Conflict Technology As a Catalyst of State Formation

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Abstract

The rapid introduction of artillery to late medieval Europe initiated a massive security crisis by rendering existing urban fortifications obsolete. Instead of turning to existing networks of alliance and patronage to strengthen collective security, cities surrendered their sovereignty and agglomerated into states. How were nascent states able to consolidate authority over the formerly sovereign polities? We propose that cities had to surrender sovereignty to states because the gunpowder revolution forced them to construct new fortifications that required external financing. States were better positioned to use concentrated political authority to efficiently finance the new fortifications and coordinate inter-city security cooperation. We test the theory using detailed data on city-level urban defensive investment, the locations of artillery manufacturers, and the changing locations of national borders. We find that after the development of gunpowder technology, new defensive investments were more likely to be located in areas where borders disappeared, were built closer to politically relevant national borders, and were further from the sites of raw building materials. These findings are consistent with the theory that states arose in part as a consequence of changes in the technology of warfare.

1 Introduction

On May 29, 1453, the walls of Constantinople were breached by Ottoman forces, effectively ending the Byzantine Empire and introducing a major new power into the geopolitics of Europe. The

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Ottoman victory was made possible by new technology – a massive bombard designed by the Hungarian gunmaker Orban. It was not the first cannon used in European siege warfare, but it exemplified how gunpowder had transformed the nature of conflict. Within a relatively short period of time, nearly all of Europe's urban defensive fortifications were rendered obsolete by advances in artillery. The same period also saw the upheaval and evolution of the European political system. When Constantinople fell, most states in Europe were city-states, kingdoms, or empires — either small, autonomous polities or large ones without centralized, differentiated, and autonomous structures (Tilly 1990). Within three hundred years, however, Europe was characterized by states that used consolidated political authority to collect taxes, make laws, and support standing armies. The old system of cities that autonomously made alliances during wartime and cooperated to form trade unions was dismantled as cities were absorbed by territorial states. How were nascent states able to consolidate authority over the formerly sovereign polities?

We contend that the "gunpowder revolution" created an unprecedented security crisis in Europe requiring massive investments in defensive technology that could not be managed by cities acting on their own. Cities whose defenses had been effective protection for decades or even centuries became vulnerable to cannon fire within a single generation. All but the wealthiest cities required external financing to construct the massively expensive new fortifications that were needed to resist artillery fire. Security cooperation became essential because a perimeter of walled cities could protect interior cities far more economically. In principle, cities and kingdoms could have drawn on existing alliances, such as networks of feudal patronage or trade confederations, for mutual support and assistance. However, the severity and suddeness of the gunpowder revolution created strong incentives for cities to secure their own limits before contributing to collective resources even if collective security was stronger. The authority of national states was required to ensure that 1) cities could not free ride on the investments of others and 2) that wealthy cities did not waste resources by constructing expensive walls in strategically inferior locations. Cities agglomerated, either willingly by treaty or involuntarily by force, into states that could use coercive authority to overcome obstacles to inter-city security cooperation and manage the security crisis caused by the gunpowder revolution.[1]

To validate our theory, we empirically test the spatial and temporal relationship between the impact of the gunpowder revolution and the rise of modern states in Europe. We contribute a new

[1]For our purpose, we use "city" to refer to any stand-alone settlement, regardless of size or formal legal status.

dataset on the construction timelines of urban fortifications for over 4000 European population centers in the medieval and early modern periods by geolocating the work of Stoob (1988). We combine these data with information on the locations of artillery manufacturers from Kennard (1986) and state borders in five-year increments from Abramson (2017).[2] Our first test compares the spatial distribution of sophisticated urban fortifications and a measure of territorial consolidation. Consistent with the theory, we find that fortifications capable of resisting artillery were constructed in places where states consolidated authority over territory. Second, we show that sophisticated fortifications were more likely to be constructed in strategic locations for the defense of states after artillery were introduced. Third, an analysis of the timelines of defensive investment supports the theory that states actively redistributed resources to support wall construction in strategically important cities.

The work that most directly relates to ours, Tilly (1990), studies the variation in paths to state formation in Europe. Tilly and the literature his work inspired describes state development in Europe as a positive feedback cycle in which states "accumulated coercion and capital" from cities for the purpose of waging war against other states (Bean 1973; Spruyt 1996, 2017; Gennaioli and Voth 2015; Kaspersen and Strandsbjerg 2017). We further develop Tilly's pioneering work in two main ways. First, we explain why Tilly's cycle where "war made the state and the state made war" began in Europe when it did (Tilly 1975). We assert that the relatively rapid introduction of gunpowder and the sudden obsolescence of existing defensive technology were necessary catalysts. Second, we explain why it was necessary for cities and smaller territories to lose the sovereignty and autonomy they had maintained for centuries. Our answer is that only a national state had the necessary political authority to overcome obstacles to investments in collective security.

Our theory also demonstrates how the political economy of security cooperation relates to the process of state formation. We argue that the costs of cooperation determine whether security is provided by alliances or by extending the state's borders. The argument echoes the work of Coase (1960) and Williamson (1979), which invokes transactions costs to explain the division of activities between markets and firms. Our work also contributes to the literatures on the economic determinants of state size and urbanization. Alesina and Spolaore (1997) and Alesina and Spolaore (2005) argue that the number and size of nations depend on the costs of providing public goods to

[2]We owe a debt of gratitude to Scott Abramson for sharing data on state borders from Abramson (2017).

heterogenous populations. Our contention is that economies of scale in the provision of a particular public good – collective security – encourage states to consolidate political authority. Dincecco and Onorato (2016) shows that populations flocked to cities in Europe because they were "safe harbors" from violence. Our work describes how the high costs of maintaining fortifications to create safe harbors in the face of an evolving threat from gunpowder necessitated support from states.

Our work also speaks to recent debates about the internal and external validity of the bellicist theory of state formation. Abramson (2017) argues that the bellicist thesis is unpersuasive because small states persisted long into the post-Westphalian era.[3] Our study partially reconciles Abramson's critique with the bellicist theory by explaining why some cities could resist incentives to agglomerate and persist as city-states. Cities that were rich enough to upgrade their defensive technology without outside help resisted agglomeration for longer. Other critiques of the bellicist theory come from studies of state-making outside Europe. Centeno (1997), Centeno (2002), and Herbst (2014) find negative relationships between conflict and state formation in South America and Africa. Our study supports an explanation for why the bellicist theory appears better suited to Western and Central Europe: the relatively rapid and relatively equal introduction of gunpowder in late medieval Europe created a security crisis best addressed by agglomerating the existing polities into states.[4]

Our work also relates to the literatures on international cooperation and conflict. A large literature studies how states use international organizations to overcome collective action problems (Keohane and Nye Jr 1973; Axelrod and Keohane 1985; Keohane 1986; Gowa 1986; Powell 1991). A subliterature applies this theory to the provision of collective security (Kupchan and Kupchan 1995; Acharya 2004; Thakur 2016; Hough 2020; Meijer and Brooks 2021). Our work describes what happens when existing international institutions are insufficient to overcome obstacles to cooperative investments in collective security. We find that polities are ultimately forced to surrender their sovereignty and voluntarily join a national state for protection or be conquered and forcibly assimilated. Thus, we find that the strength and boundaries of national states depend on the costs to enforcing inter-polity cooperation.

Some literature has previously considered the relationship between the military revolution and

[3] See Appendix Figure A1 on changes in the size and number of states in Europe over time.

[4] Hoffman (2015) provides a theoretical foundation for this claim. He shows that relatively even costs of conflict were a necessary precondition for the tournament structure of state development that characterized European political development.

state formation. Bean (1973) discusses how various changes in the technology of war incentivized states to develop tax capacity. Our work differs from his by describing 1) the unique importance of defensive fortifications and 2) the logics of interstate conflict and cooperation that resulted in the agglomeration of states. McNeill (1982), particularly Chapters 3-5, traces the concomitant political and military developments in Europe during the early modern period. Spruyt (1996) in Chapter 8 considers why the Hanseatic League was supplanted by states. His argument emphasizes the superiority of the state at managing inter-city economic affairs and markets. Following Spruyt, our argument acknowledges the role of economics in encouraging cities to agglomerate into states. We additionally explain that agglomeration occurred when it did because of the security crisis initiated by the gunpowder revolution.

2 Historical Background on the Technology of Conflict and the Gunpowder Revolution

Prior to the introduction of cannons, fortified settlements provided very effective defense against conflict. Thus, while siege warfare was a relatively common offensive strategy, it was frequently unsuccessful (Eltis 1989; Tracy 2000). The best defense against a besieging army was a tall city wall – the purpose of the fortification was to keep soldiers and projectile fire from trebuchets from coming into the city. Early walls were relatively thin because it was wasteful to use stone to thicken a wall rather than build it higher. While sieges were much more common than pitched battles in the medieval era, they were also unlikely to succeed against walled cities. Most cities that were conquered during this period were brought down by domestic insurrection rather than a foreign menace (Parker 1976; McNeill 1982; DeVries 2012).

The domestic politics of towns and cities, including the politics of self-defense, were intertwined with the incentives of local and regional powers. Local nobility frequently contributed to the financing of fortifications, which not only protected urban residents but also provided safety for the rural population that worked the land immediately around the town. Other wealthy urban residents frequently contributed large sums as money as well. Regardless of whether the local lord contributed monetarily, his permission was generally required to erect a wall, as doing so made a city more self-sufficient and thus lowered the cost of revolt (Tracy 2000; Wolfe 2000). If no local

Table 1: Timeline of major innovations in ordnance technology (adapted from McNeill 1982).

