↑	
		1680 ↑	

felling dates, we additionally calculated the correlation coefficients excluding the war years, with little effect on the negative relationship between the number of plague outbreaks and felling dates, and thus construction activity.

SEA experiments reveal a clear drop in construction activity in the four years following the 10 and 20 years with most plague outbreaks (Fig. 4; Table 4). The number of felling dates is lowest three to four years after a major plague outbreak but recovers to pre-outbreak levels in the fifth year. Moreover, we observe that the major plague outbreaks occurred when construction activity is already below the long-term mean. This relationship is most evident for the Black Death, the plague outbreak 1400 CE, and the for the plagues occurring during the Thirty Years' War. We tested the robustness of the obtained SEA results by the alternative lists of plague outbreak years and found that these alternative approaches to ranking the plague years (Section 2.4) only had a modest influence on the results.

3.2. The Late Medieval Crisis

Reduced construction activity is evident from c. 1300 to 1415 CE, thus starting about five decades before the Black Death (1346–1353 CE) and about two decades before the Great Famine (1315–1322 CE) (Table 2). The 50-year period 1250–1299 CE lists 4045 felling dates with a mean of 81 per year and decreases in the following 50-year period 1300–1349 CE to only 2589 with a mean of 52 per year. In the 50 years following the Black Death (1350–1399 CE), the number of felling dates rises insignificantly to 2785 with a mean of 56 per year

Table 3

Correlation values between the number of (300-year filtered and standardized) felling dates and other variables. Values significant at a 95% level, using a two-tailed significance test, are highlighted in bold.

Correlated variables	Pearson <i>r</i> value			Spearman's ρ value		
	Data series smoothing					
	None	10-yr spline	10-yr box-car	None	10-yr spline	10-yr box-car
Felling dates vs. plague outbreaks	-0.25	-0.43	-0.47	-0.25	-0.43	-0.57
Felling dates vs. temperature	0.04	-0.04	-0.09	-0.01	-0.03	-0.13
Felling dates vs. hydroclimate	0.00	-0.01	-0.04	-0.02	-0.01	-0.01
Felling dates vs. grain price	-0.32	-0.37	-0.39	-0.30	-0.35	-0.34
Plague outbreaks vs. temperature	0.01	-0.06	-0.05	0.05	-0.04	-0.16
Plague outbreaks vs. hydroclimate	0.12	0.14	0.36	0.14	0.17	0.43
Plague outbreaks vs. grain price	0.24	0.26	0.45	0.29	0.33	0.46

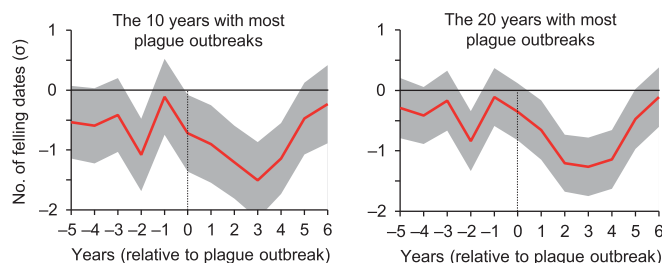


Fig. 4. Superposed epoch analysis of the number of felling dates aligned by the 10 (left panel) and 20 (right panel) years with most recorded plague outbreaks using 300-year filtered data and the median response values. The 95% confidence interval is shown in grey shading.

(Table 5). When considering different 31-year periods, an even clearer picture emerges (Table 6). Whereas the decrease in the number of felling dates between 1317–1347 CE and 1348–1378 CE is only 7%, it is 24% between 1255–1285 CE and 1286–1316 CE, and 12% between 1286–1316 CE and 1317–1347 CE. A maximum decrease of 33% is found between the periods 1255–1285 CE and 1317–1347 CE.

Prior to the Black Death the most wide-spread mortality crisis in Europe during the past millennium was the Great Famine (1315–1322 CE). However, this famine leaves no clear imprint in the record of felling dates. Not even the Black Death results in more than short-term impacts. Its worst year – 1349 CE in central Europe – showed the lowest number (23) of felling dates of any year in the entire (unfiltered) dataset. The following years 1350 CE and 1351 CE also belong to the group of 15 years with the lowest number of felling dates. Yet, the years with the second and third lowest number are 1344 CE (26) and 1340 CE (28), just a few years before the pandemic. Notably, the year 1340 CE corresponds to a vast and mortal flooding event in central Europe. All 15 years with the lowest number of felling dates in the (unfiltered) dataset belong to the fourteenth century, with nine out of 15 pre-dating the Black Death.

