Temperatures, Food Riots and Adaptation:
A Long-Term Historical Analysis of England[1]

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Abstract

A large body of research indicates that environmental conditions can influence the risk of social unrest. However, we know little about how these effects may change over time – for example, in the context of long-term climate change. Are the effects likely to remain constant or do they change as a consequence of human adaptation to different weather conditions? To investigate this question, we rely on a disaggregated analysis of England over a period of more than 300 years. Combining data on geo-referenced food riots with reconstructed climate data, we first assess the impact of annual temperatures on social unrest over the period 1500–1817. We then use our long-term time-series dataset to assess potential conditioning effects of adaptation on year-to-year associations between temperatures and social conflict. Our models show a substantive negative correlation between temperatures and food riots. This association, however, seems to be largely confined to the 18th century. In addition, we find evidence of decadal processes of adaptation: past exposure to adverse weather conditions dampens the effect of current exposure. Finally, our results tentatively indicate that regions facing high weather vulnerability exhibit the strongest adaptation effects. Taken together, these findings underline the importance of considering temporal (and geographical) heterogeneities when assessing the climate-conflict nexus and caution against any simple extrapolations of observable present-day effects of environmental conditions into the future.

Keywords: climate change; food riots; England; wheat prices; adaptation

1. Introduction

Adverse environmental conditions can negatively impact agricultural production, increase food prices, threaten people's livelihoods and trigger social unrest. In 2016, for example, riots erupted in the Indian state of Karnataka. The region was suffering a severe drought that had reduced drinking water supplies and ignited disputes over the distribution of water resources (Lodaya and Mukherjee 2016). In 2017, northeastern Nigeria saw deadly clashes between farmers and herders as a consequence of a drought that hit Lake Chad basin and escalated distributional conflicts over fertile land (Akinwotu 2017). In 2016, Bolivia experienced the worst drought in 25 years, which triggered violent protests in several urban centers (Reuters 2016). These and other examples not only indicate that environmental conditions can in fact be conducive to social unrest but also raise the important question of whether we can expect to see an increase in similar instances of violence as the frequency and/or intensity of adverse weather events increases in the long run.

There are two possible responses to this question, which differ in terms of how they expect the marginal effects of weather conditions to change over the long term: the first, rather grim answer is based on the assumption that these effects are likely to remain constant or increase over time. Consequently, we could simply interpolate the results of previous studies stressing positive associations between weather conditions and violent unrest. Given that the frequency and/or intensity of extreme weather events is likely to accelerate in the future, we would expect an increase in environmentally induced violence.

But what if the effect of each individual extreme weather period on social unrest decreases over time due to adaptation processes? As a reaction to past exposure to harsh weather conditions, people may adapt their behavior in order to reduce their vulnerability to similar conditions in the future. Consequently, even if we were to see more extreme weather events as a result of global warming, we would still not observe any substantial increase in environmentally induced violence in the long run.

This paper aims to assess the plausibility of these two competing scenarios by historically investigating their basic underlying assumptions: have associations between environmental conditions and social unrest changed in the long run? In particular, we investigate whether past weather conditions influence the subsequent effects of weather conditions on social unrest. While a large body of research has sought to investigate the effects of environmental factors on violence, long-term adaptation processes and their potential dampening effects have scarcely been considered.

Most previous studies have analyzed the effects of year-to-year weather variation on large-scale violence using relatively short time periods spanning "only" a few decades. While this research has contributed greatly to our understanding of the potential associations between weather conditions and violence in the short run, the underlying approach is limited in terms of contributing to the main research interest of this paper. In particular, the time frames investigated are simply too short to effectively assess whether weather effects remain constant or change over longer time periods – for example, as a consequence of adaptation processes.

Another research strand has focused on analyzing whether large-scale instances of violence such as inter-state or civil war have historically been more frequent in particularly cold or warm decades or centuries. This research strand has added important insights on truly long-term associations between environmental conditions and violent conflict, finding evidence of higher levels of unrest in relatively cold periods. However, it has relied on units of analysis that are temporally and geographically highly aggregated, thereby hampering the identification of adaptation processes on smaller scales.

We combine elements of both research strands to assess the extent to which associations between environmental conditions and social unrest may be mediated by previous weather histories. We focus on yearly weather conditions at a relatively high level of spatial resolution (50 x 50 km grid cells) and for an extended period of more than 300 years. England serves as our empirical case. We combine gridded information on yearly temperatures with geo-referenced historical food riots between 1500 and 1817. In line with previous research, we assume that (H1) low yearly temperatures increase the risk of food riot occurrence. Most importantly, (H2) we expect to find that previous exposure to particularly cold years dampens the effects of subsequent low temperatures on the risk of social unrest.

Our analysis proceeds through two main steps: We start by estimating the effects of temperatures on the probability of food riot occurrence using grid-years as our unit of analysis. Our models show that there was more unrest in colder years than in years with more favorable weather conditions. However, this effect is driven primarily by the 18th century while associations seem much less pronounced in the 16th century and even inverse (colder years displaying less riots) in the 17th century. Second, we use our long-term time-series dataset to assess the mediating effects of past weather conditions. We find that the number of very cold years in the past 30 to 40 years substantially dampens the effects of current exposure to low temperatures. Auxiliary investigations into heterogeneous effects tentatively indicate that cold years had the strongest effects on food riot incidence in landlocked regions with particularly vulnerable soil conditions (heavy clay soil as opposed to light soil) and that precisely these vulnerable regions show the largest decadal adaptation effects.