Date	Event
1346	First recorded military use of gunpowder at Battle of Crécy (Hundred Years' War)
1453	Constantinople's walls destroyed by Ottoman ordnance
c. 1470	Smaller, more transportable cannons developed in France and Burgundy; the design for siege weapons remains stable until 19th c.
c. 1525	Trace italienne designed in Northern Italy
1543	Improvements in ironworking technology make iron cannon cost-effective, although bronze is preferred until late 17th c.
c. 1625	Gustavus Adolphus of Sweden pioneers use of field artillery

power was dominant, a city might bargain with potential aggressors or support one side in a conflict in order to improve their material interests. For instance, in 1159, the town of Cremona, Italy, allegedly paid Frederic Barbarossa to launch an attack against its regional rival, the neighboring city of Crema. In a case of a successful siege, Barabossa attacked and destroyed Crema after its citizens refused to voluntarily demolish their walls in surrender (Freed 2016, 245).

However, the introduction of gunpowder artillery altered the strategic situation of European cities. There was no single year when cannons came to dominate the European landscape. Instead, they rose to prominence over a period of roughly 75 years (Table 1) – still a relatively short period of time. Among the earliest confirmed uses of cannons was at the Battle of Crécy in 1346, where the English deployed small bombards against their French adversaries in an open field. In the 1430s and 1440s, King Charles VII relied on bombards to reconquer English towns and cities in France (Parker 1976, 203). These early bombards were large, heavy, and unwieldy because in these early years the easiest way to increase the force of a cannonball was to increase its mass. Nonetheless, they were extraordinarily potent weapons against the thin walls that dominated European fortification design. Cities that had previously been secure were suddenly under threat.

It was not until around 1450 that a solution was discovered to close the offense-defense gap (Levy 1984; Hopf 1991; Van Evera 1998).[5] Italian military engineers, who had been experimenting with different fortification designs, converged on a new type of design that became known as the *trace italienne*.[6] Early versions involved propping up existing walls with earthen barriers that could absorb the impact of cannon fire. Later versions of the design featured low and thick walls with

[5]For more theoretical treatments of the offense-defense balance, see Jervis (1978), Fearon (1997), and Gortzak, Haftel, and Sweeney (2005).

[6]Similar defensive structures were developed in parallel by Northern European military engineers, but for brevity, we will use the term *trace italienne* to refer to all early modern bastioned star-shaped walls and fortresses.

tapered edges that gave defenders unobstructed access to fire their own artillery down on attackers. These new walls were tremendously effective. Besieging armies had to resort to encircling and starving out their adversaries, an extremely long and expensive process (Parker 1976).

However, the new fortifications came with a large price tag. Their construction required enormous resources. The expense was significant enough that local elites could generally no longer afford to construct the walls using local resources alone. In 1553, the city-state of Siena attempted to construct a *trace italienne* when faced with a threat from Florence. The city was successful at constructing the new walls before the Florentine army arrived, but they had spent so much that the city could not afford to pay enough mercenaries to defend the new walls and surrendered quickly (Parker 1996, 12). The Dutch city of Antwerp successfully invested in upgrading its fortifications beginning in 1542, but the heavy price tag put a permanent strain on the city's fiscal situation, compromising its ability to defend itself during the religious conflicts of the 1560s (Limberger 2016). Even after initial construction was completed, defensive walls required further expenses for maintenance and modification. Especially in the early years, cities needed to continuously update their fortifications in response to the evolving technology of gunpowder; there are cases of defensive fortifications rendered obsolete while still under construction (Parker 1996).

3 Theory of Agglomeration and the Technology of Conflict

Centralized states offered real advantages in an international system characterized by potent siege weapons that could only be countered with costly defenses. The first advantage was that states are territorial – they consist of both a border and an interior. Defenses at the border provided indirect security for cities in the interior.[7]. Second, states could use coercive authority to alleviate commitment and free riding problems in the provision of defense. Without states, commitment problems unique to the challenges of the gunpowder revolution would have undermined the provision of collective security.

States could provide security much more efficiently than any individual city by using investments in defensive fortifications at the border to protect cities on the interior (Tracy 2000). It was usually not an effective strategy for attackers to simply bypass border cities. Conquering border cities was

[7] Indirect security matters even in the absence of a continuous border wall. Continuous walls have been favored in other contexts, for instance, by the Chinese Ming dynasty and the Roman Empire

often itself an objective of invading forces who wanted access to their tax bases and economic assets. Fortifying border cities, therefore, forced invaders to expend extra effort and stretch their campaigns further in search of softer cities. Cities could also act as garrisons for a state's armies from which they could mobilize defenses and counteroffensives against threats.

Establishing strong border defenses required interior cities to contribute resources for border defense in return for indirect protection. Before gunpowder, this type of security cooperation was not essential. Sieges against walled cities were costly and risky, and domestic insurrection was a more potent security threat (Eltis 1989). Once gunpowder was introduced, it increased the probability of a successful siege, which also increased the salience of external threats to cities. The extreme costs of protecting a city against artillery dramatically increased the rewards to this type of security cooperation. At the same time, the proliferation of strong states meant that the primary threat to cities shifted from domestic insurrection and inter-city conflict to encroachment by expanding regional powers.

There are at least three obstacles to security cooperation that the state's consolidated central authority could alleviate. First, interior cities had incentives to free ride on the financial contributions of others – they could benefit from the security provided by border cities without contributing resources of their own. A central state with the coercive authority to extract and redirect resources could prevent free riding by requiring each city contribute. In the absence of a state to coordinate defense, cities might nevertheless have cooperated among themselves on security under threat from the "shadow of the future" (Axelrod 1986; Powell 1993). However, the shadow of the future was a less powerful incentive when cities were constantly under threat and could not guarantee future cooperation in the event that they were conquered. The coercive power of the state was necessary to solidify cooperation in an environment where the shadow of the future was potentially short.

Second, border cities might have underinvested in defenses unless they valued the security indirectly provided to other cities. The first priority of any city was to secure its immediate vicinity and its food supplies. Any security indirectly benefiting other cities was a byproduct of investments made to achieve these priorities. There was a principal-agent relationship between the interior cities and the border cities – the interior cities were dependent on the border cities to stop attackers. States could use their authority to compel border cities to take additional steps to ensure the security of the interior.

Third, wealthy interior cities may have attempted to construct a *trace italienne* to assure their own security rather than contribute resources to border cities. Cities in a defensive league sometimes withheld their financial contributions to collective security in order to prioritize their own defense. The severity of the security threat from gunpowder meant that the stakes for cities were very high, which exacerbated the commitment problems. A strong national state solved the commitment problems by forcing individual cities to make sacrifices in order to provide stronger security for all.[8]

One alternative to states was a defensive league. These leagues were common in Europe during the medieval period, but they ultimately fell prey to the kinds of problems we describe above. For instance, in the late 1300s, the cities of the Hanseatic League successfully waged war on the Kingdom of Denmark and seized Danish territory in Sweden. However, the League eventually relinquished the territory due to internal disagreements over which members should bear the cost of maintaining its security; no cities were willing to bear the cost on their own to the benefit of free-riders (Postel 1996). The Dutch Republic, a hybrid polity that combined aspects of a centralized state and independent city-states, faced serious problems balancing the security objectives of its constituent cities. The city of Delft prevented its rival, the Hague, from fortifying because of the threat the Hague would pose to other members if it became too powerful. Then, when the Dutch Republic was threatened by Spain, Delft suggested that the unfortified Hague should be burned down to prevent a Spanish occupation (Hart 1989). The Swiss Confederacy fell prey to a coordination failure on an even greater scale in 1529 and 1531, when Protestant and Catholic members of the alliance waged war on one another in sectarian conflict (Greengrass and Gordon 2002). A strong state that could successfully monopolize violence and extract and allocate resources for defense of its territory could avoid all of these pitfalls.

Cities agglomerated into national states both voluntarily and involuntarily. Our theory does not necessarily predict whether cities would resist or embrace agglomeration – rather, we contend that agglomeration is an equilibrium characteristic of the European political system following the gunpowder revolution. Some cities might voluntarily concede sovereignty to a central state in anticipation of receiving the necessary security. When facing substantial foreign threats, some cities might choose to join a central state on their own terms rather than be conquered. The cities that

[8] Of course, the state may have chosen to allow wealthy interior cities to construct strong fortifications if doing so were in the state's interest.

were either unable or unwilling to join states would be conquered and incorporated into stronger national states. Other cities could agglomerate in a piecemeal fashion over time, or *en masse* as the result of an impetus like the religious conflicts of the Thirty Years' War.

Not all cities had the same incentives to coordinate their defenses, and not all states were successful at providing security guarantees. Some cities in Europe were rich enough to construct their own *trace italienne* without outside resources. These cities did not need to agglomerate to states. To the extent that these cities constitute the persistent urban centers emphasized by Abramson (2017), we can reconcile our primarily bellicist theory of state formation with his economic approach – richer cities had fewer incentives to agglomerate and more resources to resist conquest. Abramson (2017)'s finding that larger states were less likely to survive also comports with our theory. Once a state's border was breached by an enemy, its relatively vulnerable interior could be attacked. Large states might survive if they could quickly consolidate their coercive authority, but they faced the additional challenge of asserting control over a larger area. Any existing empires that were too decentralized and unable to redistribute resources from the interior to fortify the border defenses were at risk of conquest regardless of their geographic size.