3.3. Felling dates, grain prices, plague outbreaks, and climate

Almost the same strong negative relationship between the number of felling dates and European grain prices (Fig. 5a) is found ($r = -0.32$; $r = -0.37$ for 10-year smoothed data and $r = -0.39$ for 10-year box-car filtered data) as between the number of felling dates and plague outbreaks. Less construction activity occurs when grain prices are high (Table 3). However, contrary to large plague outbreaks, the application of the SEA on the 10 and 20 years with the highest grain prices does not yield significant changes in the number of felling dates. Yet, there is an observed tendency for less than average felling dates prior to years with high grain prices, possibly resulting from some type of crisis prior to peaks in grain prices.

Table 4

The top ten years between 1250 and 1699 CE, by order of magnitude from the first (highest value) to tenth (lowest value) year, with most recorded plague outbreaks, highest/lowest grain prices, coldest/warmest summers, and wettest/driest summers, respectively. For plague outbreaks and grain prices 300-year filtered data are used.

Top ten years	1	2	3	4	5	6	7	8	9	10
<i>Most plague outbreaks</i>	1348	1665	1625	1629	1360	1374	1636	1400	1383	1628
<i>Highest grain prices</i>	1438	1437	1630	1597	1586	1651	1631	1433	1649	1650
<i>Lowest grain prices</i>	1510	1547	1688	1537	1548	1689	1514	1536	1526	1687
<i>Coldest summers</i>	1675	1628	1698	1601	1596	1695	1579	1663	1627	1692
<i>Warmest summers</i>	1540	1556	1616	1534	1536	1666	1684	1559	1503	1504
<i>Wettest summers</i>	1562	1271	1315	1628	1387	1256	1316	1606	1640	1528
<i>Driest summers</i>	1503	1517	1504	1419	1684	1306	1636	1393	1461	1417

Table 5

Statistics including sum, annual mean and median, and standard deviation (σ) of all felling dates over 50-year periods and the full period 1250–1699 CE.

50-year period (CE)	Sum	Mean	Median	σ
1250–1299	4045	80.90	81.50	24.65
1300–1349	2589	51.78	51.50	15.21
1350–1399	2785	55.70	56.50	12.87
1400–1449	3795	75.90	78.50	17.76
1450–1499	5857	117.14	115.00	21.67
1500–1549	6969	139.38	141.00	27.62
1550–1599	8047	160.94	160.00	24.76
1600–1649	6166	123.32	113.00	39.89
1650–1699	9387	187.74	182.50	46.63
<i>Full period</i>	49 640	110.31	101.50	52.62

Table 6

Statistics including sum, annual mean and median, and standard deviation (σ) in the number of felling dates over 31-year periods corresponding to the periods around the Late Medieval Crisis and the Thirty Years' War, respectively.

31-year period (CE)	Sum	Mean	Median	σ
<i>The Late Medieval Crisis</i>				
1255–1285	2509	80.94	75.00	28.42
1286–1316	1916	61.81	57.00	21.75
1317–1347	1693	54.61	57.00	15.42
1348–1378	1568	50.58	49.00	13.50
1379–1409	1896	61.16	62.00	12.17
<i>The Thirty Years' War</i>				
1587–1617	4848	156.39	152.00	25.33
1618–1648	3106	100.19	100.00	25.21
1649–1679	5102	164.58	165.00	33.56

The European summer temperature decrease around 1250 CE (Fig. 5b) occurs five decades before the decline in felling dates around 1300 CE (Fig. 3a). In addition, no clear relationship between the number of felling dates (smoothed or unsmoothed), temperature and hydroclimate data is observed (Table 3), also when taking possible lag effects into account. Considering the top 10 and 20 warmest, coldest, driest, and wettest years, statistically insignificant results are found using the SEA method. However, there is the suggestion of a slight (but insignificant) decline in the number of felling dates during the top 10 coldest and the 10 wettest years. Moreover, we note that the top 10 and 20 warmest years – mostly occurring during warm decades – coincide with periods of overall high construction activity, lending some support to the notion that economic and demographic conditions in Europe are more favorable during warmer periods.