The outlined results contribute to the literature in two main ways. They lend support to previous research in that they show that associations between weather conditions and unrest can also be observed in other historical time periods (i.e. the 18th century) and are not confined to recent and rather short time periods that most research has focused on (i.e. the 1990s and early 2000s). More importantly, however, we also find substantial variation in the strength and direction of these correlations for different long-term time periods (i.e. 17th and 16th centuries) casting severe doubts on a linear relation between weather conditions and unrest that is independent of time and context. Our primary contribution consists of providing evidence of adaptation processes over the long term. As people are exposed to repeated instances of adverse weather, they appear to adapt in a way that reduces their vulnerability to any subsequent unfavorable climatic conditions. These dampening effects are mainly driven by areas that exhibit high baseline vulnerabilities to adverse weather conditions in terms of soil properties and agricultural dependence. Taken together, both findings underscore the temporal heterogeneity of effects and caution against any simple extrapolation of current effects of environmental conditions into the future.

2. Climate, Conflict and Adaptation

Historically, humans have always responded to actual or expected climatic stimuli in order to moderate the harms stemming from extreme weather. People react to past exposure to adverse weather conditions in order to reduce their vulnerability in the future. This, in turn, may dampen correlations between environmental factors and social unrest in the long run.

Possibly the most common adaptive behavior consists of changes in agricultural practices such as crop substitution (Bhatta and Aggarwal 2016; Kurukulasuriya and Mendelsohn 2008; Olesen et al. 2011) or crop diversification (Waha et al. 2013). The adoption of resilient crop varieties that tolerate adverse weather as well as various crop rotation systems are typical agricultural responses to climate change at the farm level (Anik and Khan 2012; Bhatta et al. 2016;

Bryan et al. 2009; Kuntashula, Chabala, and Mulenga 2014).[2] Other typical agriculture-based strategies are changes in sowing dates, in the agricultural calendar or in cropping patterns (Anik and Khan 2012) and changes in the location of fields (Reenberg et al. 1998). Closely related are technology-induced answers to weather variability including specific soil drainage techniques or irrigation systems (Laube 2009) as well as the use of new machinery or hybrid seeds. Finally, adaptation can also be based on an extension of trade (Dean et al. 1985), migration (Black et al. 2011) or various institutional responses such as the adoption of social security measures (Agrawal 2010). In the remainder of the paper, we no longer differentiate between these various types of adaptation. Rather, we seek to trace processes of adaptation in general terms understood as any processes of "adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities" (International Panel Intergovernmental Panel on Climate Change).

While a large body of research demonstrates that people do adapt to changing climatic conditions, the consideration and explicit analysis of adaptation processes remain rather scarce in studies on the environment-conflict nexus. The remainder of this section briefly sketches two types of research strategies in the field and describes their respective theoretical and empirical treatment of processes of adaptation.

Most previous quantitative analyses focus on the effects of short-term weather patterns and extreme weather events.[3] While some studies cast doubt on associations between short-term increases or variation in temperature or precipitation and civil conflict (Buhaug 2010; Buhaug and Theisen 2012; Koubi et al. 2012) several other analyses find support for substantive effects of weather conditions. Using national-level data and yearly aggregates for the period 1981–2002, Burke et al. (2009), for example, find a strong positive statistical association between temperature and civil wars in Africa. Based on their findings, the authors predict a "54% increase in armed conflict incidence by 2030, or an additional 393,000 battle deaths if future wars are as deadly as recent wars" (Ibid: 20670; see also Landis 2014). Relying on a time period of 20 years, Hendrix

[2] Providing a comprehensive review of the various adaptation types found in the literature lies outside the scope of this article. For a thorough overview, see Harmer and Rahman (2014) or Howden et al. (2007).

[3] Although referring to climate change, what these studies are truly capturing is weather variability (c.f. Buhaug et al. 2015, 270).

and Salehyan (2012) demonstrate that year-to-year variation in precipitation is linked to both large-scale and smaller-scale instances of political conflict in Africa. The authors conclude that "if the historical relationship between social conflict and rainfall continues, the future will likely see more social conflict" (Ibid, 46). Based on their findings for East African countries between 1997 and 2009, Raleigh and Kniveton (2012, 51) also expect small-scale conflict to be exacerbated with future increases in rainfall variability (Hendrix and Salehyan 2012; Raleigh and Kniveton 2012). Studies relying on short-term, sub-national variations in temperature and rainfall largely confirm the detrimental effects of climate variability on conflict found in country-level analyses (Almer at al. 2017; O'Loughlin et al. 2012; Yeeles 2015). Studying the impact of rainfall deviations on communal conflict in Sub-Saharan Africa between 1990-2008, Fjelde and von Uexkull (2012, 45), for example, warn that in the future, "an increase in climate variability could render vulnerable population groups even more exposed to organized violence threatening their physical and economic survival."

While the mechanisms linking climate to intrastate violence remain largely opaque (Buhaug 2015), various authors have shown that extreme weather events may drive social upheaval by increasing food prices. Studying the incidence of violent uprisings in Africa between the years 1991–2011, Jones et al. (2017), for example, find that climate-induced food scarcity increases the risk of conflict. Analyzing disaggregated data on 113 African markets from 1997 to 2010, Raleigh et al. (2015)show that decreased rainfall exerts an indirect effect on violent conflict through increased food prices. Focusing on Indonesia over the period 1993–2003, Caruso et al. 2016 demonstrate that higher temperatures fuel violence by reducing per capita rice production.

While the findings on short-term associations between weather conditions and conflict are important in themselves, previous studies in this research strand tell us little about how this association may change over time. Most studies neglect adaptation processes in their respective empirical models. Although the empirical analyses outlined above use deviations from historical means to capture weather shocks, this operationalization aims at controlling for rather than at investigating adaptation processes. Thus, so far, we lack a proper understanding of the presence, the magnitude, and the temporal scope of mitigating effects of past exposure to adverse weather conditions. More fundamentally, the general empirical approach of these previous studies is not well suited to investigating the long-term changes in effects of weather conditions. In particular, studies mostly rely on relatively short time frames of few decades – typically the 1990s and early 2000s –, preventing any assessment of whether the observable associations are likely to remain constant or to vary in the longer run, for example, as a consequence of adaptation.[4] Thus, we don't know to what extent the effects of year-to-year weather variation may be conditional on societies' long-term weather histories and to which degree we should expect the intensity of environmentally induced violence to increase as a consequence of long-term climatic developments.

