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ADVANCED REVIEW

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Climate and society in European history

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Abstract

This article evaluates 165 studies from various disciplines, published between 2000 and 2019, which in different ways link past climate variability and change to human history in medieval and early modern Europe (here, *c*. 700–1815 CE). Within this review, we focus on the identification and interpretation of causal links between changes in climate and in human societies. A revised climate–society impact order model of historical climate–society interactions is presented and applied to structure the findings of the past 20 years' scholarship. Despite considerable progress in research about past climate–society relations, partly expedited by new palaeoclimate data, we identify limitations to knowledge, including geographical biases, a disproportional attention to extremely cold periods, and a focus on crises. Furthermore, recent scholarship shows that the limitations with particular disciplinary approaches can be successfully overcome through interdisciplinary collaborations. We conclude the article by proposing recommendations for future directions of research in the climatic change–human history nexus.

This article is categorized under:
Climate, History, Society, Culture > Ideas and Knowledge

KEYWORDS

climate–society interactions, common era, history, impact order model

1 | INTRODUCTION

Numerous studies, from several disciplines, have in the past two decades addressed various possible influences of climatic change on different aspects of European history (for reviews, see e.g., Camenisch & Rohr, 2018; Degroot, 2018a; Diaz & Trouet, 2014; Haldon et al., 2018; Ludlow & Travis, 2019; McCormick, 2019). Overall contemporary awareness of the consequences of ongoing and future anthropogenic-induced global warming has encouraged scholars to explore how past climatic changes have influenced societies throughout history (e.g., Adamson, Hannaford, & Rohland, 2018; Curtis, van Bavel, & Soens, 2016; Mauelshagen, 2014). Knowledge about, for example, *how*, and to *what extent*, food security has been determined by climate variability may be policy relevant (e.g., Collet, 2015; Collet & Schuh, 2018; D'Guedes, Crabtree, Bocinsky, & Kohler, 2016; Engler, 2012; Nelson et al., 2016).

For a long time, historians were relatively reluctant to include climatic change as a factor in human history. This can partly be traced back to the deep-rooted separation of human and natural history (Chakrabarty, 2009). Changes in the environment, including climate, have erroneously been perceived to be too minor to be relevant in human history (see the discussion in, for example, Campbell, 2010). However, with ongoing global warming it is increasingly difficult to deny that climate would not have an influence on societies. Furthermore, recent advances in palaeoclimatology and historical climatology, in tandem with an increasing availability of historical datasets in digital format, now allow the investigation of long- and short-term relationships between climate variability and human history.

The German geographer Eduard Brückner (1862–1927) pioneered the study of multi-decadal climate variability and linked it to past economic and societal conditions (Brückner, 1895). The works of the American geographer Ellsworth Huntington (1876–1947) had a wider scope—though they unfortunately demonstrated climate determinism—and integrated evidence from tree-ring data, when dendroclimatology still was in its infancy, in his interpretations of climate-induced “pulses” of migration in Eurasia (Huntington, 1907). Examples of truly interdisciplinary climate history research, though rare, exist already from the early 1960s (Lamb, 1962; Le Roy Ladurie, 1963). French historian Emmanuel Le Roy Ladurie (1967), in English in Le Roy Ladurie (1971), emphasized the importance of using quantitative methods to study past climatic impacts on human history and called for the use of natural palaeoclimate proxy archives along with documentary sources. The works by Hubert H. Lamb (1977, 1982), a British meteorologist interested in history, challenged the then prevailing perception of centennial-scale climate stability. Quantitative assessments of the risk for harvest failures under various climate conditions were introduced by British geographer Martin L. Parry (1978). Swiss historian Christian Pfister (1978, 1988) further advanced the field with studies on the interlinkages between climate, harvests, grain prices, and economy in Central Europe.

Studies in the early 1980s, including Wigley, Ingram, and Farmer (1981), pioneered methodological and conceptual questions and served as foundations for later climate–society interaction research. However, this generation of scholars still lacked adequate palaeoclimate data and could only make rough estimations of past climate conditions. Consequently, scholars interested in the interactions of climate and history focused during the following two decades on historical climatology: the practice of reconstructing past climate variability from documentary sources (*sensu* Brázdil, Pfister, Wanner, von Storch, & Luterbacher, 2005). In particular, Christian Pfister (1984, 1999) and Rudolf Brázdil (1996) were pioneers in this subfield. By the turn of the twenty-first century, some historians and archeologists had started to employ natural palaeoclimate archives (Campbell, 2009, 2010, 2016; Huhtamaa, 2018, 2020). This became possible with the advancement in high-resolution palaeoclimatology capturing long-term variations and trends of temperature and hydroclimate as well as interannual variability and extremes (Figure 1). Throughout this article, *climate* denotes the average weather conditions on longer time-scales; *weather* denotes hourly to monthly conditions. With *climatic change*, we are not only referring to changes in long-term averages, but also to changes in the *frequency* and *magnitude* of certain weather or climatic conditions (e.g., extreme cold) and systematic *shifts* (e.g., a later onset of the growing season).

It is increasingly difficult to obtain an overview of the growing, but dispersed, field of climatic change–human history research. We aim to remedy this situation by offering a critical review which summarizes the state-of-the-art research, published 2000–2019, on climate change–human history links in medieval and early modern Europe (here, *c*. 700–1815). We focus on: (1) suggested causal links between climate and some aspect(s) of human history, (2) interpretations of causes and effects, and (3) controversies and agreements in the scholarship. We are not reviewing literature about climatic impacts during Roman times or Late Antiquity as an extensive bibliometric analysis by Marx, Haunschild, and Bornmann (2018) and a theoretical and methodological evaluation by Sessa (2019) have recently been published.

2 | MATERIALS AND METHODS

We assess studies published during the past 20 years (2000–2019) that link climatic change to human history of medieval or early modern Europe. Studies with the publication year 2020 are included when appearing “first online” in 2019.

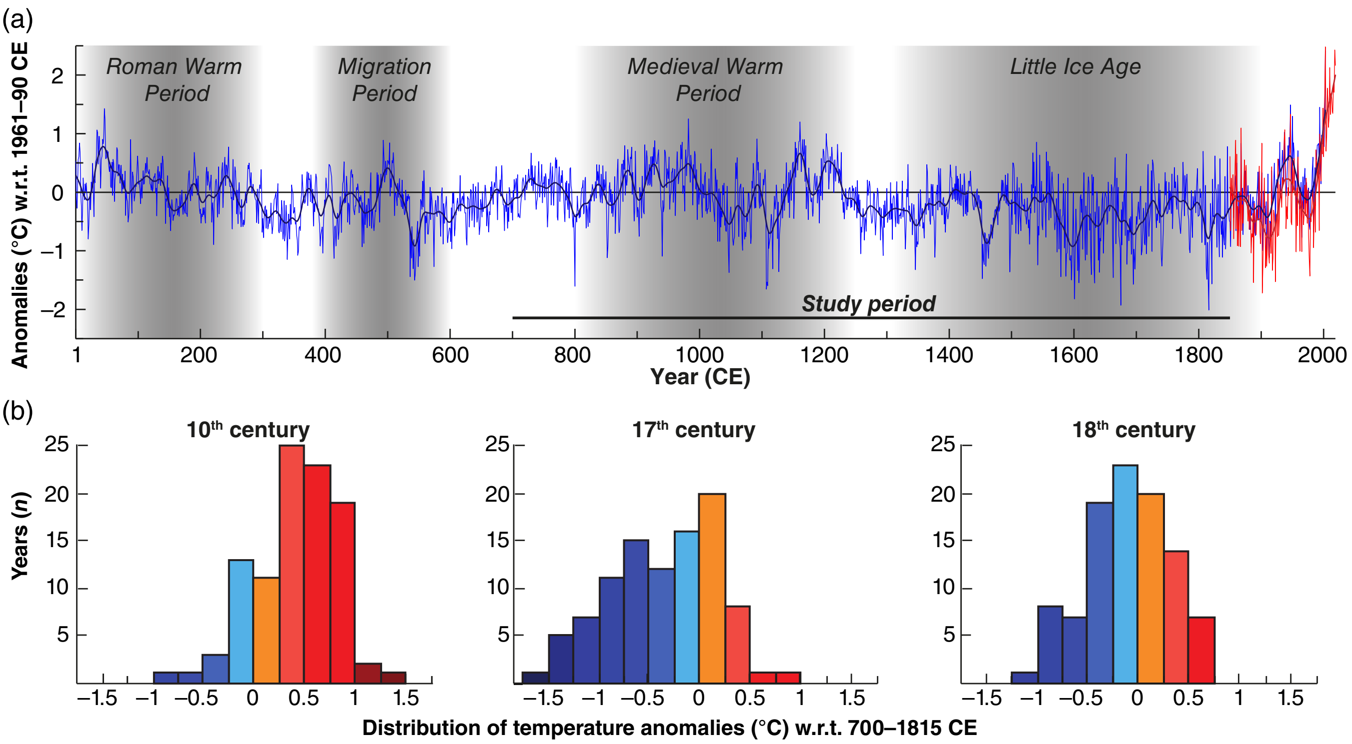

FIGURE 1 (a) Reconstructed average European June–August temperature anomalies over the period 1–2003 by Luterbacher et al. (2016) (blue line) together with instrumental mean June–August temperature anomalies for Europe 1850–2019 (red line). All anomalies are with respect to the 1961–1990 mean. (b) Distribution of reconstructed June–August temperature anomalies, with respect to the mean of the study period 700–1815, over the tenth century (warmest century of the Medieval Warm Period a.k.a. Medieval Climate Anomaly), the seventeenth century (coldest century of the Little Ice Age), and the eighteenth century (being close to the long-term mean)

For inclusion of a study, it should be either published as an article in a peer-reviewed journal or as a monograph or collection of articles by an established academic publisher. The focus was on studies published in English as they presumably have the widest outreach and the strongest impact across the scholarly community. To a lesser extent, we included studies published in other, to us accessible, languages, in particular German and the Scandinavian languages.