In addition, we compared the number of recorded plague outbreaks to grain prices and find that outbreaks are significantly more common during periods of high grain prices ($r = 0.24$; $r = 0.26$ for 10-year smoothed data and $r = 0.45$ for 10-year box-car filtered data) (Table 3). Comparing the number of plague outbreaks and climatic conditions we find that plague outbreaks are positively correlated to wet years/decades but not to temperature.

3.4. The Thirty Years' War

The most prominent decline in construction activity besides the Late Medieval Crisis occurred during the Thirty Years' War (1618–1648 CE). The impact and timing of the war is visually and statistically evident (Table 2). In the 31-years preceding the war, 4848 felling dates are recorded with a mean of 156 per year. During the war, this number drops to 3106 with a mean of 100 per year, resulting in a decrease of 36% (Table 6). Interestingly, the year-to-year variation remains almost the same in both periods (the standard deviation is ~ 25 felling dates). In the 31-year period following the war (1649–1679 CE), the number of felling dates increases to 5102 with a mean 165 per year (Table 6). Much of the Thirty Years' War, i.e. c. 1625–1640 CE, overlaps with a period of increased plague activity (Fig. 2), that may be linked to the conflict, and being a contributing cause to the reduced building activity and the population decline. We note distinct regional differences in the impact of the Thirty Years' War. Comparing three regions with large numbers of felling dates – northern and central Germany, southern Germany and Switzerland – only the two German regions show a distinct impact of the war whereas Switzerland, mainly outside the conflict zone, only shows an indistinct decrease in construction activity (Fig. 6).

4. Discussion

Our results show that large collections of felling dates from construction timbers capture major trends in settlement and demographic dynamics and pin-point severe social crises. This is clearly demonstrated by the vibrant and strong imprints of plague epidemics on the tree-ring-based history of construction activity as well as by the sharp decrease in the number of felling dates during the Thirty Years' War (1618–1648 CE).

4.1. Uncertainties in the felling dates and plague outbreak datasets

The year a tree was cut is approximately equal to the year of construction, as the wood was usually utilized while fresh, although wood was often harvested in the autumn before the construction year and transported during winter (e.g. Büntgen et al., 2006; Miles, 2006; Eckstein, 2007). However, the felling dates are not randomly distributed over space and time. Limitations are imposed by the geographically imbalanced dendroarchaeological work of the laboratories that have contributed data to this study. Still, we expect that most long-term trends related to decreasing wood preservation rates, and thus number of felling dates, back in time have been removed by the application of the 300-year filter. It is important to note that changes in the number of felling dates are not equal to changes in the number of individual buildings and constructions that once existed. We lack information about how many individual measurement series come from the same constructions. Even so, the temporal dynamics of the felling dates must broadly be expected to mirror variations in the intensity of construction activity.