Another research strand focuses on actual long-term associations between climate and violence. Identifying six major cycles of "warm" and "cold" weather phases in Eastern China between 1000 and 1911, Zhang et al. (2007), for example, find that peaks of warfare frequency occurred in cooling phases. The authors argue that cooling phases shrank agricultural production and interacted with population pressure, thereby promoting wars. Based on a similarly long time-series, Zhang et al. (2010) show that periodic climate cooling is directly associated with external aggression. According to the authors, "food production during the last two millennia has been more unstable during cooler periods, resulting in more social conflicts" in ancient China (Ibid: 1). The historical impact of climate change on conflict has also been analyzed for Europe. Zhang et al. (2011) find that the cold phases of the Little Ice Age dampened agricultural production, increased grain prices and furthered social disturbances such as rebellion or armed conflict within Europe over the period 1500–1800. Analyzing the effect of temperature on wars in Europe within the period 1000–1900, Tol and Wagner (2010) find some evidence that periods with lower temperatures in the pre-industrial era experienced more violent conflicts, although the authors stress that this result is not particularly robust. Relying on geo-referenced data on historical conflicts in Europe, North Africa, and the Near East from 1400 to 1900, Iyigun et al. (2017) find associations between changes in temperature over 50-year intervals and wars and battles with more than 32 combat fatalities.

These long-term studies use large geographical areas and long time periods (decades or centuries) as their units of observation. This high degree of temporal and spatial aggregation has allowed for very long-term analyses in the context of scarce historical data. In particular, it has provided important evidence on long-term adaptation processes, thereby speaking directly to the research interest of this paper: Iyigun et al. (2017) find that cooling has a positive impact on conflict

[4] Theisen (2017, 210) notes that the extrapolation of current patterns into the future is problematic "since we do not know whether adaptation or intensification effects dominate, and if future change is nonlinear or if the effects of changes to climate have a nonlinear effect on damage."

incidence within the same 50-year interval, while cooling that occurred more than 50 years previously has little direct effect on violence.

However, high levels of aggregation also have some relevant downsides when it comes to investigating the changing effects of environmental conditions. Due to aggregation, a substantial amount of temporal and spatial within-unit variation of weather conditions, violence and adaptation is neglected. For example, analyses using 50-year periods can only capture very long-lasting linear adaptation processes where people's behavior is influenced by climatic experiences that occurred 50 or 100 years previously. Conversely, they neglect decadal processes of adaptation in which people adapt their behavior to experiences from the past 10, 20 or 30 years. Similarly, the focus on vast regions masks effective adaptation processes in smaller areas. Specific regions may implement particularly effective adaptation measures (for example, because higher baseline vulnerability creates particularly strong incentives). However, these adaptive responses on the part of smaller units are averaged out by research designs employing rather aggregated units of analysis. Finally, country-level analyses in this research strand have focused on large-scale forms of violence such as civil wars – neglecting less organized and more decentralized forms of unrest that are arguably much more sensitive to weather conditions.

Our empirical approach combines elements from both of the research strands outlined above to assess short-term weather variations on small geographical scales for very long time periods. Thus, we can actually test the more or less explicit assumption of several previous studies that effects of climate variability on decentralized forms of violence observable in the 1990s and 2000s are not confined to these short and arbitrary time periods but represent more general patterns. Moreover, contrary to previous studies we don't implicitly control for potential prior processes of adaptation by simply relying on deviations from long-term weather trends but explicitly investigate if and over what time periods the exposure to extreme weather conditions in the past can influence the impact of subsequent climatic conditions. Finally, compared to previous long-term studies, we can assess effects of weather conditions and adaptation processes on a much smaller temporal and geographical scale and for more low-scale violence – all of which help us to better align our empirical analyses to dominant theoretical models that highlight decadal and regionally confined processes of adaption as well as weather effects on decentralized forms of violence.

3. Changing Climate, Social Unrest and Adaptive Behavior: The Case of England

Our analyses focus on England between 1500 and 1817. This time period falls within the so-called "Little Ice Age" that extended from the sixteenth to the nineteenth century and brought substantially lower temperatures to many parts of the world. Excessively low temperatures were commonly accompanied by excessive rainfall that often lasted for more than a decade (Fagan 2001). Grain production within Europe diminished particularly strongly during the cold phases (c.f. Pfister and Brázdil 1999) reducing food security and causing population declines through increased mortality, reduced fertility and increased out-migration (Parker 2013, 25).

The timing and extent of cooling varied across Europe. In England, the average temperature in the late sixteenth and early seventeenth centuries was 0.6 to 0.8 degrees Celsius below the average of the early twentieth century (Lamb 1995, 212). Figure 1 illustrates the aggregate temporal development of average yearly temperatures for the English mainland over the period 1500–1817. The data points represent a moving 20-year average (see data description in the empirical section below). The figure shows a long-term decrease in temperatures from the early sixteenth century onwards following the end of the extended Medieval Warm Period.

FIGURE 1 ABOUT HERE

Describing three major famines in Northern English counties at the end of the sixteenth century, Appleby (1978), for example, argues that hunger was caused by a combination of population growth and crop failure due to cold weather. In the 1730s, crop failures caused surges in food prices throughout Britain (Fagan 2000: 139). In-depth historical analyses have stressed the link between harvest, food prices and popular disturbances in 18th century England (Ashton 1959). Thus, during the Little Ice Age, English counties experienced widespread food riots. Aggrieved by food shortages, citizens intercepted food transports; attacked mills, dealers' houses, granaries and stores of cereals; and engaged in forcible price-fixing and the regulation of market places.