Positive feedback was an important feature of state formation in Europe. The feedback process between the threat of conflict and the formation of states has previously been studied by Tilly (1990). The standard theory emphasizes how the proliferation of strong states in Europe caused a surge in military threats, which encouraged the concentration of coercive authority and led to stronger and more threatening states (Spruyt 1996, 2017; Voigtländer and Voth 2013; Gennaioli and Voth 2015; Kaspersen and Strandsbjerg 2017). Our theory modifies the existing literature by studying how the geopolitical component of this feedback process interacts with the technology of conflict. One key component of our geopolitical theory is the relative salience of internal and external threats. Collective security was more effective when cities faced external threats because the defense of any one city also benefitted the polity as a whole. The gunpowder revolution increased the salience of external threats by rendering traditional defenses obsolete. The concentration of coercive authority in states also meant that the origins of external threats became more predictable. As threats increasingly originated from foreign states, the concept of border defense became more essential, encouraging cities to invest in border fortifications.

4 Research Design

Our theory is that states supplanted existing political networks of cities in medieval Europe in part because they were better positioned to coordinate necessary investments in urban fortifications that could defend against artillery. To provide empirical support for this theory and to illustrate the political implications of the economics of conflict in the medieval period, we subject the theory to several tests. Additional analyses and robustness checks can be found in the Appendix.

First, we test whether localities that constructed walls in the post-gunpowder period were also places that saw the most political consolidation into states. Our work introduces a new measure of political consolidation based on territorial agglomeration, or the disappearance of political borders. If the need for updated walls were an important factor driving consolidation, then we expect a positive relationship between the locations of new defensive investment and agglomeration. Our primary objective in the statistical analysis is to evaluate whether there exists a positive relationship between these variables after accounting for potential confounders.[9] Questions related to the precise timing of wall construction are additionally investigated in a case study of France.

Second, we test whether new walls were constructed near the borders of states, where they were more strategically valuable for defense. Our theory portrays economies of scale in defensive investment as an important reason that states were better suited to the post-gunpowder world. Before gunpowder raised the costs of effective defense, many cities could afford protection. States, however, could mitigate the expense of upgraded fortifications by spreading the cost among many cities. Our second test, conducted at city level, examines this important aspect of the theory by comparing the relative proximity of new defensive investments to borders across time.

Third, we test whether states were able to effectively redistribute resources for the purpose of coordinating defenses. Our theory predicts that the rise of states changed the spatial distribution of defensive investment as states redirected resources to their borders. To test this theory, we construct a panel dataset about historic defensive investments in each city over time.[10] Empirically, we observe that the cities that upgraded their walls to protect against artillery were not always the same as the cities that built the strongest walls before the gunpowder revolution. We find that the

[9] We perform this analysis using a grid of 0.5×0.5 degree cells. See Section 4.1.1 for data construction details.

[10] Details on the construction of this dataset are available in Appendix XX.

cities that "caught up" to the technological frontier were located in places that experienced political consolidation.

Our work also includes a direct test of resource redistribution. We examine whether proximity to an important construction material, limestone, predicts wall construction. Before states, cities had to rely on local resources to construct walls. We find that in the pre-gunpowder period, distance to limestone predicts wall construction because it was very costly to move raw building materials across long distances. However, as states gained political authority, they could subsidize construction costs, weakening the link between access to resources and local investment.

4.1 Data

4.1.1 Agglomeration and Borders

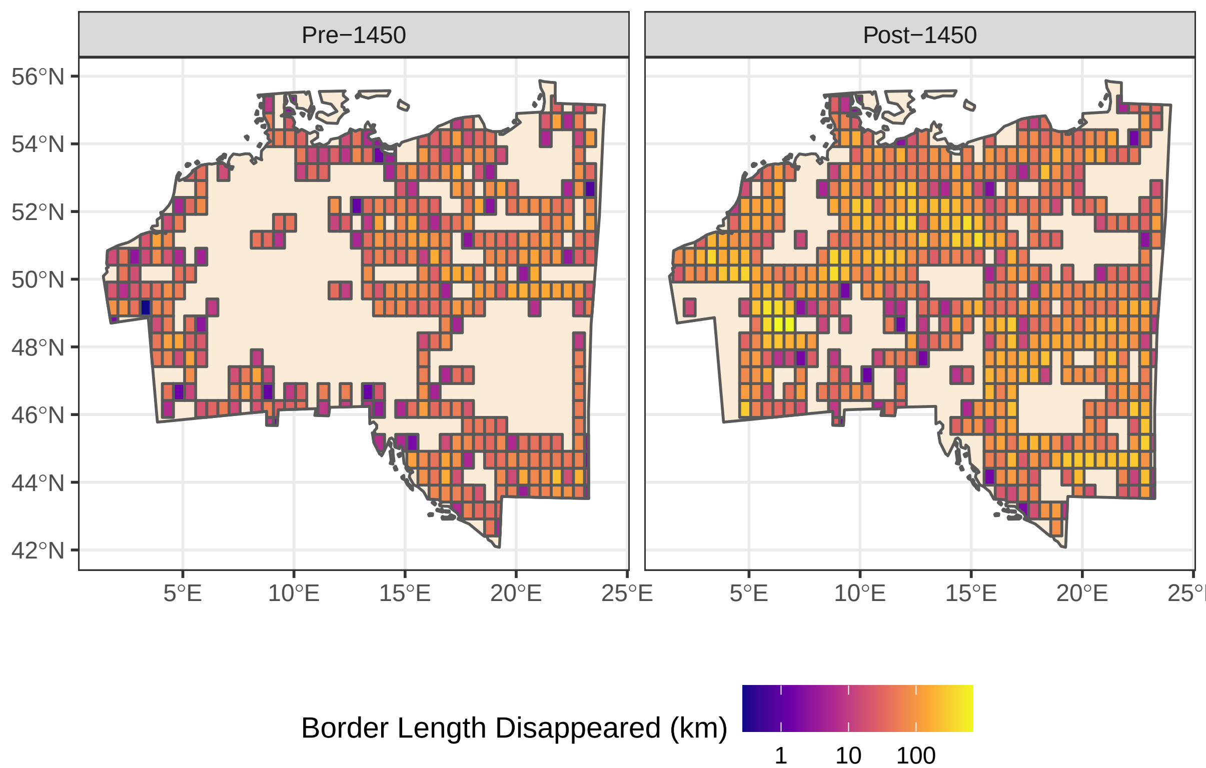

Figure 1: Heatmaps of border changes. The scale corresponds to the summed length of smoothed border that disappears within each cell.

We want to measure political consolidation, which was marked by the territorial agglomeration of small polities into larger states. We measure agglomeration by observing the disappearance of political borders from one period to another. The agglomeration of polities into states almost always results in the disappearance of a border. The border could disappear as a result of conquest or voluntary cession. We omit new borders from the analysis because they could contaminate our measure with instances of political fragmentation. More specifically, the sample space is divided into grid cells and the length of borders eliminated across five-year periods in each cell is calculated.[11] From 1190-1450, the mean (median) amount of border eliminated in one grid cell is 49.16 km (41.86 km); for the post period, lasting from 1450 to 1790, the mean (median) is 94.52 km (66.31 km).