Relevant literature was identified in several ways: We conducted multiple search queries within Google Scholar, completed in April 2020, using the keywords “climate,” “Europe,” and “history” in combinations with either of the keywords “agriculture,” “archaeology,” “climate extremes,” “early modern,” “famine,” “harvest,” “impact,” “medieval,” “political,” “society,” “socio-economic,” and “vulnerability.” In a next step, retrieved results were further screened by reading the abstracts to determine whether a study is relevant for this review. Furthermore, we examined the citations in Google Scholar of the retrieved publications. To identify additional literature, we systematically assessed the references in key publications. In total, this assessment includes 12 monographs and 153 journal articles and book chapters (Table A1). We structured this review after an updated conceptional climate–society impact order model (Figure 2), which was first introduced by Ingram, Farmer, and Wigley (1981), and later modified by Pfister (2005), Krämer (2012, 2015), and Luterbacher and Pfister (2015). We revised the model since it did not fully consider cultural responses to climatic changes at all levels (Degroot, 2018a) (see further Section 4.2).

3 | RESULTS

3.1 | Studies of first-order impacts: (bio)physical effects

3.1.1 | Crop cultivation and viticulture

Many first-order impact studies focus on certain crisis events, like the Great Famine (1315–1322; Aberth, 2001; Huhtamaa, 2020; Slavin, 2017) or the Late Medieval Crisis more generally (Campbell, 2009, 2010, 2016; Fraser, 2011;

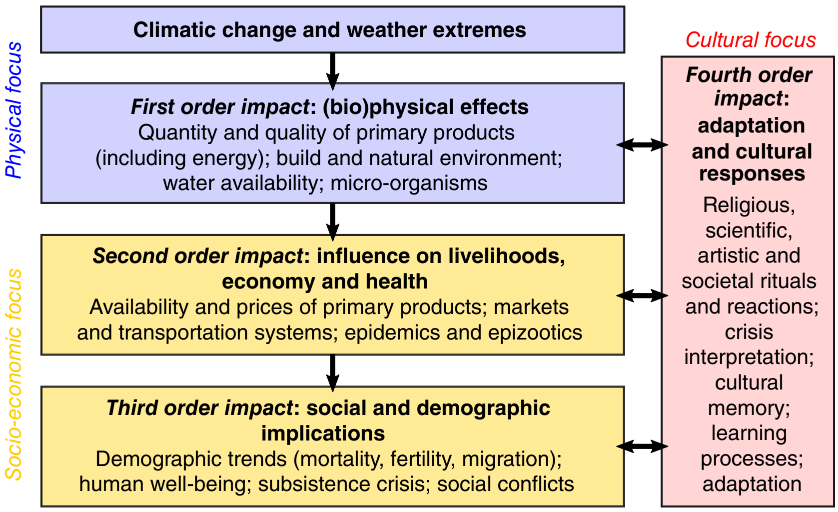

FIGURE 2 A revised schematic model of historical climate–society interactions ranging from first-order effects on biomass production to fourth-order cultural effects with the latter interacting also on all preceding levels

Gerrard & Petley, 2013; Hoffmann, 2014). In addition, for example the cold periods of the 1430s (Camenisch, 2015a; Camenisch, 2015b; Camenisch et al., 2016) and the 1690s (Cullen, 2010; D'Arrigo, Klinger, Newfield, Rydval, & Wilson, 2020), and production failures following particular volcanic eruptions, like the 1257 Samalas eruption (Bauch, 2019; Campbell, 2017; Guillet et al., 2017; Stothers, 2000), have received considerable attention. Furthermore, studies on extreme drought or flood events commonly include discussion about impacts on the grain harvest (see, e.g., Kiss, 2019; Kiss, Piti, Sebok, & Teiszler, 2020; Pribyl & Cornes, 2020; Stone, 2014). Although a majority of the studies focus on particular crisis events, some publications explore the dynamics between climate variability and crop yields on multi-decadal or even multi-centennial time-scales (see, e.g., Brázdil et al., 2019; Campbell, 2010; Huhtamaa & Helama, 2017a; Huhtamaa & Helama, 2017b; Landsteiner, 2005; Parker, 2013; Pfister, 2005; Pfister, 2007b).

White, Brooke, and Pfister (2018) divided Europe into three zones with regard to climatic impacts on agriculture: (a) *Northern Europe*, where growing season length and temperature were of crucial importance, and where short growing seasons increased the risk of frost damages on crops. (b) *Western/Central Europe*, with a mixed sensitivity to temperature and hydroclimate, where mainly cold springs, wet (and cold) mid-summers, and wet harvest times posed risks. (c) *Mediterranean Europe*, where droughts, especially in spring, as well as extremely cold winters damaged crops. Within this general outline, however, various case studies indicate far greater spatio-temporal variability in the crop sensitivity to weather and climate.

Within Northern Europe, crop cultivation in the northernmost agricultural areas is found to be especially temperature sensitive, and even relatively small temperature changes had a considerable impact on the grain harvest (Dodgshon, 2004; Dybdahl, 2012, 2014a, 2014b; Holopainen & Helama, 2009; Huhtamaa, 2018; Lunden, 2002; Myllyntaus, 2009; Pillatt, 2012). In these northernmost locations, cold springs—which delayed and thus shortened the growing season—along with wet and cold summers were the major hazards for crop cultivation. Especially in Finland, such conditions could cause wide harvest losses if the crops did not ripen before the first autumn frosts (Holopainen & Helama, 2009; Huhtamaa, 2018). Moreover, as the cultivation depended heavily on local production, also regarding seed grain, crop yields could remain low for a couple years after harvest failures due to a lack of seed grains (D'Arrigo et al., 2020; Dodgshon, 2004; Dybdahl, 2012; Huhtamaa & Helama, 2017a). The main agriculture areas of Sweden demonstrated a more diverse sensitivity to climate variability, with high January–April temperatures in combination with high June–July precipitation being favorable for high grain yields (Edvinsson, Leijonhufvud, & Söderberg, 2009).

In England, periods with cooler and wetter climate increased the risk of unfavorable weather conditions during the growing season (Brunt, 2004; Michaelowa, 2001; Pribyl, 2017; Tello et al., 2017). Frequent or heavy rainfall during the growing season and/or harvest constituted the greatest hazard to the crops (Dodds, 2004). Heavy precipitation, also outside the growing season, could regionally water-log the soils and, in medieval times before barns were in widespread use, damage stacked sheaves (Pribyl, 2017). In particular English wheat yields were positively influenced by high July–August temperatures in combination with low December–March rainfall (Brunt, 2015). Yet, in the drier parts of England, severe and prolonged droughts, for example, during the 1320s and early 1330s, could occasionally devastate harvests (Pribyl & Cornes, 2020; Stone, 2014). Interestingly, Campbell and Ó Gráda (2011) found no difference in

English harvest yield variations prior to and after the Black Death (1346–1353). This implies that climate fluctuations, rather than population pressure or labor force availability, determined the harvest outcome in medieval agriculture.

In Central Europe, cold springs and rainy mid-summers—as observed during the climax of the Little Ice Age—posed the largest hazard to grain cultivation (Degroot, 2018b; Parker, 2013; Pfister, 2007b; Pfister & Brázdil, 2006). Low spring temperatures resulted in a delayed harvest, when higher amounts of precipitation, or even early autumn frost on higher elevations, threatened the crops. A rainy harvest time reduced the flour content of the grain corn and thus made stored grain more vulnerable to infestations by insects and fungi (Pfister, 2005). Moreover, high autumn and winter precipitation reduced the calcium, phosphates and nitrogen content of the soil, in addition to having an adverse effect on sowing and survival of winter grain (especially rye) (Pfister, 2007b). Long-lasting rains during harvests led to the germination of the grain and, consequently, to a defective harvest and a poor quality of the seeds for the next year (Landsteiner, 2005). In addition, prolonged snow cover led to suffocation of seedlings or spreading of mold fungi (Landsteiner, 2005). The effects of drought in Central Europe appears to vary over time (Brázdil, Možný, et al., 2019). Very low soil moisture during drought years is documented to have had severe negative impacts on crops in the early modern period (Esper et al., 2017). In addition, dry soils could make sowing difficult which consequently resulted in lower yields (Brázdil et al., 2019). On the other hand, for example, the megadrought of 1540 had no negative impact on grain or wine harvest in Switzerland (Wetter et al., 2014).

Research focusing on Mediterranean Europe is more limited. Here, since winters are part of the early growing season, cold and/or dry winters are harmful to many crops (White et al., 2018; Xoplaki, Maheras, & Luterbacher, 2001). Winter droughts were the greatest climatic hazard to grain cultivation in the western Mediterranean (Barriendos, 2005; Pfister, 2005). Wetter climate conditions were found to benefit yields in Sicily (Sadori et al., 2016) and the eastern Mediterranean region (Xoplaki et al., 2016, 2018), except excessive precipitation (Alfani, 2018; Bauch, 2016; Enzi, Becherini, & Sghedoni, 2019). According to White (2011) and Izdebski, Mordechai, and White (2018), the combination of cold weather and droughts seems to have created the most unfavorable conditions for crop cultivation and viticulture in Mediterranean Europe. At higher elevations, cold extremes alone were the main threat to crops and viticulture in the western (Barriendos, 2005) and eastern (Mrgić, 2011) Mediterranean. Warmer climate conditions favored the growing of temperature-sensitive crops in the northern Aegean region (Gogou et al., 2016) and Albania (Morellón et al., 2016). Prolonged winter frosts were particularly adverse for olive cultivation throughout the Mediterranean region (Xoplaki et al., 2016).