It is important to note that weather-related crop failures were not the only cause of high food prices and social distress in England during the period under analysis. As for example highlighted by Thompson (1971, 92), food price advances where often substantially higher than crop deficiencies would actually justify. In particular, rioters blamed cereal exports to larger cities for rising food prices and dearth. As noted by Bohstedt (2010: 108), [e]xports during dearths were particularly offensive since working families' budgets were dominated by bread." Other factors that contributed to rising food prices were parliamentary land enclosures, market manipulations including speculations and the formation of monopolies by farmers and dealers, and wars (Bohstedt 2010; Thompson 1971; Tilly 1978). Adverse weather conditions often interplayed with the detrimental social consequences of these factors. As highlighted by Rose (1961, 291), riots during the 18th century were – to a large extent – caused by a combination of harvest and trade fluctuation.

The most common answer to food riots was violent repression, which was ordered by magistrates and ministers throughout England between the sixteenth and nineteenth centuries. However, the needs of a hungry population were also partially met by a series of institutional measures. Among the most important ones were occasional export bans (particularly for wheat and rye). Other governmental answers to social unrest included the codification of the Poor Law in the Act of 1598, the building of municipal granaries, communal control of scarce food supplies, the procurement of imported grain, and municipal food relief funds (Bohstedt 2010: Chapters 3 and 4).

Moreover, agricultural adaptation processes are likely to have moderated the effect of climatic conditions on riots. Martínes-González (2015) and Tello et al. (2017) show that the colder and more humid climate during the second half of the seventeenth century can be viewed as the key driving force behind major improvements in traditional organic farm systems and a long-term increase in crops under milder weather conditions. In response to weather extremes, for example, farmers started to look for new crops (c.f. Iyigun et al. 2015). One agriculture-based innovation was the Norfolk four-course rotation system. In four-year cycles and in the absence of a fallow year, this system rotated wheat, turnips, barley and clover, thereby increasing soil fertility and restoring some of the plant nutrients (see (Overton 1996, 121, 167).

In taking a closer look at the incidence of food riots in England during the Little Ice Age, we plan to assess the role of such adaptation processes.

4. Data, Models and Results

Our empirical analysis has two main objectives: identifying the effects of weather conditions on the occurrence of food riots and investigating the mediating effects of long-term adaptation processes. Thus, we seek to answer two related questions: How does year-to-year temperature variation affect the risk of riot occurrence in the long-run? And how does past exposure to adverse weather conditions affect associations between yearly temperatures and social unrest?

4.1. Weather Conditions and Food Riots

In line with previous research on temperate climate zones, we assume that low temperatures increase the risk of social unrest. In order to investigate the effects of weather conditions on the social unrest, we have constructed a grid-cell dataset spanning a period of more than 300 years. This period of analysis (1500–1817) is predefined by the availability of data for our main explanatory and outcome variables. We create a grid net with each cell measuring 50 x 50 km and use the grid-year as our unit of analysis.

Our main outcome variable measures the incidence of food riots per grid cell and year. We rely on a "riot census" produced and generously shared by John Bohstedt Bohstedt (2010). It compiles information on the date, location and other characteristics of riots from the fourteenth century to the early nineteenth century. The data rely on a variety of historical public records (magistrates' reports and court records) and newspaper articles combined with data provided in secondary sources. A riot is defined as "an episode of crowd force or violence, meaning a collective assault on persons or property, illegal seizure of property, and/or coercion of a person to do something he/she would not otherwise do." Events are included in the dataset only if they involved a crowd of at least "several dozen rioters" (Bohstedt 2010). Individual events are defined by actor, time period and location: one event comprises all riotous violence carried out by the same group, in an individual contiguous territory (e.g. a parish) in a week's time.

Importantly, as the compiler of the data concedes, it is unlikely that the dataset represents a true census of all riots that occurred in England in the period under investigation. Rather, it represents a sample of events that is likely to be systematically biased towards the incorporation of rather large-scale riots relative to smaller riots. Most specifically, by focusing particularly on specific periods of food riots, the dataset underreports single, isolated riot events. Consequently, years for which no riot has been reported in the dataset may either have seen no riots at all or only single and/or minor riots. We explain below how we deal with the dataset's shortcomings.

We have systematically geo-coded the location information provided in the census dataset. Our main outcome variable is measured with a binary indicator showing the occurrence or absence of a riot in a given grid-year. In our main models, we consider only those food riots that we have been able to precisely locate in individual towns and cities. We consider all events as part of our robustness checks, which are summarized below. Figure 2 illustrates the grid net used for our empirical analysis as well as the geographical distribution of food riots in the period under investigation.

FIGURE 2 ABOUT HERE

In terms of assessing historical climatic conditions, we focus on yearly temperatures rather than on precipitation levels because the former have been found to be more consistently and more strongly related to grain yields in historical England (Scott, Duncan, and Duncan 1998; Wigley and Atkinson 1977). We rely on gridded seasonal temperature data available for the period 1500–1817. This data has been reconstructed based on directly measured temperatures, sea-ice and temperature indices, and documentary records, as well as proxy temperature reconstructions from Greenland ice cores and tree ring series from Scandinavia and Siberia (Luterbacher et al. 2004). While this reconstructed data is prone to substantial measurement error, it also provides for a unique opportunity to investigate long-term associations between weather conditions, food prices and unrest. Moreover, we expect measurement error not to be systematically correlated with either riot occurrence or food price developments. Overall, we expect errors to bias results against finding systematic correlations between weather conditions and our outcome variables of interest. Figure 3 displays the mean yearly temperatures for the period 1500 through 1817 for the grid-net introduced above.