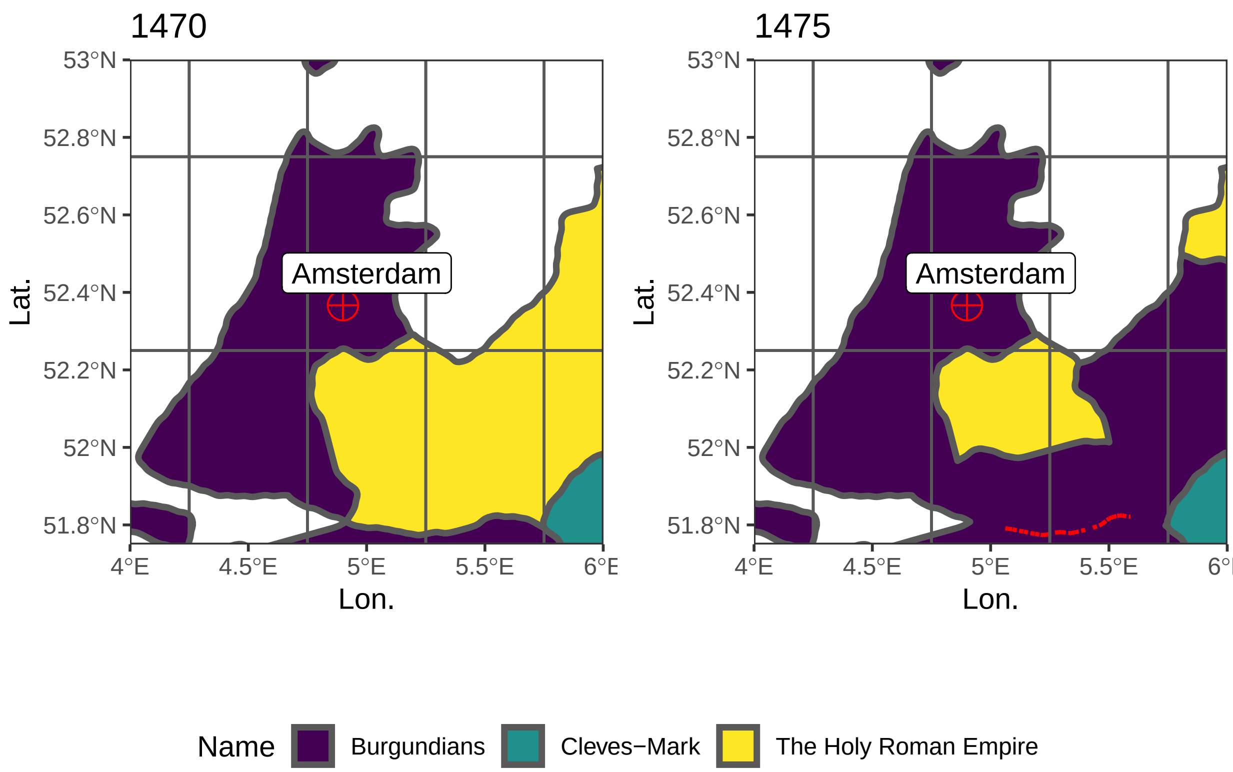

Figure 2: This example demonstrates our border elimination measure. The left-hand figure shows borders around the city of Amsterdam as they stood in 1470. The right-hand figure shows borders five years later, in 1475. The red line in the bottom right-hand corner of 1475 image shows a border that is counted as eliminated since 1470 due to victories of Charles the Bold, Duke of Burgundy, against the Holy Roman Empire near Amsterdam between 1470 and 1475. Only parts of the 1475 border that fall outside of a 10-km buffer zone around 1470 borders are counted as a significant eliminated border. The 0.5-by-0.5-degree grid is overlaid.

A heat map showing border changes is included in Figure 1 using the cells discussed in Appendix B. Consistent with the literature, the map shows that states consolidated their territory much more

[11] The grid cells are 0.5×0.5 degree polygons (roughly 55 square kilometers). To avoid capturing noise arising from small, politically insignificant border changes, we only count borders that are outside of a 10-kilometer buffer zone of newly created borders. To avoid falling prey to the "coastline problem," borders are smoothed before the length of eliminated borders is summed (Mandelbrot 1967). More details are available in Appendix B.

aggressively after 1450.[12] But it also shows that they did so in two complementary ways. First, the map shows that grid cells saw more borders disappear during this period. This is evidence that territory was consolidated along an intensive margin: the average cell saw more consolidation in this period. Second, the map shows that more grid cells saw borders disappear after 1450. This is evidence of consolidation along an extensive margin. An example illustrates precisely how our variable measures agglomeration. Appendix Figure 2 shows an example of our methodology in action for the grid cell containing Amsterdam, which experienced a significant border change between 1470 and 1475 due to the seizure of territory by the Duke of Burgundy during the Burgundian Wars.

We test hypotheses relating to the distribution of walls within states by calculating the distance from every wall construction to the nearest border. For each city, we construct a measure of the *border-centroid ratio*, the ratio of the city's distance from the nearest border to its distance from the geographic centroid of its state. Our theory indicates that states will make defensive investments where they are most strategically useful: near the state's borders. Smaller values indicate that the city is relatively far from the geographic centroid of the state and relatively close to the border. For example, a border-centroid ratio of 1/2 indicates that the city is twice as far from the centroid as it is from the nearest border. One challenge in calculating the border-centroid ratios is that while we observe European borders in five-year increments, we can only observe wall construction at longer horizons (as discussed in Section 4.1.2). We calculate the border centroid ratio for every wall in every map and then use the minimum distance over a defined period as the outcome variable. The minimum ratio is appropriate because it represents the maximum strategic value of the city to the state's defense.

We use the border-centroid ratio instead of simply the border distance to ensure our results do not mechanically depend on the shape of the borders or the state's size.[13] To the extent that a state's size can be substantively linked to the border-centroid ratio, the relationship is endogenous to our theory. For example, small states may contain only a single city near their geographic centroid. These instances may reflect wealthy cities that can update their walls without external support.

[12] In particular, we can recreate figures similar to the key graphs of Abramson (2017) in our sample space. See Appendix Figure A1.

[13] We demonstrate by simulation in Appendix D.

4.1.2 Changes in Defensive Technology

For data on the development of urban defenses, we geocode a map from Stoob (1988), which documents the locations of 6,378 fortified cities. The map covers territory stretching from modern-day Central France to the Polish-Russian border longitudinally and from the North Sea to the Swiss-Italian Alps latitudinally. It encodes the construction dates and construction types of each city's defenses. The map breaks down construction dates into four broad time periods: pre-1190, 1190-1250, 1250-1450, and 1450-1800, corresponding to the early, high, and late medieval eras and the long early modern era. The map details six distinct types of wall construction: earthen, wooden, stone, reinforced stone, bulwarks, and bastions. Figure 3 illustrates the spatial distribution of wall construction over time. Appendix Table A1 shows the number of walls by type and period.

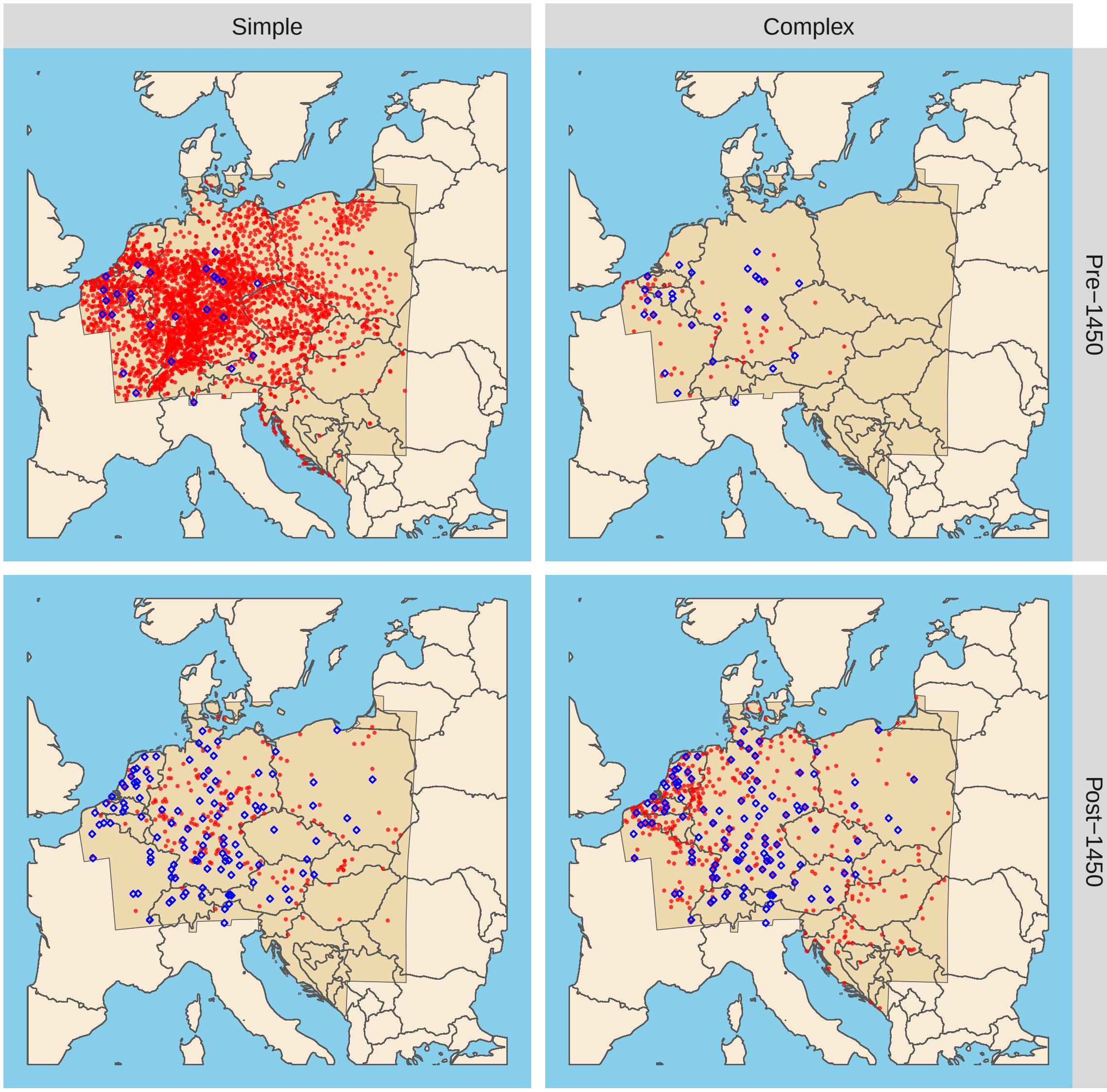

Figure 3: Each red point represents new simple (stone or reinforced) and complex (bulwarks and bastions) wall construction in that period for the specified wall type. Definitions for each construction type can be found in the text. While Stoob (1988) originally reported the data in four periods (pre-1190, 1190-1250, 1250-1450, and 1450-1800), for ease of viewing, we have collapsed the data into just two: pre-1450 (largely pre-gunpowder, except for the very end of the period) and post-1450 (clearly post-gunpowder). Each blue diamond represents the location of a gunmaker (Kennard 1986). The shaded area represents the part of the map for which fortification data is available. Modern borders are shown for reference.