Some of the limitations with the digitized and georeferenced plague

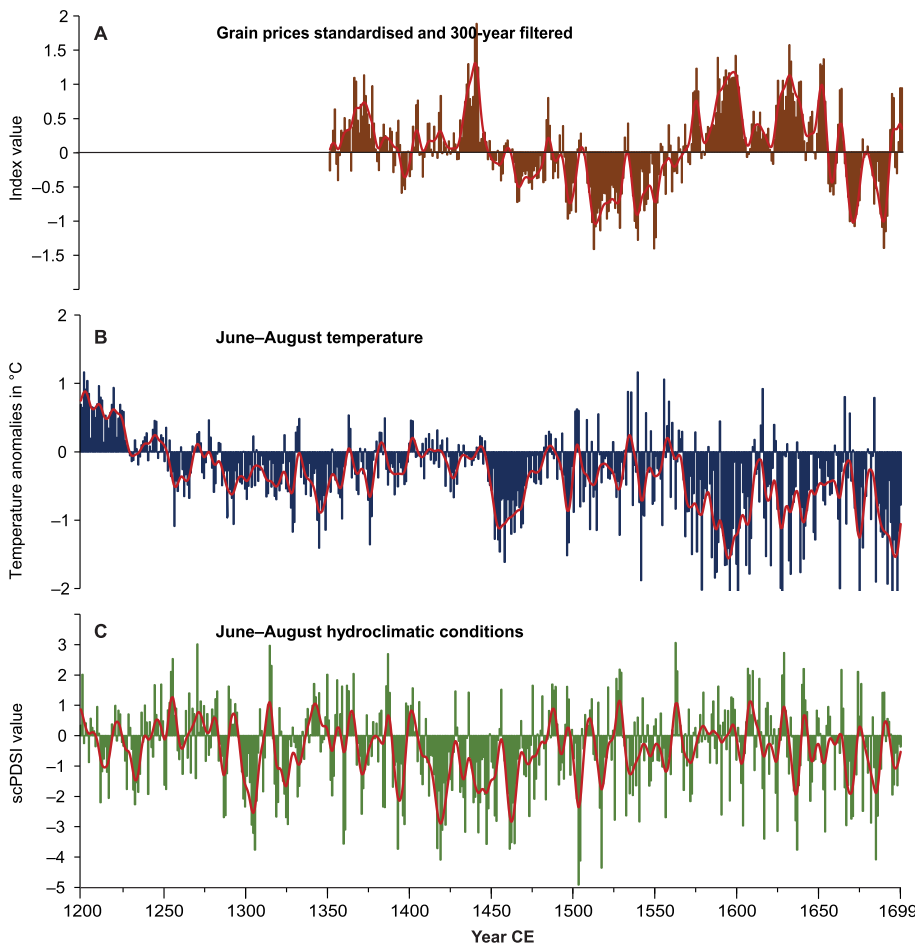


Fig. 5. (A) 300-year filtered standardized average of European grain prices from Esper et al. (2017). (B) Annually resolved June–August temperature reconstruction from Luterbacher et al. (2016) averaged over western and central Europe (0–20°E, 45–55°N) from 1200 to 1699 CE and expressed as anomalies in °C with regard to the modern reference period 1961–1990 CE. (C) Annually resolved June–August drought reconstruction from Cook et al. (2015) averaged over western and central Europe (0–20°E, 45–55°N) from 1200 to 1699 CE representing relative growing season hydroclimate anomalies. A 10-year low-pass filter (red lines) is applied to all three time-series. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

outbreak dataset by Büntgen et al. (2012), based on inventory of Biraben (1975–1976), need to be especially highlighted: (a) there are spatial biases in data coverage, with the highest density of recorded outbreaks in France, and a strong underrepresentation, or entirely missing data, in particular in eastern Europe as well as in Belgium, the Czech Republic, the Netherlands, Poland, Portugal, Spain, and in the Scandinavian countries (Alexander, 1980; Tsiamis et al., 2011; Myrdal, 2012a; Alfani, 2013; Roosen and Curtis, 2018), (b) the lack of information regarding the length or severity of plague instances, (c) a critical assessment of whether *Yersinia pestis* was indeed the cause for a widespread and mortal disease. Biraben (1975–1976) retrospectively diagnosed outbreaks of a disease as *Yersinia pestis*; attempts to follow up on the compiled dataset is problematic as necessary references are missing, (d) the underrepresentation of recorded plague outbreaks further back in time, and (e) an urban bias of recorded plague outbreaks. The underreporting of small plague outbreaks back in time may, like the long-term trends in the felling dates, be expected to have been removed by the application of the 300-year filter. Random underrepresentation of plague outbreaks, and multi-decadal variations in data quality, would nonetheless still affect the results from the comparison with the felling dates. However, by aggregating the plague data to a single annual average, we have minimized the impacts of these spatial biases.