FIGURE 3 ABOUT HERE

We estimate two types of models: Our main models consist of logit regressions with unit fixed effects and robust standard errors clustered per grid cell. In addition, we use linear probability models as an alternative specification. In order to account for the fact that the riot dataset focuses on riot periods as well as for the resulting measurement error, we estimate models based on two samples. The first set of models uses the entire sample, assuming that the years without reported events have in fact not seen any riots. The second set of models treats years without any riots as missing data. It is restricted to riot periods, limiting the analysis to all those years in which at least one grid cell has seen at least one riot. All models control for a linear and quadratic time trend. [5]

[5] As an alternative, we have also estimated models with a full set of time and unit fixed effects – reproducing our main results reported below (see tables A.12.). While this specification is more conservative in terms of controlling for time trends, it is also heavily over-specified.

TABLE 1 ABOUT HERE

Table 1 presents the results of our main models. The first two columns present logit models estimating correlations between yearly temperatures and the likelihood that the respective grid-year experienced at least one food riot – for the entire sample (column 1) as well as for riot periods only (column 2). Columns 3 and 4 report the results for linear models. Across all models, we find a statistically significant correlation between weather conditions and riot occurrence. As we move from the minimum to the maximum temperatures in the sample, the overall riot risk decreases by approximately 10 percentage points (based on model 4). While this represents a substantive association between yearly temperatures and riot occurrence, the effect size is also rather moderate, mirroring the fact that the decentralized and spontaneous occurrence of riots was determined by a variety of factors beyond weather conditions.

Before we move on to assess the extent to which adaptation processes may affect these correlations, we implement a series of robustness checks to assess the sensitivity of our basic findings to changes in model specifications. First, we re-estimate our main models, adding riots without precise geo-locations. We have located all these events on the respective counties' centroids. Adding these events to the measurement of our outcome variable does not affect our main results (see Table A.1. in the appendix).

Second, we use an alternative measurement for the explanatory variable. We draw on long-term information on the Palmer Drought Severity Index (PDSI) to assess annual variation in moisture. We rely on the PDSI rather than on raw precipitation data because previous studies on historical England have found soil moisture levels to be more relevant for wheat yields than rainfall (Wigley and Atkinson 1977). We use data from the Old World Drought Atlas that provides a gridded (0.5 x 0.5 degree) reconstruction of the PDSI for Europe and the Mediterranean region for the period under investigation (Cook et al. 2015). In line with previous research, we assume associations between moisture and riot occurrence to be more complex than those for temperatures. In particular, research suggests that moisture deficits and surpluses can negatively affect agricultural yields with a one-year lag (Scott, Duncan, and Duncan 1998; Brandon 1971). Estimating the effects of moisture conditions on riot occurrence, we find further evidence of the role of weather conditions in influencing the risk of social unrest: very wet and very dry conditions increase the riot risk in the subsequent year (see Table A.2. in the appendix).

Third, we include three sets of control variables in our analysis (unless specified otherwise, we temporally lag all time-variant explanatory variables by one year). Drawing on projected population data provided by the History Database of the Global Environment (HYDE) developed under the authority of the Netherlands Environmental Assessment Agency (Klein Goldewijk et al. 2011; Klein Goldewijk, Beusen, and Janssen 2010), we include a measure of population size. Among other things, the database presents a time series of population for the last 12,000 years. Information is provided in gridded maps providing population counts per 5′ longitude/latitude grid on a five-year basis until 1500 and on a yearly basis thereafter (Klein Goldewijk et al. 2011).

We also control for the strength of local social institutions. To this end, we focus on churches, which arguably represented the most widespread and most influential social institutions in the period under investigation. "Historic England" is the public body formally responsible for, among other things, the listing of historical buildings in England. Historic England provides a geo-coded dataset on churches that covers our period of analysis. The data on most churches includes precise construction dates, while others have only rough estimated temporal information (e.g. built in the seventeenth century). We have coded the construction date as precisely as possible and have included a simple count of churches in our main models.

In order to account for serial correlation, we also control for the occurrence of riots in the year t-1. Note that we do not include any spatial lags. The degree of spatial clustering of the outcome variable is very low in our dataset due to the relatively small number of riots compared to the overall number of observations.[6] The inclusion of control variables does not affect our main results (see Table A.3. in the appendix).

Next, we aim at assessing the plausibility of one likely mechanism that may link environmental conditions to food riots: food prices. If correlations presented above really indicate a causal effect of temperatures on riot occurrence, we would also expect to see a negative correlation between temperatures and wheat prices. We therefore combine our climate data with historical information on wheat prices provided in the Abstract of British Historical Statistics (Mitchell 1971) and compiled and standardized (silver) in the Allen-Unger Global Commodity Prices Database (Allen and Unger 2017). The dataset provides information on a variety of commodities on a yearly basis for selected cities across the globe. The historical periods covered vary across cities. Information on wheat prices in years falling within the period of our investigation

[6] The average Moran I for all years featuring at least one riot is only 0.08.

is provided for four English cities: Exeter, Winchester, Eton and Essex. We focus on wheat prices rather than on other agricultural commodities because, throughout the period of analysis, no other grain played a more important role in English agricultural production in terms of the total share of agricultural land use (Broadberry 2015). We investigate these associations more systematically in linear panel regressions using the city-year as the unit of analysis. Models with city fixed-effects provide evidence of a negative correlation between temperatures and wheat prices (see Table A.4. in the appendix) lending support to the plausibility of our main underlying assumption that environmental conditions may have affected livelihoods through changes in agricultural prices in the specific case and time period under investigation.

We also assess whether our findings are driven by any specific geographical regions of England. We have divided our sample into four equally sized geographical subsamples (northwest, northeast, southwest, southeast). We find negative correlations between temperatures and riot occurrence across all four subsamples, while the effects are strongest in the southeast and the northwest. Consequently, in the case of England, adverse weather effects do not seem to be limited to any sub-regions with specific structural baseline conditions (see tables A.5. to A.8. in the appendix).