Earthen fortifications were typically large defensive trenches dug around a town and only appear before 1250; wooden fortifications were palisades that could be built in combination with earthworks or stone gates. Stone walls were typically the tall and thin walls described above. Reinforced walls were stone walls that had been substantially modified for height or strength. Collectively, we refer to these stone and reinforced permanent structures as "simple" walls, to contrast them with the later "complex" walls designed to withstand gunpowder. However, early stone and reinforced styles were advanced defensive construction compared to earthworks or wooden palisades.[14]

Only two types of walls reported in Stoob's dataset could certainly have withstood cannon fire: bulwarks and bastions, which we term "complex" construction. Bulwarks were typically quadrilateral walls effectively reinforced with earth. Bastions were the *trace italienne* described above: tapered walls in a star shape whose corners were reinforced with bastions (DeVries 2012). The time periods delineated by the map do not cleanly correspond to the timeline of the introduction of gunpowder to Europe. Cannons become relevant as effective weapons against walled cities in the last several decades of the third period as delineated by Stoob (1988), and the 65 complex walls that predate 1450 were built late in the period. Similarly, this source fails to date the exact years in which the 2,104 simple stone and reinforced stone walls constructed between 1250 and 1450 were built (and, as discussed in Section 5.4, it is usually infeasible to assign a single year of construction to any fortification), but cannons were not yet a threat to cities for the bulk of that 200-year span. We therefore choose to simplify the timeline and consider 1450 to be the dividing line between the world before vs. after effective gunpowder artillery in Europe.

4.1.3 Offensive Technology

Our offensive technology data comes from Kennard (1986), which documents the locations and first known year of operation of 422 artillery manufacturers located in 129 unique European cities. We drop all observations without a specific city identified, as well as those that began operations after 1800 or that were based outside of the area also covered by the Stoob wall construction dataset. The Kennard data is drawn from the records of museum collections and historical records and is thus confined to the set of manufacturers for whom at least one physical specimen, or historical documentation, survived. Figure 3 shows a map of the locations of manufacturers alongside those of new fortifications. The earliest manufacturer included in this dataset began operations in 1358 in Laon, Northern France, twelve years after the first known use of artillery in 1346.[15]

[14] A very small number of "partial bastions" and "partial walls" reported by Stoob were dropped entirely from the dataset.

[15] Appendix Figure A3 shows the number of new entrants into the European artillery industry by 50-year periods.

4.1.4 Geographic and Historical Covariates

Our analyses use a slate of control variables to account for geographic and historical pre-conditions that could be potential confounders. Rivers and coastal access both promote economic activity, which is a potential competing explanation for political development; thus, our analyses account for the locations of major navigable rivers (based on data collected by Bosker, Buringh, and Van Zanden 2013) and proximity to the Atlantic coastline. On a similar note, we use natural variation in suitability for rain-fed wheat growth as a measure of agricultural productivity, which is both a correlate of wealth and a measure of ability to support population (FAO Geospatial Unit - CBDS 2021). We use the location of major Roman roads to account for historical presence of the Roman Empire (McCormick 2021). Rugged terrain could influence cities' outcomes by affecting economic activity and providing a natural substitute for man-made fortifications, thus, we also include a terrain ruggedness index (Nunn and Puga 2012).

5 Analysis

5.1 Agglomeration and Technological Change

Our central contention is that cities agglomerated into states because they could not otherwise commit to making the investments in collective security that were necessary in the gunpowder era. This section conducts an empirical analysis to determine whether variables associated with the threat from artillery can predict the observed agglomeration of small territories into larger ones. We first demonstrate a corresponding link between defensive investment and agglomeration.

We examine dynamic relationships between wall construction and agglomeration using a differences-in-differences estimator suggested by De Chaisemartin and d'Haultfoeuille (2020).[16] The estimator, which we implement dynamically at fifty-year intervals, is designed to be robust to heterogeneous effects and differential timing of treatment.[17] Figure 4 shows no evidence of any

[16] Due to the potential presence of these unobserved confounders, we employ the DID_M estimator of De Chaisemartin and d'Haultfoeuille (2020) which guarantees that all observations are given non-negative weights when forming the estimates. Other approaches to estimating a differences-in-differences model in the presence of heterogenous effects could sometimes assign negative weights to some observations, potentially leading to a scenario where the estimated effect within every subgroup has the opposite sign of the overall average effect. Effect sizes for OLS and standard differences-in-differences specifications are available in Appendix H.1.

[17] Our primary specification compares grid cells that eventually contain at least one complex wall to those in which a complex wall is never built.

such relationship before the gunpowder era. In every 50-year period before 1450, grid cells that eventually contain a complex wall experience roughly the same amount of agglomeration as those that never do. Between 1450 and about 1550, there is similarly little difference, but by 1600, there is a clear relationship between the elimination of national borders and the construction of walls that could withstand modern artillery.[18]

We interpret these results in the context of an evolving offense-defense balance between walls and artillery. The *trace italienne* did not develop into a consistently effective defense against artillery until at least 1525. Until then, the offense-defense balance shifted erratically as technological advances in artillery were countered by new types of defenses (Parker 1976). Initially, cities were able to repel attacks by constructing earthen supports behind existing walls, but as cannons became more powerful, this approach was rendered obsolete. The strategic implications of the new geopolitical environment were only made clear to all cities once both types of technology had matured.

The concentration of the observed effects during a period covering 1618 to 1648 suggests the importance of the Thirty Years' War to the agglomeration process. As discussed in the historical background, the introduction of artillery occurred earlier and the *trace italienne* was developed by 1525. The difference in timing is consistent with our theory which claims that the gunpowder revolution was necessary but not sufficient to stimulate political consolidation. Agglomeration only occurs after cities experience a threat of conflict – no city would consider surrendering its sovereignty without facing some external threat. The Thirty Years' War was the first time that nearly every city in our sample space experienced a threat of conflict. Thus, the effect of the changed nature of conflict does not manifest until this time.

[18] Appendix Section H.1 provides supplementary, qualitatively similar results for this exercise varying the size of grid cells.

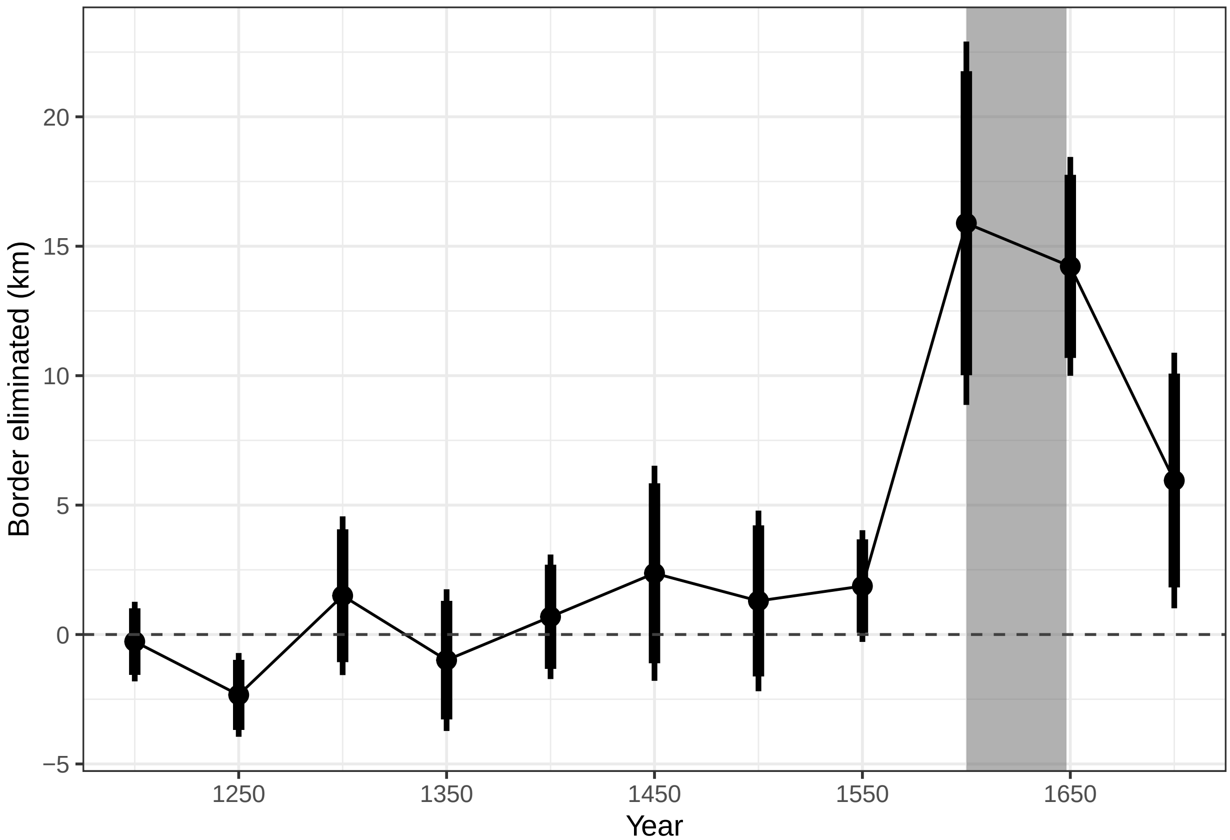

Figure 4: The dynamic relationship between complex wall construction and agglomeration at the grid cell level. Agglomeration is measured by meters of border eliminated from the grid cell. Complex walls include points marked as either bastions or bulwarks in Stoob (1988). The placebo tests show that grid cells which eventually build complex walls are on parallel trends with those that do not. The relationship is strongest during and following the Thirty Years' War (gray band).