4.2. Felling dates as demographic information

Prior to the eighteenth century reliable documentary sources of demographic fluctuations are, at best, patchy for most of Europe, and the potential of using felling dates as a source should be carefully evaluated. Felling dates have an advantage over, for example, pollen

data in capturing population and settlement development due to their annual resolution and absolute dating. However, an increase or a decrease in the number of felling dates is not necessarily equivalent to a population increase or decrease. A small population decline or even a stagnation of population levels may be enough to affect a decrease in felling dates as a lack in demand for new construction is sufficient to affect felling date numbers. This means that a sharp population decline, following a stagnation period, may not be visible in the felling date data. Thus, during periods of population stagnation or decline, we can expect a non-linear relationship between construction activity and population. On the other hand, during periods of a population increase, we anticipate a more linear relationship between construction activity and population growth. A non-linear relationship between construction activities and demography may explain why no long-term decline is visible in the number of felling dates following the mass mortality of the Black Death, distinguishable from an overall lower construction activity observed between c. 1300 and 1415 CE.

There is additional biologically archived information, relevant to the discussion of past demographic changes, that in future research may be extracted from tree-ring width records in historical construction timbers. Unusually fast-growing trees, in periods following known demographic crises, are likely to have grown on abandoned agricultural lands that were reforested following widespread farm desertion. This phenomenon has been inferred in several parts of Europe for the Late Medieval Crisis (Kuniholm and Striker, 1983; Schmidt et al., 1990; Baillie, 1982, 1995; Eckstein, 2007; Thun and Svarva, 2018). Although reforestation, in most cases, does not occur immediately following desertion, germination dates from unusually fast-growing trees may provide a *terminus ante quem* for the start of widespread farm abandonment. Reforestation of farmland on a large scale, and across wide

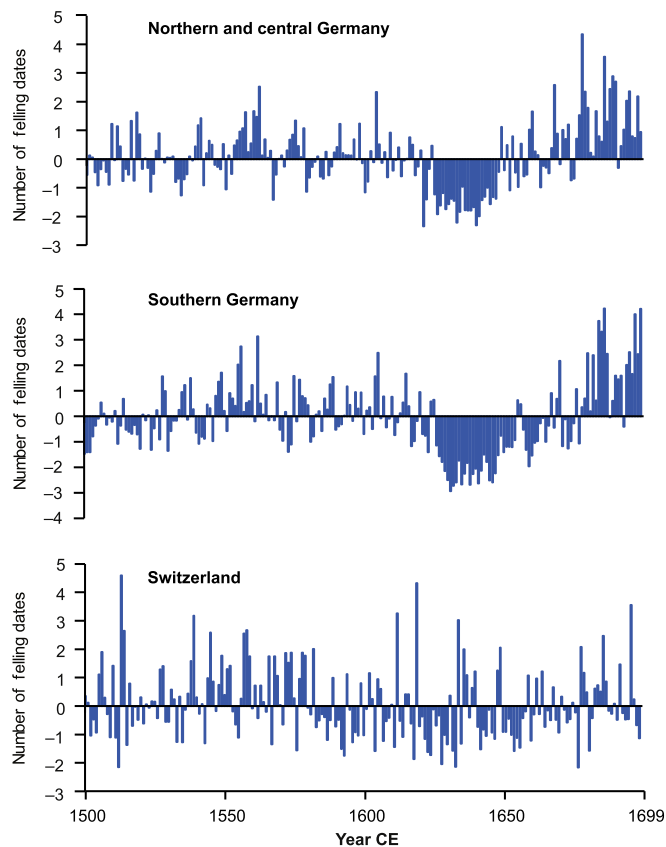


Fig. 6. Comparison of 300-year filtered standardized number of felling dates from northern and central Germany, southern Germany, and Switzerland, respectively, over the period 1500–1699 CE. The clear impact of the Thirty Years' War (1618–1648 CE) is evident in both northern and central Germany and in southern Germany but not seen in Switzerland.

regions, points towards a substantial population decline (Leuschner, 2005; Billamboz, 2014; Trouet et al., 2017). Determining the germination dates of fast-growing trees, presumably from reforested farmlands, can arguably refine the dating and magnitude of population declines.