Finally, we investigate whether the observable correlations between temperatures and riot occurrence have been driven by any specific historical time periods. We therefore split our sample into three 100-year time periods (sixteenth, seventeenth and eighteenth century) and estimate our main models for all three individual subsamples. We find that associations are strongest for the eighteenth century, followed by substantially weaker effects in the sixteenth century. We find some inconsistent evidence of an inverse relationship between yearly temperatures and riot occurrence in the seventeenth century. This may be due to the fact that the seventeenth century – contrary to the sixteenth and eighteenth centuries – experienced an extended warming period of approximately 60 years. Thus, while associations between temperatures and riot occurrence do not seem to be narrowly confined to specific time periods, these findings indicate heterogeneous effects of weather conditions depending on aggregate climate contexts casting doubts on linear relationships between weather conditions and unrest in the long run (see tables A.9. to A.11. in the appendix).

4.2. Adaptation

We now turn to adaptation processes. In particular, we hypothesize that past exposure to low temperatures dampens the effects of subsequent cold temperatures on riot occurrence. We start by estimating interaction effects between weather conditions and the total number of years with particularly adverse weather conditions in the past. If adaptation processes have taken place, we should find that the effects of temperatures on riot occurrence decrease in response to an increasing number of previous extreme weather events. In order to proxy previous exposure to particularly adverse weather conditions, we count the number of years in which a grid cell experienced temperatures lower than 2 standard deviations below the grid cell's temperature mean - measured for the period ranging from the first year in our dataset up to the respective year t-1. We assume that such cold weather shocks have had particularly pronounced negative socioeconomic effects, therefore providing strong motives for subsequent adaptation.

We don't have any strong theoretical expectations regarding the temporal scope of adaptation processes. Generally speaking, we assume that weather shocks in the very near past (e.g. within the past five years) should not have any strong adaptive effect. Previous research indicates that individual extreme weather events trigger short-term coping strategies rather than actual adaptation. Conversely, weather shocks that occurred a very long time ago (e.g. 50 or more years previously) may not strongly influence current agricultural practices, as awareness of climate histories wanes over time and past adaptive strategies may not be transmitted across several generations. We therefore expect to see the strongest mitigating effects of past weather shocks when measuring processes of adaptation at intermediate temporal scopes (10 to 40 years).

We have estimated interaction effects between temperatures and the number of previous cold weather shocks within the preceding 5, 10, 20, 30, 40, 50, 60, 70 and 80 years. Across models, we find positive interaction terms, which indicate that past exposure in fact reduces the negative effect of temperatures on the current risk of riot occurrence (see detailed results in tables A.13. to A.21. in the appendix).

FIGURE 4 ABOUT HERE

The left hand side of figure 4 shows that coefficients of interaction effects are comparatively small for very short and very long time periods and largest for an intermediate time period of approximately 30 to 40 years. The right hand side illustrates the interaction effect for the 40 year time period. Taken together, these results indicate that past weather histories do in fact impact the effect of current weather conditions. While we cannot differentiate between various agricultural or institutional channels of adaptation, the findings indicate that as people are exposed to repeated instances of extremely adverse weather conditions, they appear to implement political, social or economic changes that reduce their vulnerability to any subsequent unfavorable climatic conditions and conversely lower the risk of social unrest. Moreover, we find that these processes of adaptation appear to materialize over periods of several decades. This speaks against potential alternative explanations of interaction effects, such as the following: A reduction in the impact of temperatures could be a consequence of increasing destitution, with recurrent cold weather shocks leading to extreme poverty, out-migration and the fomentation of fatalistic attitudes. Consequently, we may observe increasing apathy rather than adaptation. Moreover, previous extreme weather events may have triggered riots, leading the state to reinforce its repressive institutions in the respective areas. As a consequence, low temperatures may still generate grievances, but changes to the repressive apparatus prevent effective group mobilization. However, the interaction effects relating to destitution and changing patterns of repression should be strongest for the periods immediately preceding those under investigation (i.e. 5 to 10 years).

To further substantiate our assumption that the interaction effects presented above do in fact reflect processes of adaptation, we investigate interaction effects (using 40-year periods for the measurement of previous exposure) across two different subsamples that represent varying degrees of weather vulnerabilities and motives for adaptation.

First, we investigate the role of soil types. Different soil types have been argued to be more or less vulnerable to adverse weather conditions. Heavy soils are less amenable to effective adaptation and diversification as they are not particularly suitable for the cultivation of crops such as turnips or clover that increase nitrogen in soils and are essential for crop rotation (Overton 1996, 119). They are also particularly prone to moisture surpluses and therefore especially vulnerable to cold and wet periods (Mendelsohn and Seo 2007; Michaelowa 2001). In addition, heavy clay soils are more difficult to plough (Overton 1996, 59). Thus, while capabilities for adaptation should be substantially lower in heavy soil areas, motives for adaptation to extreme weather should be substantially higher. We split our sample into light and heavy soils (above and below mean share of light soils) based on data provided by the British Geological Survey (see detailed results in Table A.22. in the appendix).

Second, we distinguish between coastal and inland regions. Motives for adaptation in terms of vulnerability to adverse climate conditions should be substantially higher in inland regions. Most notably, coastal areas are likely to have relied less on agriculture and more on fishing. Consequently, they should have been less affected by weather-induced increases in food prices. Also, these areas may have established trade networks as a buffer against negative climatic shocks (Durante 2009). We divide our sample into grid cells containing coastal areas and those that do not (see detailed results in Table A.23. in the appendix).