3.1.2 | Animal husbandry

Climatic conditions can have various impacts on pastures and fodder production and, thus, on animal protein production (dairy products and meat). In northern and central Europe, long winters with late springs (with long-lasting snow cover) prolonged the period for domestic animals being without fresh grass. This resulted in decreased milk production and increased mortality (Baten, 2001, 2002). Furthermore, late grain harvests, typically caused by cold springs, led to shorter grazing periods on the grain fields after harvests for domestic animals. Based on Pfister (1988), Baten (2001, 2002) approximated that in Switzerland, with its high-elevation pastures, milk production decreased by at least 50% during the extreme late-sixteenth century cooling, and it could take a long time for the animals' milk production to recover (Pfister, 2005). The most extreme winters during the Little Ice Age caused an excess mortality among livestock across much of Europe, including comparatively mild Ireland, with lasting effects on the food supply for the population (Ludlow & Crampsie, 2018; White et al., 2018).

The amount and seasonality of precipitation also played a role in the production of animal protein (Michaelowa, 2001). Drought in spring and summer decreased the quality and quantity of pastures and hay yields even in relatively humid locations such as England and Scotland (D'Arrigo et al., 2020; Stone, 2014). Whereas the 1540 drought had no impact on grain and wine harvests in Switzerland, it had a devastating impact on animal husbandry, as domestic animals died from heat-stroke, thirst or hunger (Wetter et al., 2014). Extremely rainy summers were likewise detrimental, as haymaking had to be delayed until dry weather, which likely lowered the quality of the hay. Furthermore, very rainy weather during the hay harvest lowered the raw protein content of the hay by up to two-thirds, resulting in starvation among the animals the next winter (Pfister, 2005). Alternatively, continuous harvest time rains could rot the cut hay on the fields, resulting in poor quantity and quality of hay-stocks for the winter (D'Arrigo et al., 2020).

3.1.3 | Fishery

Though little studied, the impacts of climate and weather on historical fish catches and fisheries appear to have been considerable. Fishery data from the Barent and White Sea during the seventeenth and eighteenth centuries showed that the catch of salmon, cod, and halibut decreased during colder periods (Lajus, Lajus, Dmitrieva, Kraikovski, & Alexandrov, 2005). Likewise, colder ocean temperatures, with more sea ice, reduced cod fish stocks in Icelandic waters and the presence of sea ice in addition prevented people from reaching the cod banks (Ogilvie & Jónsdóttir, 2000). On the other hand, drought and high temperatures could deteriorate the water quality in freshwater fish ponds in Central Europe leading to extensive fish mortality (Brázdil, Dobrovolný, et al., 2019). Hoffmann (2005) suggested that the Little Ice Age played a role in the collapse of herring stocks in the southern North Sea and the Scanian coast in the late-fourteenth and early-fifteenth centuries. Nevertheless, he emphasized the effects of over-exploitation, habitat alteration, and other human activities as the main factor behind the collapse of the fisheries. By studying millennium-long herring catch data from the south-eastern Swedish coast, Alheit and Hagen (2001, 2002) related periods of 20–50 years of good herring catch, separated by periods of 50–70 years of poor catch, to the modes of the North Atlantic Oscillation (NAO). Furthermore, they found similar evidence from English and French herring and sardine fishery data. However, causal links between changes in ocean temperatures and changes in herring catches remain unclear (Alheit & Hagen, 2001, 2002).

3.1.4 | Agricultural and pastoral adaptation

All agrarian societies have adapted, with varying success, to the adverse climatic effects on food production (Ljungqvist, 2017). These strategies have included a diversification of crops and domestic animals, cultivation at various elevations and sites with different soil properties, and storage buffers of seed corn (Krämer, 2015). In medieval England, the lack of seed corn after larger harvest failures decreased harvests even with good growing conditions in subsequent years (Bekar, 2019). Adequate storage facilities, or grain imports, lessened this problem later in England and elsewhere, whereas regions like Scotland and Finland struggled with this problem long into early modern times (D'Arrigo et al., 2020; Dodgshon, 2004; Huhtamaa, 2018). On the other hand, Finnish farmers responded to the cold phases that lowered yields by increasing the practice of slash-and-burn cultivation, which provided higher yields than arable cultivation (Huhtamaa & Helama, 2017a). The state of the agricultural technology mattered too. Grain yields decreased during the climax of the Little Ice Age (*c.* 1570–1710) both in western and eastern Europe but with different recovery patterns. In western Europe, yields increased well *above* their pre-1570 level but not in eastern Europe. These differences are attributable to socio-political and technological differences rather than to climate (Pei, Zhang, Lee, & Li, 2016). On a smaller spatial scale, similar differences have been observed between late-seventeenth century England and Scotland (D'Arrigo et al., 2020) and eighteenth century England and France (Michaelowa, 2001). Eighteenth century technological improvements, and increased investments in agriculture, substantially increased English grain yields before similar increases occurred in most other European countries (Brunt, 2015). English farmers successfully adopted mixed farming methods, improving the soil quality, from the late seventeenth century onward due to a combination of climate challenges and market incentives (Tello et al., 2017).

Cultivating different crops, which were able to cope with different climatic conditions, was a common adaptation strategy in medieval and early modern Europe. Farmers in most of Central Europe grew both wheat and rye to minimize the risks associated with bad harvests (Landsteiner, 2005). They also planted barley and oats, which ordinarily mainly served for beer production and animal feed, but in times of shortage could also serve as a human food source (Landsteiner, 2005). As these grains tolerate cold (and wet) conditions, they were cultivated as staple crops in northern-most Europe where wheat cultivation was less feasible (Dodgshon, 2004; Huhtamaa, 2018). Presumably for the same reason, wheat was partly replaced by barley and oats in late medieval England (Campbell, 2016). In large parts of seventeenth century Finland, autumn-sown rye replaced barley, which ripens later, as the main crop—likely as an adaptation to the cold climate regime by minimizing the risk of autumn frost damage (Huhtamaa & Helama, 2017b). A strong decrease in the cultivation of wheat in favor of barley, spelt wheat, and oats along with a strong decrease of wine in favor of plum for the production of plum brandy in Ottoman Bosnia during *c.* 1550–1650, have likewise been interpreted as an adaption to a colder and wetter climate (Mrgić, 2011). To compensate for the traditional cash crops like wine and wheat, Bosnian farmers furthermore increased pig rearing, beekeeping, and market gardening (Mrgić, 2011).

3.1.5 | Other first-order impacts and adaptation responses

Studies focusing on other (bio)physical impacts, unrelated to food production, are rather few. One exception constitutes the study of historical floods and their damages to the built, managed, and natural environments (Glaser et al., 2010; Soens, 2013, 2018; Vadas, 2020). As this research field is too wide for this review, we only present a few relevant studies. For example, research concerning the rivers Rhine (Toonen, 2015; Wetter et al., 2011) and Danube (Kiss, 2019; Rohr, 2013) include detailed assessments of flood damages beside discussions on the human responses. Rohr (2013) described how Austrian towns living under permanent flood risk developed a "culture of flood management" during the medieval and early modern period. Likewise, various activities aiming to reduce future flood risks followed the winter 1783/1784 floods across Europe (Brázdil et al., 2010).

Other direct impacts, beside floods, are commonly addressed in publications solely through their influencing role on second- or third-order impacts such as the effects on transportation and prices. For example, Wetter et al. (2014) explored the aftermaths of collapsing water power during the 1540 megadrought in Switzerland and Nowosad and Oliński (2019) of forest fires in Poland. Another far-reaching first-order impact constitutes the increased area, and prolonged period, of frozen water bodies during very cold periods. The blocking of ice on rivers and canals in the Low Countries, 1330–1800, affected shipping considerably. The ice cover had such an adverse effect on communication and commerce that large-scale and labor-intensive ice removal was already being undertaken in the fourteenth century (De Kraker, 2017). Moreover, ice cover hindered the essential transport on water-ways, including food imports to famine-struck regions, across Europe in an era of wooden ships (Krämer, 2015). During periods of frequent and prolonged winters, which led to the freezing of the Baltic Sea, trade was impeded between the grain-producing regions around the Baltic Sea and the North Sea region, including the British Isles, for many months per year (Baten, 2001). Similarly, Finland was isolated by sea ice over the winter, reducing the coping capacity of the population (Huhtamaa & Helama, 2017a). Conversely, warm winters lacking ice and snow negatively influenced essential transports in the mining districts of central Sweden, which depended on sleighs in winter (Edvinsson et al., 2009).

Climatic impacts on the landscape, and human responses to those, can also be considered as first-order impacts. For example, people in the late medieval Campine, North Sea coast, region altered the landscape to minimize the constant risk of sand drifts by winds (De Keyzer, 2016). However, such mitigation strategies were not successful everywhere. On the Shetland Islands, overgrazing and poor land management in combination with increased storminess during the late seventeenth century accelerated wind-driven erosion, having different impacts between farm locations (Bampton, Kelley, & Kelley, 2018) and even leading to the abandonment of farms (Bampton, Kelley, Kelley, Jones, & Bigelow, 2017). Climate and weather could also have direct impacts on building activities. For example, the relatively dry conditions during the construction period favored the building progress of the *Fossa Carolina*, Charlesmagne's most ambitious hydro-engineering project, but heavy rains likely contributed to the end of the project in 793 (Muigg et al., 2020).

3.2 | Second-order impacts: influence on livelihoods, economy, and health

3.2.1 | Food prices

The current perception, at least among historians, is that grain price variations were not *per se* a result of climate variability. Grain prices rather evolved from an interplay of supply and demand, influenced by market regulations, and climate-induced variations in harvests are generally considered to only partly influence price changes (e.g., Mauelshagen, 2010). However, consecutively occurring severe harvest failures could increase grain prices four- to six-fold, which was the case for example at around 1570 after crop failures across Central Europe (Landsteiner, 2001, 2005). Increases in grain prices varied regionally and typically the largest price increases were observed in landlocked regions (Dybdahl, 2012; Krämer, 2015). Depending on prevailing socio-political and socio-economic circumstances, even modest increases in grain prices could lead to increasing mortality and decreasing birth rates (Alfani & Ó Gráda, 2017; Krämer, 2015).