Though the number of felling dates cannot be precisely translated into demographic changes, we note that most of the detected regime shifts in the number of felling dates capture population changes recorded in documentary data (Clark, 1977; McEvedy and Jones, 1978; Biraben, 1979; Bardet and Dupâquier, 1997). The Late Medieval Crisis identified here had already begun by c. 1300 CE, fitting with increasing evidence of, at the very least, a population stagnation already by c. 1300 CE (see Sections 1 and 4.3). A recovery from the Late Medieval Crisis, suggested by the increasing number of felling dates, at c. 1415 CE is somewhat earlier than commonly assumed. The increase in felling dates by the mid-sixteenth century corresponds to a well-documented population and settlement expansion in much of Europe. The decrease in felling dates in c. 1580 CE is a likely reflection of the onset of the “crisis of the seventeenth century” (Hobsbawm, 1954), when increasing famines, wars and other hardships resulted in population stagnation or decline (Parker, 2014). It is evident that the sharp drop in felling dates during the Thirty Years' War (1618–1648 CE) reflects the large population loss directly due to the conflict (Theibault, 1997; Parker, 2006) in combination with adverse political and economic conditions owing to the war. The step-wise increase in the number of felling dates in the second half of the seventeenth century, following the Peace of Westphalia in 1648 CE, directly corresponds with the start of a new phase of population increase and settlement expansion (Bulst and Pfister, 1997).

Finally, the slight decline in felling date numbers in the 1690s is likely associated with the severe and widespread European food shortages and famines that occurred during this decade and which were triggered by exceptionally cold climate conditions causing harvest failures and high livestock mortality across regions in Europe (Ladurie, 1971; Appleby, 1979, 1980; Neumann and Lindgrén, 1979; Cullen, 2010; Alfani and Ó Gráda, 2017).

4.3. The interlinkage between plague, food security, and construction activity

We find that large plague outbreaks tend to occur when the number of felling dates is below the long-term average (Section 3.1; Table 3). Below average construction activity arguably signifies some sort of pre-existing societal crisis frequently preceded plague outbreaks. This notion is reinforced by the fact that using SEA, we found a drop in the number of felling dates two years preceding the plague outbreaks (Fig. 4). Moreover, we find that plague outbreaks are more common during periods of high grain prices (Section 3.3). It remains unclear if plague outbreaks were a contributing cause to the higher grain prices, or if plague occurred more frequently during times of high prices and, consequently, possibly more widespread malnutrition. Our finding that the number of plague outbreaks is weakly, but positively, correlated to wet years/decades is in line with earlier results of plague epidemiology (Schmid et al., 2015; Tian et al., 2017) though contrary to those of Yue and Lee (2018).

Besides plague, the availability and affordability of food is found to have a strong effect on the number of felling dates (Table 3). Construction activity was significantly higher when grain prices were lower and vice versa. In times of food shortage (e.g. high grain prices) new constructions were obviously less of a priority. Although climate impacts are indirectly filtered through grain prices (Esper et al., 2017), no direct links between climate conditions and the number of felling dates were detected. This could be a consequence of that the casual links between climate-mediated changes in agricultural productivity and food availability to a large extent were dependent on the prevailing socio-political and socio-economic systems (Behringer, 2007; Carey, 2012; Engler, 2012; Slavin, 2016; Alfani and Ó Gráda, 2017; Ljungqvist, 2017a; b; Collet and Schuh, 2018; Huhtamaa, 2018).

Critical reassessment of written sources (Campbell, 2016 and references therein), as well as pollen evidence of agrarian activities (Yeloff et al., 2006, 2007), increasingly suggests that a population decline, in many parts of Europe, pre-dated the Black Death. Our finding that the crisis started already around 1300 CE is in line with this perception and, moreover, indicates that it also preceded the Great Famine. Still, it is remarkable that no clear long-lasting imprint of the Black Death is visible in the number of felling dates. This can be best explained if one views the Black Death as the catastrophic climax of problems that started far earlier.

To our knowledge this is the first time that a large decrease in construction activity has been shown in connection with the Thirty Years' War (1618–1648 CE), as demonstrated by tree-ring data or by any other evidence. This result is not surprising given it was likely the most devastating war in European history measured in per capita casualties, resulting in laying to waste large areas, and directly or indirectly responsible for c. 12 million deaths (Parker, 2006). With regional variations, present-day Germany lost about 40% of its rural population and about 33% of its urban population, with similar losses in the present-day Czech Republic and in parts of present-day Poland (Theibault, 1997; Parker, 2014).