Across models, we find stronger indications for pronounced interaction effects (in terms of coefficient size and levels of statistical significance) for those areas assumed to be more vulnerable to weather shocks: areas with heavy soils as compared to light soils and inland areas as compared to coastal ones. Within these areas, each additional prior exposure to cold weather shocks seems to lead to a substantially stronger decrease in the average marginal effects of yearly temperatures than in areas assumed to be less vulnerable (coastal and light soil areas). The high vulnerability faced by farmers relying on heavy soils types may have pushed them to adapt their livelihood by switching between cropland and pasture according to the prevailing climatic conditions. Also, these farmers may have more readily introduced new technologies such as the so-called Rotherham plough,[7] deep ploughing and deep drainage that were key to increased productivity on clay soils (Overton 1996, 122, 194). Landlocked regions exhibiting bad weather histories may have been prompted to establish regional networks with a high geographical crop differentiation to tackle climatic vulnerability. Richardson (2005), for example, emphasizes the role of rural fraternity networks as an example of intercommunity cooperation in addressing weather-related agricultural risk in medieval England (see also Durante 2009, 6-7).

Combined with the results summarized above, these findings appear to indicate that greater needs for adaptation in terms of higher levels of structural vulnerability to weather shocks have played a role in driving adaptation processes. Note, however, that while coefficients and observable differences between subsamples point in the expected direction our results don't allow us to establish substantive differences of interaction between these subsamples at conventional levels of statistical significance. Thus, while these auxiliary analyses lend some first very tentative

[7] Patented in 1730, the Rotherham plough was a light general-purpose swing-plough that reduced ploughing time and required less horsepower (Overton 1996, 122).

support to heterogeneous adaption processes, further work is required to substantiate these initial findings.

5. Discussion

Our analyses have produced three main results: first, the impact of climate on social unrest varies across long-term time periods. The fact that we can observe strong effects in one century does not mean that similar effects are present in other centuries. Second, the effects of extreme weather periods are conditioned by weather histories in the medium (decadal) term: previous exposure reduces effects of subsequent exposure. For our case, we find that weather histories and adaptation processes over a period of 30 to 40 years seem to be particularly relevant. Third, these adaptation effects themselves are contingent on specific socio-economic context conditions.

How can these findings on historical England inform wider research on the climate-conflict nexus? While the external validity of our analysis is, of course, limited by the mainly data driven focus on a specific case and time period, our results can nonetheless provide relevant insights for research on other regions and present-day effects of environmental conditions.

Across analyses, our results underscore the heterogeneity of climate effects. In particular, adding to previous research stressing the differential impacts of climate change across political and economic contexts, we demonstrate that this effect also varies substantially across long time periods. In line with our own argument, we cannot directly transfer findings for one specific timespan to other long-term periods. More generally, however, our results cast substantial doubt on the assumption that findings on effects of environmental conditions can simply be extrapolated across time. The aggregate climatic conditions, people's weather vulnerability, institutional capacities and technological development vary in the long-term and shape the effects of weather conditions. Such longer-term temporal developments are certainly not specific to our empirical case. Consequently, it seems plausible that temporal heterogeneities can also be observed in other regions and other temporal periods. To advance our theoretical understanding of the climate-conflict nexus and better assess adaptation and mitigation processes, it seems indispensable to further explore this historical heterogeneity (for example why – in the case of England – extreme weather events seem to have triggered riots particularly in the 18th century).

Similar arguments apply to our findings on processes of adaptation. Periods of adaptation as well as conditions for adaptation are certainly context specific. We therefore don't expect mitigating effects of past weather conditions to be strongest in a 40-year time window as well as in hinterland areas with heavy soils in other contexts. What is more likely to apply to other cases, however, is the general observation that past weather conditions shape the effects of subsequent weather conditions and that the magnitude of this mediating effect is as context specific as the direct effect of environmental conditions itself. This is in line with the results of previous studies addressing similar questions in other spatial and temporal contexts as well as for other forms of unrest – such as analyses on peasant rebellions in historical China or on large-scale violent conflict in Europe as a whole (Jia 2014; Iyigun, Nunn, and Qian 2015). Thus, our findings add to a more general picture on context-specific adaptation processes that preclude simple temporal extrapolations of present-day associations of environmental conditions and violent unrest.

6. Conclusions

This paper has analyzed the changing impact of yearly temperature variation on riot occurrence in England over a period of more than 300 years. Our analyses have produced two main findings. First, colder temperatures (especially during winter and summer) lead to a higher risk of riot occurrence. While these results lend credibility to the argument that year-to-year weather variation can spur social conflict, we also show that these effects are mainly driven by a certain time period (the eighteenth century). Thus, while effects of weather conditions do not seem to be strongly confined to specific recent periods (i.e. the 1990s and 2000s), we should be particularly cautious when trying to extrapolate associations between climate change and conflict across time.

Second, and more importantly, our analyses demonstrate that scholars should pay more attention to adaptation processes when studying the effects of environmental conditions on local livelihoods and conflicts. We find evidence that weather histories matter in explaining current risks of violence: the more weather shocks a grid has experienced in the previous 30 to 40 years, the weaker the negative effect of temperature on current riot incidence. As demonstrated in the empirical analysis, this finding does not apply for very short (e.g. 5 or 10 years) or very long (e.g. 50 years) weather histories, indicating that adaptation processes – rather than coping strategies (e.g. migration) or increased state repression – are actually taking place. These findings speak against common assumptions that present-day associations between weather conditions and social unrest can be used to predict climate-related violence in the future.

In addition, our paper underscores the role of context-specific factors. Specific structural factors can make regions more or less vulnerable to the repercussions of weather shocks. This, in turn, increases the motives for adaptive behavior that can contribute to mitigating the negative effects of adverse weather conditions in the future. In particular, we find tentative evidence that processes of adaptation seem to have had particularly strong mitigating effects in landlocked areas with vulnerable soil conditions.