Different scholars have reported contrasting results on whether a distinct climate signal can be found in grain prices. Söderberg (2006) found no significant correlation between temperature and grain prices in late medieval Europe using a pioneering millennium-long Northern Hemisphere temperature reconstruction (no European-scale temperature reconstruction was available at that time). Conversely, Camenisch (2015b) demonstrated for the Burgundian Low

Countries during the late Middle Ages that the grain prices showed a close relationship with local reconstructed seasonal temperature and precipitation. Likewise, Pribyl (2017), also using appropriate climate data, found that climate conditions during the growing and harvest seasons in late medieval England were crucial for grain price levels. A decrease in the association between harvest size and grain prices between the two periods 1268–1480 and 1750–1800 has been detected for England (Campbell & Ó Gráda, 2011). For early modern Moravia, 67% of all years during the fifteenth and eighteenth centuries with unusually high grain prices could be attributed to adverse weather conditions during the same and/or preceding year (Brázdil & Durd'áková, 2000), though in almost half the cases factors related to human agency or epidemics played a role too.

The conventional view has been that climate factors mainly influenced grain price variability in the high-frequency domain, that is, in the year-to-year variability (see e.g., Kelly & Ó Gráda, 2014a, 2014b). Besides identifying that extreme droughts were related to years with extremely high grain prices, Esper et al. (2017) found a persistent and significant negative relationship between long-term, especially multi-decadal, grain prices and temperature trends in southern and central Europe (i.e., colder climate condition = higher prices). Furthermore, Esper et al. (2017) highlighted that climatic and socio-political factors shifted over time as the climate–price relationship broke down during the Thirty Years' War (1618–1648). Camenisch and Rohr (2018) have tentatively suggested that during the late Middle Ages and the early modern period, the link between climate conditions and grain prices was stronger than the link between weather/climate conditions and crop yields. The proposed reason is that grain prices, to a certain extent, represent grain production over an extended geographical area and thus, are less influenced by local-scale growing conditions.

3.2.2 | Epizootics

Newfield (2009) explored a cattle panzootic which spread west from central Europe *c.* 1315 and lasted until *c.* 1325, resulting in a high cattle mortality. As retrospective diagnostics are challenging, Newfield (2009) did not directly attribute prevailing (extreme) climate conditions to the outbreaks or severity of cattle panzootics. However, Slavin (2012) argued that cold temperatures and excessive precipitation for several years were weakening the bovine population due to malnutrition which decreased the animals' resistance to pathogens. White (2014) more generally referred to "Little Ice Age panzootics" and argue that changes in livestock have played a large and often overlooked role in climate history research. Besides the influence from changes in biomass production for pasture and fodder on livestock health, White, Sylvester, and Tucker (2014) pointed to very excessive livestock mortality from exposure during individual extremely cold winters. Newfield (2015) furthermore linked epizootic mortality to malnutrition among domestic animals from prolonged dearth of fodder and pasture, which, in turn, was typically related to adverse weather conditions. Newfield (2015) found that major livestock plagues tended to follow droughts and cold winters or other climatic anomalies. Epizootic mortality after cold winters has also been associated with livestock mortality during later, better documented, centuries (White et al., 2018).

3.2.3 | Epidemics and pandemics

Changes in temperature and hydroclimate strongly influence the distribution and abundance of hosts and vectors and the transmitted pathogens (Gubler et al., 2001; Mills, Gage, & Khan, 2010). A prominent example constitutes the argument for climate-driven plague outbreaks in late medieval and early modern Europe (Schmid et al., 2015; Stenseth et al., 2006) caused by the bacterium *Yersinia pestis* transmitted by fleas hosting at rodents (e.g., great gerbils in Central Asia and rats in Europe). Depending on geographical location, plague outbreaks can be attributed to different climatic conditions. For instance, warm springs and hot summers favored outbreaks in Central Asia (Stenseth et al., 2006) and the Mediterranean (Cohn, 2008; Welford & Bossak, 2009) whereas low temperatures hamper early-phase transmissions by *Xenopsylla cheopis* (Rothchild) fleas (Schotthoefer et al., 2011) and cold and dry winters were unfavorable for plague outbreaks in the eastern Mediterranean (Xoplaki et al., 2001). McMichael (2012) provided an overview of the climatic impacts at the pathogen, vector, and host (human) level of the trophic cascade influencing the location and timing of the plague outbreaks. However, differing results were obtained in studies directly linking climate to plague outbreaks. Schmid et al. (2015) found significant relationships between *Yersinia pestis* outbreaks at its rodent plague reservoirs and climate in Central Asia and renewed plague re-introductions with a delay of 15 ± 1 years via trade routes into Europe.

By comparing climate conditions to plague outbreaks in Europe, Yue and Lee (2018a) found no clear links at different temporal scales (annual to interannual), spatial scales (country to continent) and for different climate parameters and circulation indices, and statistical approaches (linear and nonlinear). However, more recent studies by the two authors found that plague outbreaks occur with 5-years delay after cold and dry periods having significant coherencies at decadal time-scales and different regional scales (Yue & Lee, 2018b) whereas synchronous plague outbreaks across Europe were caused by droughts (Yue & Lee, 2020). Conversely, Ljungqvist et al. (2018) found highly significant negative correlations between drought (using the same reconstructed drought data by Cook et al. (2015) as Yue and Lee (2020)) and the number of recorded plague outbreaks indicating that cold and moist summers favored outbreaks of plague. This result is in line with a 35% higher probability of an epidemic in central-eastern China during cold spells over the 1300–1850 period as reported by McMichael (2012).

Extreme weather events could contribute to an increase in diseases such as Hepatitis E, gastrointestinal disease, and leptospirosis especially for the more vulnerable segments of the population (Alderman, Turner, & Tong, 2012) and increase the contact between rodents and humans (McMichael, 2012). Generally, extreme climate events such as very cold or very hot spells increase ill health and mortality (Diaz, Kovats, McMichael, & Nicholls, 2001). For example, high summer temperatures resulted in more malaria cases and deaths in the early modern North Sea region (Knottnerus, 2002) and in Finland (Huldén, Huldén, & Heliövaara, 2005) as warm summers enhanced larval development of the vector which determined the number of malaria cases for the following transmission season (Huldén & Huldén, 2009).

3.3 | Third-order impacts: societal and demographic implications

3.3.1 | Famines

Historical famines were generally triggered by a combination of biophysical factors causing a reduction in food productivity and factors internal to human society governing the access to available food resources (Collet, 2015; Engler, 2012; Nelson et al., 2016). The importance of endogenous or "institutional" factors for the occurrence, duration, and severity of famines are nowadays generally acknowledged at the same time as contemporary scholarship increasingly has included climate factors to explain famines (for a review, see Slavin, 2016). The scholarship agrees that the major cause of famine mortality is found in epidemics since the biological resistance to diseases is reduced and famine-driven population movements that facilitate their spread are increased (see, e.g., Alfani & Ó Gráda, 2017; Campbell, 2009; Dybdahl, 2014b; Landsteiner, 2005).

Some large-scale quantitative studies have detected significant negative correlations between temperature and the number of famines (i.e., low temperature = more famines) although without establishing causality (e.g., Zhang et al., 2011; Zhang, Brecke, Lee, He, & Zhang, 2007). Studies taking more qualitative, and local- to regional-scale, approaches also acknowledge that famines occurred more frequently during cold climate conditions (e.g., Campbell, 2016; Huhtamaa, 2018; McCormick, Dutton, & Mayewski, 2007). The most widespread famines correspond to almost continental-scale cold conditions over Europe, while drought was a less frequent and more regionally restricted, climatic trigger mainly confined to southern Europe (Alfani & Ó Gráda, 2017). Regardless of the clear temporal correlation between climate and famines, some scholars, like Alfani and Ó Gráda (2018), argued that first-order climate impacts on food production should be considered more as triggers than genuine causes of famines. Several studies have addressed famines following sharp volcanic cooling during the Carolingian times (McCormick et al., 2007), late medieval times (Campbell, 2017; Stothers, 2000), and the early modern period (D'Arrigo et al., 2020; Huhtamaa & Helama, 2017a).

Climatologically marginal agricultural regions, as at the northern edge of agriculture, appear to have been particular famine-prone, for example, northern England (Campbell, 2009), Scotland (Cullen, 2010), Denmark (Hybel, 2002), Norway (Dybdahl, 2013, 2014a), Sweden (Edvinsson et al., 2009), Finland (Huhtamaa, 2018), Iceland (Ogilvie, 2019), and northern Russia (Helama, Huhtamaa, Verkasalo, & Läänelaid, 2017; Huhtamaa, 2015; Klimenko, 2016). Regions at high elevations, with short and cold growing seasons, likewise showed a higher risk for famines (Pfister, 2005, 2007a). However, even comparatively advanced economies in medieval and early modern Europe, in fertile agricultural areas, could occasionally suffer famines during particularly unfavorable conditions (e.g., for Italy, see Alfani, 2010, 2018; Bauch, 2016; Nanni, 2020), especially during periods of armed conflicts or other disturbances (Parker, 2013). Except for societies with an especially high vulnerability to food shortages, the occurrence of climate-triggered famines typically required adverse climate conditions lasting at least 2 years, with some of the worst famines resulting from three (or more) consecutive years of extremely adverse climate conditions for agriculture (Alfani & Ó Gráda, 2017; Camenisch & Rohr, 2018).