Observing which cities upgraded to complex walls is a useful way to track the impact of artillery on the European landscape, since upgraded fortifications are immobile, permanent, and well-documented. However, we can also gain additional information from observing the geographic distribution of artillery manufacturers documented by Kennard (1986).[19]

The early bombards were enormously heavy and could generally be carried long distances only at high cost. For example, the Dardanelles Gun of the Ottoman Empire (manufactured in 1464 and inspired by the Orban cannon) weighed around $16,800$ kilograms ($37,000$ pounds) (Blackmore 1976). Therefore, especially in the early years of gunpowder, cities near the point of artillery manufacture faced a higher threat level. Over time the weapons became smaller, more powerful, and more mobile, meaning that they could be transported more easily. Cannons had a secondary role as defensive

[19] Artillery technology was developed by a pre-existing European metallurgy industry. The technology needed to make a cannon is similar to that needed to make church bells and was pioneered by those same experts.

complements to fortifications. The star shape of the classic *trace italienne* is intended to eliminate blind spots of wall-mounted cannons that defend the fortified city from attackers. Thus, having a local gunmaker improved the defensive resources of the city.

To examine the relationship between the locations of artillery manufacturers and defensive investment, we use a linear probability model that regresses the presence of a complex wall on the presence of an artillery manufacturer.[20] Table 2 shows a large and statistically significant relationship between the presence of artillery manufacturers and defensive investments. Grid cells containing at least one manufacturer at any point during our sample period were about $20-30\%$ more likely to contain a complex wall. This relationship persists after adjusting for the presence of at least one reinforced wall (a measure of pre-gunpowder defensive investment at the technological frontier) and the number of stone walls ever built, a measure of overall defensive investment that, because of their prevalence, also proxies for population.[21]

Table 2: Results from a linear probability model of complex wall presence on artillery manufacturer location conducted at the 0.5-by-0.5 degree grid cell level.

	Dependent variable:		
	Count complex walls > 0		
	(1)	(2)	(3)
Manufacturers > 0	0.361^{***}	0.230^{***}	0.215^{***}
	(0.049)	(0.048)	(0.048)
Reinforced walls > 0		0.400^{***}	0.326^{***}
		(0.042)	(0.050)
Count stone walls			0.015^{***}
			(0.005)
Lat-lon	Yes	Yes	Yes
Observations	486	486	486
R^2	0.144	0.289	0.305
Adjusted R^2	0.139	0.283	0.297
Residual Std. Error	0.460	0.420	0.415
F Statistic	26.996^{***}	48.900^{***}	42.072^{***}
Note:			*p<0.1; **p<0.05; ***p<0.01

5.2 The Increasing Salience of National Borders

The previous section tested whether the cities that built complex walls were located in areas that were threatened with conquest. This section addresses how defensive investments were distributed

[20] Although some cells contain multiple manufacturers, we dichotomize this variable because we do not know anything about the production scale of any individual manufacturer. We conduct this analysis at the grid cell level rather than the city level because we have no evidence that a manufacturer who worked in a particular city did not supply artillery to nearby cities that were allied or under the control of the same state.

[21] We include stone walls as a count, despite dichotomous variables being more interpretable in a LPM model, because of the more frequent occurrence of stone walls in our data; most squares would be treated if it were also dichotomized.

within states before vs. after the gunpowder revolution. Our theory predicts that centralized states redistributed resources from the interior of a state to the border to amortize the costs of defense over a consolidated territory.

We run variations on the following OLS regression to model the relationship between fortification construction and border proximity:

$$\text{LBC} = \alpha + \beta \text{type} + \mathbf{X}\gamma + \varepsilon \tag{1}$$

where N is the number of cities included in the regression, LBC is an N vector of minimum log border-centroid ratios observed during a given period, α is a scalar intercept, β is the scalar coefficient of interest, type is a vector of indicators describing the type of wall in each city, $\mathbf{X}$ is an $N \times K$ matrix containing K control variables, γ is a K vector of coefficients, and ε is an error vector of size N. Our slate of historical and geographic covariates is described further in Section 4.1.4. A log border-centroid ratio of zero indicates that the wall is equally far from the centroid and the border. Negative values indicate that the wall is closer to the border, and positive values indicate that the wall is closer to the centroid.[22]

Results are reported in Table 3. The first column compares the log border-centroid ratios of walls built during the pre-gunpowder period to walls built during the post-gunpowder period. Cities with new wall construction post-1450 have smaller log border-centroid ratios compared to cities that received new construction pre-1450. This indicates that they are located closer on average to a border and further from the center of the state or other political entity in which they are located. The second column compares only complex walls built post-1450 to all other wall types (wooden, stone, and reinforced). The point estimate is negative, consistent with our theory. The third column indicates why this is the case: cities with bastions – the largest, most technically complex, and most expensive defensive structure available to counter artillery – are significantly closer to borders than cities with relatively less-advanced bulwarks. Relative to the centuries before gunpowder became a serious threat, borders became better-defended overall, and after 1450, the most expensive and

[22]We use the log of the border-centroid ratios because the distribution of border centroid ratios are log-normally distributed (see Appendix Table A7). Log-normal distributions are common in studies of economic geography; for instance, see Gabaix (1999) and Dittmar (2009).

effective resources were devoted to protecting cities located in areas of maximal external threat.

Table 3: The first three columns compare the log border-centroid ratios of all walls build pre-1450 to those built post-1450. The fourth through sixth columns compares post-1450 complex walls to post-1450 simple walls, and the last three compare post-1450 complex walls classified as bastions to post-1450 walls classified as less-sophisticated constructions, including bulwarks meant to counter artillery that were not as effective as the bastioned *trace italienne*. Controls are a dummy for proximity to the Atlantic Ocean, log distance a large navigable river (defined following Bosker, Buringh, and Van Zanden 2013), and log distance to a major Roman road, as well as indices for soil quality and terrain ruggedness. Standard errors are clustered using the Voronoi polygon approach described in the accompanying Appendix B. Appendix Table A3 shows alternate specifications using Conley standard errors, which produce qualitatively similar results.

	Dependent variable:								
	Log border-centroid ratio								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Post-1450 (v. pre-1450)	-1.041^{***}	-1.021^{***}	-1.032^{***}						
	(0.100)	(0.104)	(0.105)						
Complex post-1450 (v. simple post-1450)				-0.154	-0.269^{*}	-0.346^{**}			
				(0.153)	(0.154)	(0.144)			
Bastion post-1450 (v. bulwark post-1450)							-0.374^{*}	-0.363^{*}	-0.394^{**}
							(0.191)	(0.191)	(0.194)
Atlantic coastline			-0.594^{***}			-0.661^{**}			-0.772^{**}
			(0.182)			(0.269)			(0.328)
Log dist. to river			-0.051			-0.120^{***}			-0.128^{**}
			(0.033)			(0.046)			(0.050)
Ag. prod.			-0.0001			0.0004			0.001^{**}
			(0.0001)			(0.0003)			(0.0003)
Ruggedness			-0.001			-0.002			0.0002
			(0.0005)			(0.002)			(0.002)
Log dist. to Roman road			-0.047			0.119^{**}			0.089
			(0.037)			(0.055)			(0.059)
Lat-lon	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Observations	6,559	6,559	6,559	735	735	735	483	483	483
R^2	0.040	0.042	0.050	0.002	0.031	0.073	0.009	0.021	0.073
Adjusted R^2	0.040	0.042	0.049	0.0004	0.027	0.063	0.007	0.015	0.057
Residual Std. Error	1.611	1.609	1.603	1.725	1.702	1.670	1.696	1.690	1.653
F Statistic	272.607^{***}	96.414^{***}	43.479^{***}	1.326	7.785^{***}	7.195^{***}	4.227^{**}	3.369^{**}	4.633^{***}

Note: *p<0.1; **p<0.05; ***p<0.01

5.3 The Changing Spatial Distribution of Defensive Investment

Our theory predicts that states strategically allocated investment to cities that were particularly useful for defending the state's territory. Thus, we expect that in the post-gunpowder period, states directed resources to where they were needed bolster their defenses. Some cities developed new strategic significance due to their location near their state's borders. We expect some of these cities, which may have never previously constructed strong walls, to receive significant defensive investment after the gunpowder revolution. We also hypothesize that some cities fell off the technological frontier after the gunpowder revolution as they sent resources to the borders in exchange for the state's protection.

We test this hypothesis by regressing the distance of a city to a border that was dissolved in the post-gunpowder period on a city's progression path of defensive technology controlling for historical and geographic covariates. We define several paths. "Progressive development" denotes a city that always received the most advanced fortification available. "Falls off" denotes a city that had a state-of-the-art wall in the pre-gunpowder era, and thus was at the forefront of defensive technological development, but failed to acquire a bastion or bulwark once gunpowder became a threat. "Catches up" denotes a city that did not have a stone or reinforced wall in the pre-gunpowder era when these were the most effective defensive technology but which leapfrogged to a bastion or bulwark after 1450. The reference group is all cities that never acquired even a stone wall, permanently stalling at earthworks or wooden defenses. The results in Table 4 show the results the following OLS regression:

$$\text{Border Change Distance} = \alpha + \text{pathway}\beta + \mathbf{X}\gamma + \varepsilon \tag{2}$$

where N is the number of cities included in the regression, Border Change Distance is an N vector of minimum distances to border disappearances in the post gunpowder period, α is a scalar intercept, β is a 3 vector of coefficients of interest, pathway is an $N \times 3$ matrix of indicators describing which pathway a city followed, $\mathbf{X}$ is an $N \times K$ matrix containing K control variables, γ is a K vector of coefficients, and ε is an error vector of size N.[23]

[23] The pathways "Progressive Development", "Catches Up", and "Falls Off" are represented in pathway. The residual

Table 4 shows that cities which built strong fortifications capable of resisting artillery even despite having been slow to build reinforced and stone walls were located closer to areas that agglomerated. The results are robust to the inclusion of a set of control variables and are classically statistically significant. We interpret these results as evidence that states were redirecting resources to these cities. As states expand their borders they must continuously invest in border defenses. This phenomenon is observed in the France case study in Section 5.4. As cities receive those investments they construct stronger defenses.