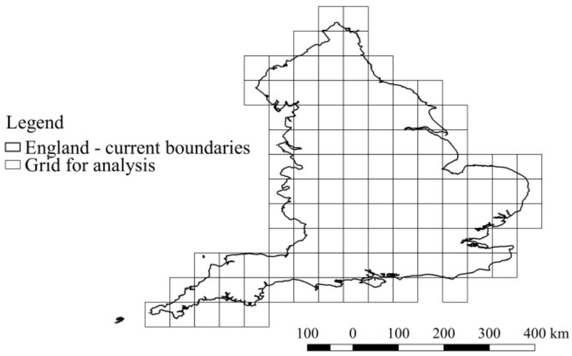
However, our analysis also suffers from several shortcomings in addition to those discussed above. First, our very long-term historical data introduce a number of uncertainties into our analyses – most notably with respect to the comprehensiveness of the riot data as well as the reliability of temperature reconstructions. While the consistency of our findings increases our confidence in our analyses, other studies may assess our results based on shorter and more recent time periods (e.g. the nineteenth century) that allow for access to observed weather variation and other – potentially more fine-grained – data on social unrest.

Second, and most importantly, we only assess adaptation processes indirectly by observing previous exposure to harsh weather conditions. We don’t know, however, whether past weather histories dampened the risk of social unrest by promoting agricultural adaptation practices or rather by unleashing sociopolitical responses such as the enactment of food export bans or poverty alleviation programs such as the Old Poor Laws. Future research could investigate more specific associations between past environmental conditions, concrete adaptive processes and the subsequent risk of unrest.

Tables and Figures

Figure 1. Average yearly temperatures across England (1500–1817)

Figure 2. Grid for analysis and location of food riots



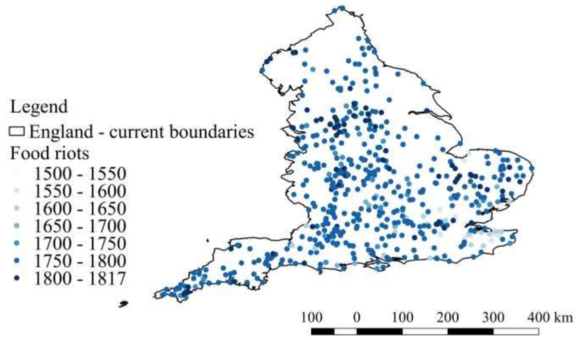
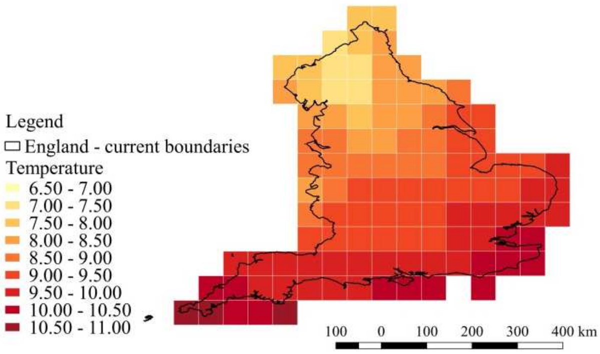


Figure 3. Mean yearly temperatures in 1500 and 1817



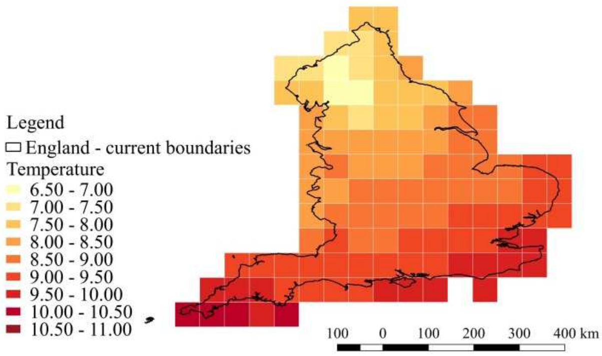


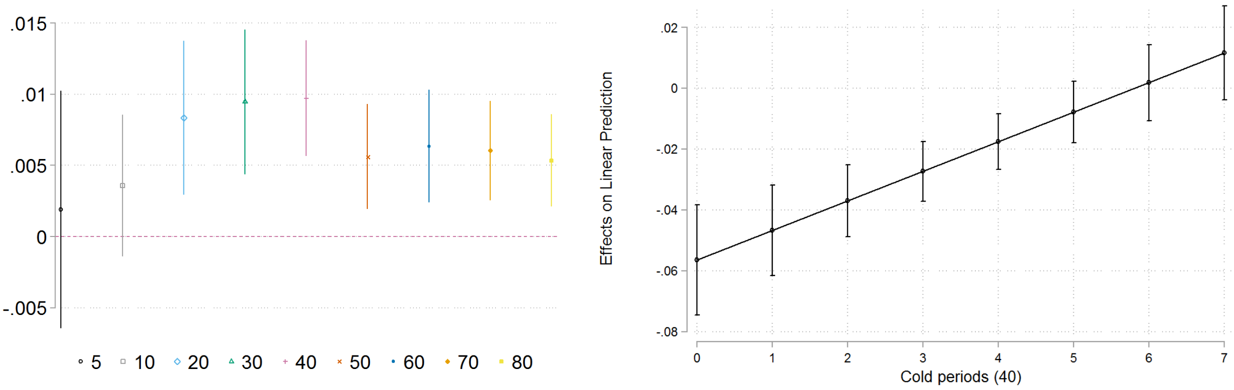
Table 1 Correlation between temperatures and riot occurrence

	(1) Logit - full sample	(2) Logit - riot episodes	(3) OLS - full sample	(4) OLS - riot episodes
Temperature	-0.857***	-0.475***	-0.012***	-0.025***
	(0.084)	(0.084)	(0.001)	(0.005)
Constant			0.154***	0.346***
			(0.015)	(0.066)
t1, t2	Yes	Yes	Yes	Yes
Observations	27984	5456	33708	6572
AIC	3597.770	2500.093	-54184.628	-531.702
Ll	-1795.885	-1247.046	27095.314	268.851
r2			0.018	0.040

Logit and OLS regressions with standard errors clustered on the grid-cell level; standard errors in parentheses. All models include grid-cell fixed effects.

$^{+}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Figure 4. Adaptation with different temporal scopes



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