Contemporary scholarship has become increasingly aware that the risk for climate-triggered famines depended on the level of famine vulnerability. This was influenced by many different environmental and societal factors (Collet, 2012, 2018; Huhtamaa, 2020; Krämer, 2012; Lassen, 2016; Schroeder, 2019). Some attempts have been made to quantify famine vulnerability in such a way that it allows for comparisons in space and time. By studying a number of historical societies, Nelson et al. (2016) evaluated eight environmental and social factors for determining vulnerability to food shortage prior to the onset of adverse climatic change. They confirmed a tendency for severe food shortage to occur in regions which showed *a priori* a high vulnerability. Engler (2012) offered a more elaborated approach with famine "vulnerability indices" consisting of 24 factors for social vulnerability and nine for environmental vulnerability to allow for multi-causal assessment of famine risk factors. These "vulnerability indices" were empirically tested through application on Ireland for the famines of 1728–1729 (Engler & Werner, 2015) and 1740–1741 (Engler, Mauelshagen, Werner, & Luterbacher, 2013).

Vulnerability to famines not only differed between societies, but also *within* societies. Distinct regional variations in the duration and intensity of famine mortality were a common feature during most famines. Such patterns depended on factors such as the extent of alternative food sources, population density, the extent and magnitude of prefamine poverty among the population, and on famine relief measures (Collet, 2018; Collet & Schuh, 2018; Huhtamaa & Helama, 2017a; Jütte, 2005; Krämer, 2012; Lassen, 2016; Pfister & Brázdil, 2006; Slavin, 2016). Even marginal agricultural regions could improve the resilience against climate-induced famines by, for example, landscape management (for Iceland, e.g., Streeter, Dugmore, & Vésteinsson, 2012) or constructing public grain magazines (for Norway, e.g., Hansen, 2015). Population pressure on available resources appears to have played an important role (Alfani & Ó Gráda, 2017). For example, European famine vulnerability by *c*. 1300 can be understood in light of deteriorating standards of living for large segments of the population with adverse effects on health (Aberth, 2001; Campbell, 2016; Slavin, 2017). The same holds true for famine vulnerability in the late sixteenth century (Behringer, 2003; Campbell, 2010). The risk for famines could increase considerably during armed conflicts or civil unrest. Parker (2013) maintained that the high mortality following adverse climate conditions during the seventeenth century was not always necessarily caused by direct climatic impacts on agriculture, but could often rather be devastating synergies arising from food shortage and ongoing armed conflicts.

3.3.2 | Demography, stature, health, and age of death

Unfavorable climate conditions contributing to famines and the development and spread of diseases could have far-reaching demographic consequences. Macro-scale analysis by Zhang et al. (2007, 2011) revealed an inverse relationship between population growth and temperature. Using a modeling approach with temperature and population estimates, Lima (2014) investigated changes in per capita population growth, over 50-year time-intervals, during 800–1800 in western Europe and found, depending on region, that temperature predicted between 2 and 38% of the changes in per capita population growth. However, this relationship was stronger for several regions prior to 1550 and considerably weaker after 1650. Studying demographics in Iceland from 1734 to 1860, Turner, Rosenthal, Chen, and Hao (2012) found a decrease in population growth for 2 years following a cold year.

Some effects of malnutrition and disease can be traced through the study of human remains. Anthropometric research employs data on human stature (height) from documentary sources or osteoarchaeology, which is an indicator of nutritional status during childhood. During the past 20 years, climatic change as an explanatory factor behind changes in nutrition, and thus stature, has increasingly entered anthropometric research. The long-term decline in body height in medieval northern Europe partly corresponded to the long-term decline in temperature as average male height was largest during the warm ninth–eleventh centuries and lowest during the cold seventeenth and eighteenth centuries (Steckel, 2004). For the eighteenth century in southern Germany and other regions mild winters had a positive influence on nutrition compared to colder winters as elsewhere in eighteenth century Europe (Baten, 2002), with male stature being lowest among those born during the food crisis in 1771/1772 (Baten, 2001).

Comprehensive anthropometric estimates of the biological standard of living over the past two millennia from 9477 (mostly) skeleton-based stature measurements for both genders from 314 sites across Europe confirmed this picture (Koepke & Baten, 2005a). The authors found a marginally significant positive relationship between higher temperatures and body height. A more quantitative analysis of temperature–height relationships over the past millennium found that stature reached a maximum during the eleventh century, whereas the largest decrease was observed during the 13th, 14th, and seventeenth centuries. These trends were most pronounced for Scandinavia and eastern Europe, making Koepke and Baten (2005b) link it to a larger climate sensitivity in nutrition status in these regions. A comparison of the age at death of many thousands of individuals buried in several London cemeteries showed younger ages at death during the thirteenth century compared to the eleventh and twelfth centuries (DeWitte, 2015) and ages first increased again after the Black Death (DeWitte, 2018). The author connected the increased mortality in the thirteenth century with climatic cooling causing widespread famines combined with an increasing population pressure (DeWitte, 2015). Likewise, an examination of 241 adult skeletons from Denmark buried *c.* 1050–1536 revealed an increasing abnormal development of tooth enamels and an increasing frequency of infectious middle ear diseases from the late thirteenth century, linking this to poorer nutrition status with climatic cooling (Primeau, Homøe, & Lynnerup, 2019).

Almost all studies on climate-mediating effects on demography, human stature, or health focus on agrarian societies where crop failures played a major role in fertility and mortality rates. One example of climatic impacts on hunter–gatherer population dynamics is found in the study of how mean temperature affected annual births and deaths among three Sámi populations in sub-Arctic Finland over the 1722–1850 period (Helle & Helama, 2007). Results showed only weak temperature effects on the demographics of this population living from fishing, hunting, and reindeer herding, although births increased and the mortality decreased during warm years. Looking at the birth-sex ratios of those three Sámi populations for the 1745–1890 period, Helle, Helama, and Jokela (2008) found a ~1% increase in the proportion of boys born per 1°C increase in annual mean temperature; however, they were unable to explain the mediating mechanisms.

3.3.3 | Economic and political change

Though possible climatic impacts on past socio-political change requires thorough consideration of economic, political, and societal conditions (e.g., Campbell, 2010; Degroot, 2018b; Le Roy Ladurie, 2004–2009; White et al., 2018), the majority of studies rely on temporal correlations or simple climate–society interaction models. For example, possible relationships between climate and large-scale agricultural productivity were interpreted to act as an agent for macroeconomic changes (Pei, Zhang, Lee, & Li, 2014; Pei, Zhang, Li, & Lee, 2013, 2015). For central Europe, relative stability in temperatures and precipitation *c.* 700–1200 were supposedly beneficial for sustained demographic growth whereas cold (or very variable) climate periods were presumed to have caused greater hardships (Büntgen et al., 2011). For southwestern Albania, Morellón et al. (2016) found by investigating sediment data that settlement intensity peaked under warm conditions during the first half of the first millennium CE. More intense agricultural land use in Sicily has been found to coincide with wetter conditions prevailing *c.* 450–750 and *c.* 1400–1800 (Sadori et al., 2016).

Changes in the political structure of the Ottoman Empire, which was dependent on a large-scale circulation of resources within its territory, in the light of unfavorable climate during the climax of the Little Ice Age, were investigated by White (2011). Extreme coldness and regional drought in the 1590s resulted, especially on marginal lands, in high mortality (exceeding 50%) among sheep and cattle through a combination of starvation and outbreaks of disease among exposed animals. At the same time, as population growth in marginal regions within the empire increased, increasing number of landless men became a destabilizing factor. When major military campaigns required additional resources, it resulted in an outbreak of banditry in the Anatolian countryside. Bandit gangs transformed into rebel armies with additional recruitment triggered by continued economic disruption. Thus, a range of social pressures and conditions laid the ground for the rebellion rather than climate-induced agricultural failures alone (White, 2011). Similar developments for the same region appear, though less well-founded, in for example, Ellenblum (2012) who proposed that a widespread drought-driven societal collapse occurred in the eastern Mediterranean during the tenth and eleventh centuries, followed by a rebuttal by Preiser-Kapeller (2016). Haldon et al. (2014), Xoplaki et al. (2016, 2018), and Preiser-Kapeller and Mitsiou (2020) have investigated the effects of climatic amelioration during medieval times for the agrarian economy and imperial revival of the Byzantine Empire and showed that climatic change was only one, although not unimportant, factor for these developments.

Parker (2013) linked adverse climate conditions during the seventeenth century to the political and demographic crises which were evident across most of Europe. While the highest mortality was not necessarily caused by direct climatic impacts on agriculture on their own, devastating synergies arising from food shortage and ongoing armed conflicts in combination resulted in the largest loss of life in many places as wartime taxes and food requisitions proved lethal to peasants at the edge of starvation (Parker, 2013). All this together helped to cause socio-political crises of different types and, in some cases, even societal changes. However, not all studies found detectable climate influences on societies when they would have been expected. One such case is the reconstructed variations in the intensity of Central European building activity 1250–1699 from felling dates of close to 50,000 construction timbers by Ljungqvist et al. (2018). They found building activity to be strongly related to variations in plague outbreaks and grain prices, but *not* to either temperature or hydroclimate—despite grain prices showing significant negative correlations with temperature (e.g., Esper et al., 2017). However, climate may have influenced building activity in certain regions. It has been proposed that climatic cooling helps to explain why so many stone churches were left unfinished in Finland in 1495–1560 (Holopainen, Helama, & Huhtamaa, 2016).

3.3.4 | Migration

Studies focusing on the effects of climate on historical migration are comparatively rare. Nevertheless, deteriorating climatic conditions and a possible following agricultural crisis can trigger human migration (e.g., Collet & Schuh, 2018). For instance, both Zhang et al. (2007, 2011) and Büntgen et al. (2011) associated precipitation and temperature variations with historical migration within Europe and across continents. Rüther (2018) suggested that climate-induced harvest failures could have been a push-factor, although one of relatively minor importance, for the German eastward twelfth and thirteenth century settlement expansion. The English famine of 1258 drove migrants into London (Campbell, 2017; Stothers, 2000), the Great Famine (1315–1322) led to large-scale migration within England (Campbell, 2016), and the English food crisis of 1596–1604 contributed to emigration to Ireland (Campbell, 2010). Jakus (2019) argued for migration from the Dalmatian hinterland resulting from the food shortage of 1453–1454. The climate-triggered famines in Ireland in 1728–1729 (Engler & Werner, 2015) and 1740–1741 (Engler et al., 2013) prompted migration within Ireland, to England, and to North America.