Table 4: City-level regression of distance to post-1450 border elimination on development path of cities' defensive investments. Standard errors are clustered using the Voronoi polygon approach described in the accompanying Appendix B. Appendix Table A4 shows alternate specifications using Conley standard errors, which produce qualitatively similar results.

	Dependent variable:		
	Log dist. to border eliminiation post-1450		
	(1)	(2)	(3)
Falls behind	0.100	0.040	0.079
	(0.105)	(0.102)	(0.099)
Catches up	−0.161	−0.136	−0.223**
	(0.100)	(0.103)	(0.098)
Progressive development	−0.036	−0.041	−0.100
	(0.176)	(0.167)	(0.164)
Atlantic coastline			1.216***
			(0.160)
Log dist. to river			−0.023
			(0.031)
Ag. prod.			−0.001
			(0.001)
Ruggedness			−0.071*
			(0.042)
Log dist. to Roman road			−0.0003***
			(0.0001)
Lat-lon	No	Yes	Yes
Observations	4,489	4,489	4,489
R^2	0.002	0.026	0.059
Adjusted R^2	0.001	0.025	0.057
Residual Std. Error	1.382	1.366	1.343
F Statistic	2.327*	23.808***	27.894***
Note:	*p<0.1; **p<0.05; ***p<0.01		

Our theory implies that states redistributed resources internally to provide collective security. States ensured that strategically important cities would receive the necessary resources to construct walls capable of withstanding artillery fire. Even before the *trace italienne*, walls were still large projects that required non-trivial expense to build and maintain. These expenses were lower in places that had easy access to the raw materials needed to construct large structures using pre-modern building methods and materials. We hypothesize that before the gunpowder revolution when cities

category "Other" is the omitted category.

and local rulers were responsible for funding their own defense, cities located near building materials were more likely to construct defensive fortifications. In the early modern period, however, when cities required substantial new investment to make their fortifications capable of resisting artillery, we expect states to bring resources wherever they are needed to ensure security. Thus, we anticipate a that the link between proximity to building materials and wall construction should weaken after the gunpowder revolution.

Limestone was the preferred building material for large structures such as walls in medieval Europe. It has the advantages of being both durable (compared to sandstone and softer substitutes) and flexible (compared to granite). In the absence of access to limestone, other quarried materials (or brick) could be used. However, limestone was also a key ingredient in the mortar that bound components of walls together. Cities located near deposits of limestone (composed of calcium carbonate) had cheaper access to materials for building large projects like defensive walls relative to those far away.[24] We therefore use proximity to natural limestone deposits in the earth to proxy the costs of building a wall in a particular location.

Our data on the locations of limestone deposits comes from the Federal Institute for Geosciences and Natural Resources, which produces a high-resolution map of the four top geological components of each point on the European landmass (Asch 2003). We designate any area with limestone as one of these top components as being a potential source of limestone for building large structures such as city walls. This avoids concerns about endogeneity that might result from using the locations of known historical limestone quarries instead of natural deposits in the earth. Because calcium carbonate can also affect soil quality by changing its pH, and therefore agricultural productivity, we control for rain-fed wheat growing suitability (as well as for the other control variables discussed in Section 4.1.4) as well as a measure of soil quality.[25] We run the following OLS regression specification:

$$\begin{gathered}\text{wall construction} = \alpha + \beta_0 \textbf{limestone distance} + \beta_1 \textbf{post-gunpowder} + \\ \beta_2 \textbf{interaction} + \mathbf{X}\gamma + \varepsilon\end{gathered} \tag{3}$$

where N is the number of cities included in the regression, **wall construction** is an N vector

[24] See, for instance, an archaeological analysis from the Swedish city of Visby (Balksten and Thelin 2014).

[25] Soil quality is sourced from Van Liedekerke (2008).

indicating whether the city constructed walls of a given type during a particular period, α is a scalar intercept, β is a scalar coefficient, **limestone distance** is an N vector of distances to the nearest limestone deposit, **post-gunpowder** is an indicator for the post gunpowder period, **interaction** is an interaction of limestone distances and time period, $\mathbf{X}$ is an $N \times K$ matrix containing K control variables, γ is a K vector of coefficients, and ε is an error vector of size N.

Table 5: Results from a city-level OLS regression of whether a city ever built any defensive structure using stone-and-mortar construction on log distance to nearest limestone deposit, a dummy for post-1450, and the interaction of the two. Standard errors are clustered using the Voronoi polygon approach described in the accompanying Appendix B. Appendix Table A5 shows alternate specifications using Conley standard errors, which produce qualitatively similar results.

	Dependent variable:		
	Builds any stone-and-mortar wall		
	(1)	(2)	(3)
Log dist. to limestone	-0.007^{***}	-0.004^{***}	-0.004^{***}
	(0.001)	(0.001)	(0.001)
Post-1450	-0.315^{***}	-0.319^{***}	-0.321^{***}
	(0.021)	(0.020)	(0.020)
Log dist. to limestone x post-1450	0.007^{***}	0.006^{***}	0.006^{***}
	(0.002)	(0.001)	(0.001)
Atlantic coastline			0.028
			(0.040)
Log dist. to river			0.007^{*}
			(0.004)
Ag. prod.			0.00001
			(0.00001)
Ruggedness			-0.0002^{**}
			(0.0001)
Log dist. to Roman road			-0.021^{***}
			(0.006)
Soil quality			0.00005^{***}
			(0.00002)
Lat-lon	No	Yes	Yes
Observations	10,893	10,893	10,893
R^2	0.092	0.142	0.160
Adjusted R^2	0.092	0.142	0.159
Residual Std. Error	0.435	0.422	0.418
F Statistic	367.737^{***}	361.709^{***}	188.340^{***}
Note:			*p<0.1; **p<0.05; ***p<0.01

The coefficient on log distance between a potential city site and limestone is negative, consistent with our hypothesis that access to raw building materials increases the likelihood of a city building a stone wall, reinforced stone wall, bulwarks, or bastions, all of which can be built from limestone and require mortar. Construction after 1450 is *negatively* associated with building using limestone materials because earthen and stone walls are almost always built early in our sample period. The interaction of distance to limestone and post-1450 construction is negative and approximately of the same size as the coefficient on limestone alone. This is consistent with a theory that states supported the construction of walls in strategically important locations, reducing their reliance on easy access to raw materials obtained using only the city's own resources.

5.4 Case Study: France

As we have discussed above, a limitation of the wall construction data from Stoob (1988) is that it does not give the precise date in which walls are constructed. However, it is not historically appropriate to designate a single year, or even small range of years, in which fortifications were constructed, since these large investments could take years or decades to complete. Walls could require continuous maintenance and upgrades as offensive technology continued to improve, so a city or state that built one also committed to future investment if they wanted the structure to remain useful. Given these limitations, it can be difficult to clearly ascertain which political entity deserves credit for upgrades. For instance, the city of Gravelines was contested on multiple occasions by France and Spain, each of which made continuous improvements to its fortifications. Various additions and upgrades to the walls were made by the Spanish from 1528-1536 and again beginning in 1556 and 1640. Upon its capture by France in the 1650s, it was incorporated into the engineer Vauban's comprehensive plan of defenses along the new French border and upgraded yet again (Lepage 2009). Our theory is consistent with more than one possible ordering of events: cities that could not bear the fiscal burden of construction might choose to never even start a construction project, knowing that they could not complete it - or cities might attempt to invest in new defenses but find that they could not complete them without facing financial ruin, making them military vulnerable to conquest, as in the above-cited cases of Siena and Antwerp.

We shed further light on the question of the timing of investments relative to state expansion using a case study of France. France is well-known as a case that centralized power and bureaucratized its tax system well before many other European polities made the transformation to modern statehood. Figure 5 shows the simultaneous agglomeration of Western European territory by France after 1450 and the deployment of defensive investment to France's newly acquired territory. Before 1450, permanent fortifications (stone and reinforced walls) were not particularly concentrated near the French border. After 1450, militarily relevant walls (bulwarks and bastions) were constructed near the expanding French border as France pushed into Western Europe.

The two mechanisms can be illustrated by the experience of different French cities. For instance, the city of Gravelines was contested on multiple occasions by France and Spain, each of which made continuous improvements to its fortifications. Various additions and upgrades to the walls were made by the Spanish from 1528-1536 and again beginning in 1556 and 1640. Upon its capture by France in the 1650s, it was incorporated into the engineer Vauban's comprehensive plan of defenses along the new French border and upgraded yet again (Lepage 2009).