4.4. Recommendations for further research

Tree fellings are arguably a suitable indicator for dating past crises; a decline is likely a sensitive indicator for the onset of a crisis as new constructions are dispensable in a time of hardships. Therefore, we

encourage continued and wider efforts to collect samples of historical construction timbers from more geographic regions and periods to better estimate spatiotemporal changes in settlement and population dynamics during medieval and early modern Europe. To optimize the felling date data as a source material they need to be studied in conjunction with other types of archaeological and historical sources. In this context, we can only recommend more cross-disciplinary data exchange and collaborations beyond traditional disciplinary boundaries (for challenges, see e.g. Aagaard-Hansen, 2007; Izdebski et al., 2016; Haldon et al., 2018), and that more archaeologists and historians follow the “source pluralistic” approach outlined by Myrdal (2008, 2012b).

The study of the relative decrease in construction activity, i.e. assuming the number of felling dates is large enough to detect this, between different regions could provide new insights into the severity of impacts of plagues, famines and wars on regional scales. Such assessments are presumably most feasible for large-scale and severe impacts such as the Late Medieval Crisis, the Black Death, and the Thirty Years' War. Still, we envision possibilities to compare the impacts within well-sampled regions between different wars, plagues and famines. The spatial dynamics of historical construction activities need to be further explored, as this may, for example, shed light on regional differences in the timing and duration of such events as the Late Medieval Crisis. Expanding the spatial coverage would likely provide an insight into regional differences of European settlement history, as, for example, evident between Germany and Switzerland during the Thirty Years' War.

Another issue to address is social stratification and building activity, i.e. to investigate how changes in construction activity affected high status versus low status buildings during different periods. Moreover, the interlinkage between urban and rural economic and demographic development needs to be explored as well. Biased towards urban settings, the majority of our felling date compilation originates from artisan and bourgeois townhouses, and only to a lesser extent from ecclesiastical and noble buildings and from farm houses. Nevertheless, the here inferred construction activity represents an important part of economic and social conditions for much of western and central Europe 1250–1699 CE.

5. Conclusions

For the first time, we provide annually resolved evidence of the temporal dynamics in construction activity from 1250 to 1699 CE across a large section of western and central Europe using an unprecedentedly large collection of absolutely dated tree fellings. By conducting various statistical analyses for comparing construction activity to the number of plague outbreaks, grain prices and climate reconstructions, we conclude that: (a) construction activities decreased during periods with multiple plague outbreaks, with the greatest decrease three to four years after larger plague outbreaks, (b) the number of felling dates were significantly lower (higher) when grain prices were higher (lower), but no clear relationship is found between the number of the felling dates and temperature or hydroclimatic conditions, (c) the Late Medieval Crisis is already evident in the felling dates around 1300 CE, appearing five decades prior to the Black Death, and two decades before the Great Famine, and lasting until c. 1415 CE, and (d) an abrupt and sharp decrease in construction activity occurred during the Thirty Years' War (1618–1648 CE).

Our results show that the use of extensive datasets of felling dates from construction timbers to study past settlement and demographic dynamics for periods when only limited documentary data are available provide valuable insights into the magnitude and timing of these dynamics. Yet, we note the difficulty in using felling dates to distinguish between population stagnation and population decline. Felling date data should preferably be used together with other types of data, and be studied within an interdisciplinary and “source pluralistic” framework. The spatial aspects need to be addressed further alongside the temporal

trends to optimally use the felling dates towards the understanding of past settlement and population development.

Author contributions

F.C.L. designed the study, set up all the experiments, and wrote the article with input and assistance from W.T., P.J.K., A.S. and U.B. The felling dates were compiled and quality checked by both W.T. and U.B. F.C.L. and P.J.K. conducted the statistical analysis. F.C.L. drew Figs. 1 and 3–6. A.S. and F.C.L. drew the map in Fig. 2a. W.T. provided the photos to Fig. 2b. The felling dates used in this study were provided by F.M.G., K.H., F.H., K.-U. H., J.H., D.H., R.K., T.K., H.H.L., K.N., C.P., K.P., M.S., M.S., F.W. and T.W.

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