3.3.5 | Armed conflicts

A number of studies have linked climate variability to the frequency of war through correlation statistics between climate records and numbers of conflicts (e.g., Lee, Zhang, Brecke, & Fei, 2013; Lee, Zhang, Brecke, & Pei, 2015, 2019; Lee, Zhang, Pei, & Fei, 2016; Tol & Wagner, 2010; Zhang et al., 2007, 2011). They argue that adverse climate conditions increase war frequency through food shortages, leading to destabilized societies and an increase of violent competitions over resources (Hsiang, Burke, & Miguel, 2013). For example, Tol and Wagner (2010) concluded that cold and wet conditions increased the frequency of conflict in northwestern Europe and eastern Europe (Lee et al., 2015), whereas warmer and drier conditions apparently triggered more wars in southeastern Europe. Comparisons between the NAO and the occurrence of 835 armed conflicts in Europe 1049–1800 showed a 70% increase in southern Europe during positive phases of the NAO (Lee et al., 2013, 2016). A quantitative assessment of the climate–war association in Europe (900–1999) using a dataset of 2309 armed conflicts revealed a cold temperature–higher number of wars relationship at multi-decadal time-scales, which intensified during periods of high population pressure (Lee et al., 2019; for data-related problems with these studies, see Section 4.3).

Parker (2013) directly linked armed revolts to adverse climate conditions for food production in seventeenth century Europe. He argued that climate-induced decreasing food availability coincided with prolonged wars, which demanded increased state revenues. This increasing demand of revenues, when per capita resources had decreased, resulted in societal conflicts that could turn into revolts or even large-scale rebellions causing political and societal instability. However, Warde (2015) maintains the difficulty in establishing a causal chain between cold climate conditions and armed conflicts though the link to minor conflicts, such as food riots, is easier to establish. De Juan and Wegenast (2020) found a negative relationship between temperature and food riots in England (1500–1817), especially during the eighteenth century, whereas prior to and after this period correlations remained insignificant. More direct effects of climate or weather on particular military campaigns have also been discussed in the literature. An example of this is the Mongol withdrawal from Hungary in 1242, which Büntgen and Di Cosmo (2016) argued in part was connected to very wet conditions, creating marshy terrain, hampering the effectiveness of the Mongol cavalry. Similarly, Degroot (2014, 2018b) argued that more prevailing easterlies offered a critical advantage for the Dutch navy during the second (1665–1667) and third (1672–1674) Anglo-Dutch Wars.

3.4 | Fourth-order impacts: cultural responses

3.4.1 | Scapegoat hunting

Several studies link extremely cold conditions to an increase in early modern witch trials (e.g., Behringer, 2003, 2005; Pfister, 2007a) though quantitative analyses are rare. However, Oster (2004) found a weak though marginally significant relationship across 11 regions in Europe between cold climate conditions and the number of witch trials over the 1520–1770 period and argues that they, to a certain extent, had economic foundations rooted in climate influences on food production. However, the robustness of the results is questionable as mainly obsolete and decadally resolved temperature data were used. Conversely, Leeson and Russ (2018) found no significant effects of climate on the number of witch trials for the 1520–1769 period.

Studying the temporal occurrence of 1366 instances of Jewish persecution from 936 European cities between 1100 and 1800, Anderson, Johnson, and Koyama (2017) found that the likelihood of persecution increased significantly with a one standard deviation decrease in growing season temperature in the previous 5-year period. This relationship was most prominent in regions with poor soil quality and weak central state authority. Jews were frequently made scapegoats for various economic and social misfortunes in medieval and early modern Europe, and Anderson et al. (2017) argued that the detected low temperature–high persecution relationship was related to decreased agricultural productivity which caused economic shocks. Furthermore, a weaker, partially significant, relationship between low precipitation and an increasing number of persecutions was found over the 1500–1799 period.

3.4.2 | Scientific and artistic reactions

De Dreu and van Dijk (2018) found a significant increase in landmark discoveries in science and technology in Europe 1500–1900 during periods of colder climate, which they argued was a result of climate-induced economic pressure and resource scarcity. The partly climate-induced crises after *c.* 1560 resulted, according to Roeck (2005), in an increasing lack of work for artists, sharpening the competition, and allowing only the most skilled and innovative ones to remain in business. This increased competition of market shares is claimed to have promoted art refinement as well as the development of new styles. A common view is that colder climate had at least a subconscious influence on the occurrence of snow and ice scenes in paintings. The prevalence of ice winter motifs *c.* 1590–1675 arguably reflected the actual occurrence of cold winters making ice thick enough to allow skating in continental Europe (Robinson, 2005). In contrast, Goedde (2005) downplayed the role of cold winters for the popularity of ice scenes in Netherlandish art by highlighting that cultural factors must have played a more important role as these motifs only became popular in a few regions. Nevertheless, a quantitative analysis of the relationship between the red-to-green ratio in the skies of 554 datable paintings of sunset scenes and the aerosol optical depth following major volcanic eruptions (usually resulting in summer cooling) over the 1500–1900 period showed a strong correlation between the two (Zerefos, Gerogiannis, Balis, Zerefos, & Kazantzidis, 2007). The result demonstrated that artists indeed were influenced by contemporary atmospheric and climatic conditions.

3.4.3 | Crisis interpretation, religious responses, and cultural memory

An increasing number of studies have assessed the cultural consequences of climate variability including, for example, crisis interpretation, cultural memory, and learning processes (see Krämer, 2015). However, commonly these are discussed in the context of associated first to third-order impacts. Therefore, only a few examples of this scholarship can be provided here. For example, Rohr (2007b,a) has studied contemporary interpretations of extreme weather events in the eastern Alpine region. In medieval and early modern Europe, adverse climate conditions were commonly perceived as a divine punishment giving rise to various religious expressions and rituals (e.g., Barriendos, 2005; Bauch, 2016; Behringer, 2003, 2005; Campbell, 2016). Bell (2008) showed that Christians and Jews experienced and interpreted adverse climate events in a similar way in early modern Germany. An increasing frequency of prosecutions for suicidal despair between *c.* 1570 and 1630 appears to be partly related to adverse climate conditions as suicides were observed to increase during crisis years (Lederer, 2005). Even though melancholia emerged as a specific medical condition at about the same time, it appears on the other hand to be entirely unrelated to climate (Midelfort, 2005).

4 | DISCUSSION

4.1 | Main findings and identified research gaps

Research during the past 20 years on the climatic change–human history interface for medieval and early modern Europe has revealed significant first-order (bio)physical impacts of climate variability regarding the potentials, limits, and risks associated with agriculture (Section 3.1). The reviewed literature agrees that extremely cold periods resulted in decreasing food production across Europe. In particular, a delayed onset of the growing season increased the risk for poorer harvests. Excessive precipitation or drought had mainly negative effects during individual years, but rarely over consecutive years, and typically impacted smaller geographical areas than low temperatures (Section 3.1.1). Moreover, the publications show clear evidence that political, social, and technological factors strongly influenced climate-induced changes in food production (Section 3.1.4). A number of studies have demonstrated significant second-order climatic impacts on changes in the availability and prices of food were caused by first-order climatic impacts on agriculture. However, this research has, at the same time, revealed that the role of factors related to climate and factors related to human agency varied over time and space (Section 3.2.1). Current scholarship has only been able to link certain second-order impacts, such as epizootics and epidemics unrelated to famines, to climate variability with low confidence (Sections 3.2.2–3.2.3).

The reviewed studies present clear causal links between first-order to third-order impacts manifested in famines, effects on human health, and even demographic development (Sections 3.3.1–3.3.2). However, the influence of climate on other third-order impacts such as socio-political changes, migration, and armed conflict (Sections 3.3.3–3.3.5) as well as fourth-order climatic impacts on society including witch trials, religious responses, and artistic expressions (Section 3.4), have limited support in the form of credible causal links. Nevertheless, recent scholarship has clearly demonstrated that climate variability, and other changes in the physical world, were not an inactive backdrop to human history, but an active agent in a complex interplay of context and contingency.

Understanding the full extent of how climate influenced various aspects of human history is at present restricted by geographical biases of the scholarship, with most studies covering western-central Europe or northern Europe (Figure 3; Table A1). In addition, a disproportionately large attention in the reviewed studies has been on cold extremes

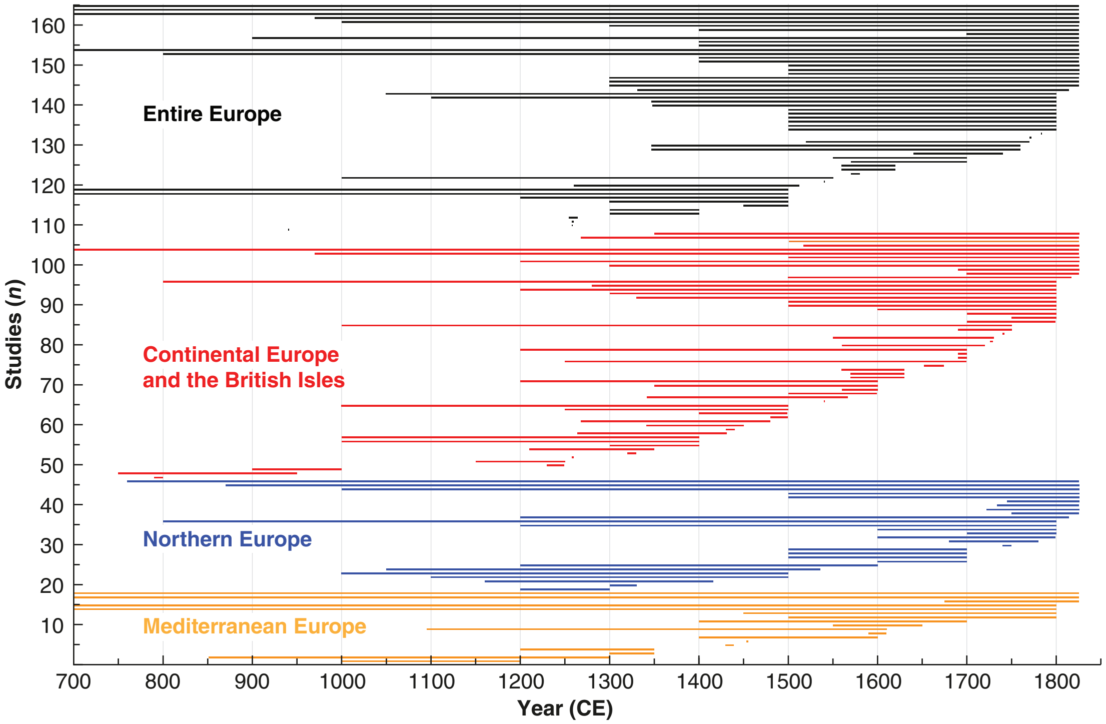

FIGURE 3 Temporal coverage of the 165 reviewed studies examining associations between climatic variations and human history for different regions between 700 and 1815 CE

and severe short-time crisis events. Several other research gaps are still present as well. We note that comparatively few studies focus on the societal effects of longer periods of "favorable" climatic conditions. Furthermore, almost all those studies focus on agrarian societies where crop yields played a major role in fertility and mortality rates. The analyses of climatic impacts on hunter–gatherer populations, on fishery, and even on pastoralism, are understudied.

An uneven temporal focus is evident too, with comparatively few studies covering medieval times, and among those, most focus on the Late Medieval Crisis (mainly the fourteenth century). The primary focus has been on the climax of the Little Ice Age (*c*. 1570–1710) with particular emphasis on the cold period *c*. 1570–1630. Moreover, most studies primarily have addressed changes in temperature, although an increasing number of studies have assessed the effects of drought or excessive precipitation. It would be beneficial to conduct comparative studies of two or more regions on a local or regional scale that address the same questions and apply similar methods. Such studies would have the potential to enhance our knowledge of similarities and differences between regions and to identify which generalizations of climate–society links are possible.

4.2 | Disciplinary differences and distinguishing causality from correlation

The questions of agency and causation are focal points in attempts to link climatic change to any aspect of human history. Causality is frequently characterized by a range of relations between causes and effects, which can be direct or indirect, linear or nonlinear. Historians and physical scientists typically approach agency, causes, and effects in rather different ways (Haldon et al., 2018). Epistemological differences thus remain a challenge to interdisciplinary collaborations, as historical scholarship favors multi-causal explanations, focusing on endogenous factors, whereas physical scientists tend to more emphasize exogenous factors within a more direct framework of causality. Statistically significant relationships between climate and historical variables are not in themselves proof of causality (e.g., Contreras, 2016). However, a more fundamental problem is that some quantitative studies in the climatic change–human history interface use an inductive approach, that is, search for explanations fitting the correlation patterns—sometimes without historical justification, proper societal contextualization, or theoretical foundation (see, e.g., van Bavel et al., 2019). Such approaches favor reductionistic mono-causal explanations (Hulme, 2011), as they essentially highlight climate as an agent and downplay other, possibly more important, agents for the analyzed historical event or change (Warde, 2015).

We argue that the establishment of correlations is an important *first step* in the analysis. Nevertheless, the *causality* between climate and society needs to be reasoned first: why would the selected climate variable influence the studied societal variable? We found that many studies, especially the ones exploring the climate–human linkages on a European-wide scale, fail to establish these relationships. Furthermore, the influence of climate on society, for all impact levels, strongly depends on a combination of prevailing societal conditions determined by human agency and geographical location. Consequently, it is hardly surprising that relatively few of the reviewed studies contain a verifiable chain of causation from first-order (bio)physical impacts to third-order impacts related to socio-political change, let alone to fourth-order cultural impacts (Zhang, Pei, Fröhlich, & Ide, 2019). To establish such causal links, the particular historical circumstances of the studied society need to be taken into account. For instance, some studies which explain an increasing number of wars in early modern Europe in terms of climatic cooling (e.g., Zhang et al., 2007, 2011) fail to mention the Protestant Reformation and the emergence of nation states, and their influence on the increased number of armed conflicts.

As already emphasized by Pfister (2005), Krämer (2012, 2015), and Luterbacher and Pfister (2015), the influence of climate is more challenging to identify the further down in the impact-order model the events are examined. Our review agrees with this notion. For example, while the links between climate and the first-, second-, and some of the third-order impacts (like famine, health, and demography) are relatively clear, the causal relationships between climate and other possible third-order impacts (such as economic and political change, migration, and armed conflicts) are less evident. At the same time, an increasing number of studies have demonstrated the human capacity to learn from, and adapt to, changing climatic conditions. Publications examining the changing agricultural practices resulting from climatic changes, for example, portray this development. Thus, we argue that climate can also indirectly influence or trigger certain long-term historical processes. Nevertheless, these *fourth-order* impacts do not necessarily require causal chains from the first to the third order impact levels. For this reason, we propose a slightly modified impact order model, where the fourth-order impacts are in direct interaction with every impact level (Figure 2).

4.3 | Improper use of palaeoclimate and historical data

Recent advances in palaeoclimatology provide a powerful empirical foundation for the study of past climate–society links that previously has been lacking. However, we found it comparatively common for studies within the humanities and social sciences to use either improper or outdated palaeoclimate data or an unawareness of the inherent limitations of the particular palaeoclimate datasets employed. This may result in spurious correlations or in erroneous conclusions, with a tendency to underestimate the full amplitude of past climate variability, and in the worst case may even challenge the research results. These observations are in line with McCormick et al. (2012) who noted that archeologists and historians sometimes fail to understand palaeoclimate data at even an elementary level and highlights the need for more interdisciplinary collaborations to integrate state-of-the-art palaeoclimate knowledge into archeological/historical scholarship (e.g., Haldon et al., 2018; Holmgren et al., 2016; Izdebski et al., 2016). Furthermore, the use of improper palaeoclimate datasets could be reduced by more easily comprehensible review articles in palaeoclimatology and a better awareness of database resources such as the World Data Center for Paleoclimatology (https://ncdc.noaa.gov/paleo).

We also noted that more or less outdated or biased archeological and historical datasets are occasionally used in an uncritical manner especially within the physical sciences. Van Bavel et al. (2019) have specified two main concerns regarding these datasets. First, they are frequently spatially and temporarily biased, with western and central Europe commonly best represented (Figure 3). As the data availability decreases back in time, this can lead to an erroneous impression of the absence of crop failures, famines, violent conflicts, and other human events during earlier times. Second, these historical datasets have a questionable representativeness of variables. For example, some climate–war studies (e.g., Zhang et al., 2007, 2011) use the “Conflict Catalogue” compiled by Brecke (1999), which includes incidents of interstate wars, inter- and intraregional struggles, as well as personal feuds. Nevertheless, in the studies reviewed here, these various conflicts are all interpreted as “wars” on an equal basis.

The use of improper and outdated historical datasets to a large extent arises from a lack of updated large datasets and that the majority of historical research still published in languages other than English. This hampers its use by the international community. The accessibility of quantitative historical data in general, along with the language problem, could be mitigated through better data repositories for historical scholarship. Small, but significant, advances have been made in this direction (e.g., the Allen-Unger Global Commodity Prices Database, Allen and Unger (2019)). However, many important datasets are outdated and show severe geographical and temporal biases. Updating such datasets would facilitate the advancement of historical studies far beyond the study of climatic change–human history nexus. Examples of relevant updates needed include the European plague outbreak dataset by Biraben (1975–1976) (its biases are summarized in Ljungqvist et al. (2018)), and the *Atlas of World Population History* by McEvedy and Jones (1978).

5 | OUTLOOK

On the basis of this literature review, we propose the following recommendations for future research: (1) Enhanced interdisciplinary and international collaborations to overcome knowledge gaps and erroneous interpretations. (2) Creating, updating and improving key historical datasets relevant for climatic change–human history research, (3) To quantify the influence of different meteorological parameters on food production over different seasons at various spatial and temporal scales. (4) Conducting more local- to regional-scale comparisons between areas which have different societal impacts and outcomes to the same changes in climate. (5) Assessing the possible relationships between the comparatively small long-term changes in climate and the frequency and magnitude of weather events with direct impacts on human livelihood. (6) Pay attention to the cultural responses, such as adaptation and learning processes, not only at the “end” of the impact order pathway, but on every impact level from the first- to the third-order level.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Fredrik Charpentier Ljungqvist: Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; visualization; writing-original draft; writing-review and editing. **Andrea Seim:** Conceptualization; formal analysis; funding acquisition; investigation; methodology; visualization; writing-original draft; writing-review and editing. **Heli Huhtamaa:** Conceptualization; formal analysis; investigation; methodology; visualization; writing-original draft; writing-review and editing.

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APPENDIX

Table A1

TABLE A1 Description of the analyzed studies including study reference, approximate region(s), and time period.

Study	Region	Period
Aberth (2001)	Europe	*c.* 1300–1500
Alfani (2010)*	N. Italy	*c.* 1450–1800
Alfani and Ó Gráda (2018)	Europe	1300–1850
Alfani and Ó Gráda (2018)	Italy	1400–1700
Alheit and Hagen (2001)	Europe	970–2000
Alheit and Hagen (2002)	NW. Europe	970–2000
Anderson et al. (2017)†	Europe	1100–1800
Bampton et al. (2017)*	Shetland	1500–1699
Bampton et al. (2018)*	Shetland	1500–1699
Barriendos (2005)	Spain	*c.* 1500–1800
Baten (2001)	S. Germany	1600–1699
Baten (2002)	North Atlantic region	1–2000
Bauch (2016)	Bologna, Italy	1430s
Bauch (2019)*	Europe	*c.* 1254–1264
Behringer (2003)	Europe	*c.* 1570
Behringer (2005)	Europe	*c.* 1550–1700
Bekar (2019)†,*	England	1210–1350
Bell (2008)	Germany	1500–1800
Brázdil and Durd'áková (2000)†	Moravia	1500–1799
Brázdil et al. (2010)	Europe	1783–1784
Brázdil, Dobrovolný, et al. (2019)†	Czech Republic	1501–2010
Brázdil, Možný, et al. (2019)†	Czech Republic	1517–2010
Brunt (2004)†	England	1700–1850
Brunt (2015)†	England	1690–1871
Büntgen et al. (2011)*	C. Europe	500 BCE–2000 CE
Büntgen and Di Cosmo (2016)†,*	Hungary	1230–1249
Camenisch (2015a)†	Netherlands	1400–1499
Camenisch et al. (2016)†,*	NW. and C. Europe	1430–1440
Camenisch (2018)	W. and C. Europe	1480–1499
Campbell (2009)*	England	1200–1899
Campbell (2010)†,*	England	1200–1799
Campbell and Ó Gráda (2011)	England	1268–1480
Campbell (2016)†,*	Europe	1200–1499
Campbell (2017)†,*	England	1258–1259
Collet (2018)	Europe	1770–1772
Cook et al. (2015)*	Europe	1–1978
Cullen (2010)	Scotland	1690–1700
D'Arrigo et al. (2020)*	Scotland	1600–1699
De Dreu and van Dijk (2018)†,*	Europe	1500–1900
Degroot (2014)	North Sea region	1652–1674
Degroot (2018b)*	Dutch Republic	1560–1720

(Continues)

TABLE A1 (Continued)

Study	Region	Period
De Juan and Wegenast (2020)†,*	England	1500–1817
De Keyzer (2016)*	Campine region	*c.* 1250–1500
De Kraker (2017)	Low Countries	1330–1800
DeWitte (2015)	London	1000–1399
DeWitte (2018)	London	1000–1399
Dodds (2004)	Durham, England	1341–1450
Dodgshon (2004)	Scotland	1600–1800
Dybdahl (2012)*	Norway	1200–1799
Dybdahl (2013)*	Norway	1200–1299
Dybdahl (2014a)*	Norway	1600–1799
Dybdahl (2014b)*	Norway	1740–1750
Edvinsson et al. (2009)†,*	Sweden	1500–1955
Engler (2012)	Europe	*c.* 1300–2010
Engler et al. (2013)*	Ireland	1740–1741
Engler and Werner (2015)*	Ireland	1726–1729
Enzi et al. (2019)	Northern Italy	1400–1600
Esper et al. (2017)†,*	Europe	1348–1800
Fraser (2011)	Europe	1300–1310
Gerrard and Petley (2013)	Europe	1000–1550
Goedde (2005)	Europe	1560–1620
Gogou et al. (2016)*	NE. Mediterranean	*c.* 500–2010
Guillet et al. (2017)*	Europe	1258–1259
Hansen (2015)	Norway	1700–1710
Helama et al. (2017)†,*	Novgorod, Russia	1160–1416
Helle and Helama (2007)†,*	N. Finland	1722–1850
Helle et al. (2008)†,*	N. Finland	1745–1890
Hoffmann (2005)	Europe	500–1500
Hoffmann (2014)*	Europe	*c.* 400–1500
Holopainen et al. (2016)†,*	S. and W. Finland	1200–1600
Huhtamaa (2015)†,*	Novgorod, Russia	1100–1500
Huhtamaa and Helama (2017a)†,*	Ostrobothnia, Finland	1600–1700
Huhtamaa and Helama (2017b)†,*	Finland	760–2000
Huhtamaa (2018)†,*	Finland	1000–2000
Huhtamaa (2020)†,*	NE. Europe	*c.* 1300–1330
Huldén et al. (2005)†	Finland	1750–1850
Hybel (2002)	Denmark	*c.* 1000–1500
Izdebski et al. (2018)*	Mediterranean	*c.* 500–1600
Jakus (2019)	Dalmatian hinterland	1453–1454
Jütte (2005)	Germany	*c.* 1500–1599
Kelly and Ó Gráda (2014b)†	Europe	*c.* 1000–2000
Kelly and Ó Gráda (2014a)†	Europe	*c.* 1300–2000
Kiss (2019)	Hungary	*c.* 1000–1500
Kiss et al. (2020)*	Hungary	*c.* 1300–1399
Klimenko (2016)*	NE Europe	*c.* 750–1700
Knottnerus (2002)	North Sea region	*c.* 1500–1950

TABLE A1 (Continued)

Study	Region	Period
Koepke and Baten (2005a)†,*	Europe	1–2000
Koepke and Baten (2005b)†,*	Europe	1–2000
Krämer (2012)*	Europe	*c.* 1700–1900
Lajus et al. (2005)†,*	White and Barents Sea	1600–1800
Landsteiner (2001)	Austria	1560–1600
Landsteiner (2005)	Europe	1550–1600
Lassen (2016)	Lower Saxony	1690–1750
Lederer (2005)	Holy Roman Empire	*c.* 1570–1630
Lee et al. (2013)†,*	Europe	1400–1995
Lee et al. (2015)†,*	Europe	1400–1999
Lee et al. (2016)†,*	Europe	1049–1800
Lee et al. (2019)†,*	Europe	900–1999
Leeson and Russ (2018)†,*	Europe	1520–1769
Lima (2014)†,*	W. Europe	1800–1800
Ljungqvist et al. (2018)†,*	C. Europe	1250–1699
Ludlow and Crampsie (2018)†,*	Ireland	*c.* 1550–1730
Lunden (2002)*	Norway	*c.* 1200–1814
McCormick et al. (2007)†,*	Carolingian Empire	750–950
Michaelowa (2001)*	England/France	1700–1799
Midelfort (2005)	Europe	1500–1800
Morellón et al. (2016)*	Albania	2420 BCE–1800 CE
Mrgić (2011)	Bosnia	*c.* 1550–1650
Muigg et al. (2020)*	Germany	790–800
Myllyntaus (2009)	Finland	1500–1899
Nanni (2020)	Florence, Italy	*c.* 1300–1350
Newfield (2015)	Europe	*c.* 940
Nowosad and Oliński (2019)*	Poland	1540
Ogilvie and Jónsdóttir (2000)	Iceland	1680–1780
Ogilvie (2019)	Iceland	*c.* 1500–1700
Oster (2004)†,*	Europe	1520–1770
Parker (2013)*	Europe	*c.* 1570–1700
Pei et al. (2013)†,*	Europe	1500–1800
Pei et al. (2014)†,*	Europe	1500–1800
Pei et al. (2015)†,*	Europe	1500–1800
Pei et al. (2016)†,*	Europe	1500–1800
Pfister (2005)	Switzerland	1570–1630
Pfister and Brázdil (2006)†	Switzerland/Czech Republic	1750–1800
Pfister (2007a)†,*	C. Europe	*c.* 1560–1630
Pfister (2007b)†	Canton of Bern	1300–1899
Pillatt (2012)†	Europe	1300–1399
Preiser-Kapeller (2016)*	E. Mediterranean	1000–1200
Preiser-Kapeller and Mitsiou (2020)*	E. Mediterranean	*c.* 1200–1350
Pribyl (2017)†,*	England	1264–1431
Pribyl and Cornes (2020)	England	1200–1700
Primeau et al. (2019)	Denmark	1050–1536

(Continues)

TABLE A1 (Continued)

Study	Region	Period
Robinson (2005)*	Europe	1400–1900
Roeck (2005)	Europe	*c.* 1560–1620
Rohr (2007b)	Eastern Alps	*c.* 1342–1567
Rohr (2007a)	Eastern Alps	1200–1600
Rohr (2013)	Upper Danube River	*c.* 1350–1600
Rüther (2018)	C. and E. Europe	1150–1250
Sadori et al. (2016)*	S. Italy	*c.* 450–1800
Schmid et al. (2015)†,*	Europe	1331–1814
Schroeder (2019)	Carolingian Empire	900–1000
Söderberg (2006)†,*	Europe	1260–1512
Soens (2013)	North Sea region	1000–1750
Soens (2018)	North Sea region	1280–1800
Steckel (2004)	Europe	*c.* 800–1900
Stone (2014)*	England	1320–1340
Stothers (2000)	Europe	1258
Streeter et al. (2012)†,*	Iceland	*c.* 870–2000
Tello et al. (2017)†,*	Europe	1640–1740
Tol and Wagner (2010)†,*	Europe	1500–1900
Toonen (2015)†	Lower Rhine basin	1350–2011
Turner et al. (2012)†,*	Iceland	1734–1860
Vadas (2020)	Hungary	*c.* 1300–1399
Wetter et al. (2011)	High Rhine basin	*c.* 1268–2010
Wetter et al. (2014)*	Europe	1540
White (2011)	Ottoman Empire	1590–1610
White et al. (2018)	Europe	*c.* 1300–1850
Xoplaki et al. (2001)	Balkans	1675–1830
Xoplaki et al. (2016)*	Byzantium	851–1300
Xoplaki et al. (2018)*	E. Mediterranean	1095–1610
Yue and Lee (2018a)†,*	Europe	1347–1760
Yue and Lee (2018b)†,*	Europe	1347–1760
Yue and Lee (2020)†,*	Europe	1347–1800
Zerefos et al. (2007)†,*	Europe	1500–1900
Zhang et al. (2007)†,*	Europe	1400–1900
Zhang et al. (2011)†,*	Europe	1500–1800

Note: A cross symbol (†) denotes studies containing statistical analysis between climate data and indices related to human history, and star symbol (*) refers to the usage of natural palaeoclimate "proxy" data (besides serving illustrative purposes). For a more extensive list of publications relating to European climate history than reviewed in this article, we refer the reader to: http://www.climatehistory.net/bibliography.