Overall, in France it was predominately the case that walls were constructed after cities agglomerated into the state, but both mechanisms occurred. During conflicts with neighboring Burgundy in the 15th through 16th centuries, France tended to seize towns with unmodernized walls and then invest in their defense. Later, as France's expansion pushed into Spanish territories in the 17th century, the cities they conquered had already received an influx of investment from the Spanish, which was sometimes not completed in time to be effective (Wolfe 2000).[26] These cities, which sometimes were conquered and re-conquered multiple times by different contesting states, were the recipients of continuous investment as they changed hands.

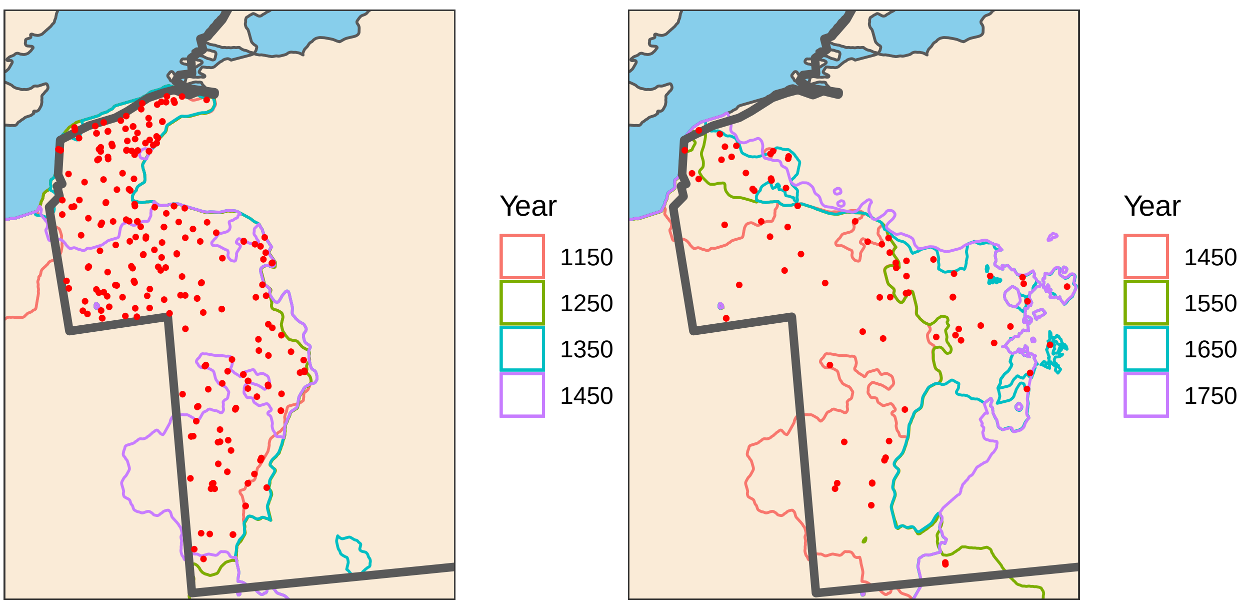

Figure 5: Map of Eastern France showing expansion and contraction of territory before (left panel) vs. after (right panel) the development of gunpowder. A dark grey line indicates the area for which Stoob (1988) provides data on wall manufacture. Red points indicate new walls built in French territory, restricted to only walls that are militarily advanced for their time period (stone and reinforced pre-1450 and bulwarks and bastions post-1450).

[26]In the case of Dole, a fortified city in modern-day Eastern France that was conquered by France while its Spanish wall was still under construction.

6 Conclusions

The central contention of our work is that the gunpowder revolution created a collective security crisis that cities could only manage by surrendering their sovereignty to central states. We argue that the use of artillery in Europe from around the year 1450 radically shifted the balance of military power in favor of the offensive side, rendering existing investments in urban security obsolete. When defensive technology caught up, the new, complex urban fortifications needed to effectively counter the artillery threat required economies of scale to fund and support. Drawing on existing networks for allies was often an insufficient solution to this problem, as the failures of the Hanse, the Swiss Confederacy, and other non-centralized alliances to successfully coordinate mutual security demonstrates. Commitment and free-rider problems made non-territorial, non-centralized networks suboptimal relative to centralized states with the necessary political authority to enforce cooperation. These economies of scale could better be borne by states, which could optimally coordinate the allocation of resources. This put pressure on cities and other small territorial entities to agglomerate into modern states voluntarily or involuntarily.

Our paper tests the theory by bringing together detailed data on the locations of artillery manufacturers, the locations and construction dates of urban fortifications, and fine-grained data on border changes of territorial political entities. We find evidence for a relationship between new offensive military threats and shifts in national borders consistent with our theory. Places where walls capable of withstanding artillery were constructed experienced more territorial agglomeration as measured by the disappearance of borders. We interpret this agglomeration, which became increasingly common over time, as evidence of the emergence of modern states that successfully contested and absorbed territory from neighboring polities. Areas with agglomeration were more likely to invest - or receive investment to build - cutting-edge fortifications. Furthermore, we demonstrate that borders became increasingly hardened after 1450. This is consistent with our theory that states strategically allocated resources towards cities that faced the greatest threat and which, if reinforced, could protect the interior. Cities that suddenly leapt to the front of the defensive technological frontier were closer to sites of agglomeration, and proximity to raw materials mattered less to whether a city built permanent defensive infrastructure post-1450, when states could redistribute resources to key locations.

Our findings, which build on the work of Tilly (1990) and Parker (1976), shed light on the relationship between conflict and economic and political development. Scholars including Herbst (2014), Centeno (1997), and Abramson (2017) have questioned whether Tilly's bellicist thesis that conflict led to the development of states is well supported. We provide a mechanism linking conflict to political change and explain why it functioned in Europe in the 15th, 16th, and 17th centuries. Specifically, a new kind of military threat raised the cost of defense, encouraging the agglomeration of previously disparate political entities into new, more efficient units of governance. We argue that other forms of conflict do not necessarily entail political agglomeration as an optimal response and will therefore not have the kind of positive externalities in growth and development that we observe in Europe. Gunpowder, which forced cities to either invest in new defenses or be absorbed by a state that could provide geographic economies of scale in defense, made the relationship between conflict and political development in late medieval and early modern Europe a positive one.

7 References

Abramson, Scott F. 2017. "The Economic Origins of the Territorial State." *International Organization* 71 (1). Cambridge University Press: 97–130.

Acharya, Amitav. 2004. "How Ideas Spread: Whose Norms Matter? Norm Localization and Institutional Change in Asian Regionalism." *International Organization* 58 (2). Cambridge University Press: 239–75.

Alesina, Alberto, and Enrico Spolaore. 1997. "On the Number and Size of Nations." *The Quarterly Journal of Economics* 112 (4). MIT Press: 1027–56.

———. 2005. *The Size of Nations*. MIT Press.

Asch, K. 2003. "The 1:5 Million International Geological Map of Europe and Adjacent Areas: Development and Implementation of a Gis-Enabled Concept." *Geologisches Jahrbuch, SA 3*. E. Schweizerbart´sche Verlagsbuchhandlung.

Axelrod, Robert. 1986. "An Evolutionary Approach to Norms." *The American Political Science Review*. JSTOR, 1095–1111.

Axelrod, Robert, and Robert O Keohane. 1985. "Achieving Cooperation Under Anarchy: Strategies and Institutions." *World Pol.* 38. HeinOnline: 226.

Balksten, Kristin, and Carl Thelin. 2014. "Construction and Materials of Visby Medieval City Wall–Risk of Damage." In *9th International Masonry Conference 2014, Guimarães, Portugal, July 7-9, 2014*.

Bean, Richard. 1973. "War and the Birth of the Nation State." *The Journal of Economic History* 33 (1). Cambridge University Press: 203–21.

Blackmore, H.L. 1976. "The Armouries of the Tower of London, Ordnance Catalogue." Ordnance Catalogue.

Bosker, Maarten, Eltjo Buringh, and Jan Luiten Van Zanden. 2013. "From Baghdad to London: Unraveling Urban Development in Europe, the Middle East, and North Africa, 800–1800." *Review* *of Economics and Statistics* 95 (4). MIT Press: 1418–37.

Centeno, Miguel Angel. 1997. "Blood and Debt: War and Taxation in Nineteenth-Century Latin America." *American Journal of Sociology* 102 (6). The University of Chicago Press: 1565–1605.

———. 2002. *Blood and Debt: War and the Nation-State in Latin America*. Penn State Press.

Coase, R H. 1960. "The Problem of Social Cost." *Journal of Law and Economics* 3.

Conley, Timothy G. 1999. "GMM Estimation with Cross Sectional Dependence." *Journal of Econometrics* 92 (1). Elsevier: 1–45.

De Chaisemartin, Clément, and Xavier d'Haultfoeuille. 2020. "Two-Way Fixed Effects Estimators with Heterogeneous Treatment Effects." *American Economic Review* 110 (9): 2964–96.

DeVries, Kelly. 2012. *Medieval Military Technology*. University of Toronto Press.

Dincecco, Mark, and Massimiliano Gaetano Onorato. 2016. "Military Conflict and the Rise of Urban Europe." *Journal of Economic Growth* 21 (3). Springer: 259–82.

Dittmar, Jeremiah. 2009. "Cities, Institutions, and Growth: The Emergence of Zipf's Law." *University of California, Berkeley*.

Eltis, David. 1989. "Towns and Defence in Later Medieval Germany." *Nottingham Medieval Studies* 33. Brepols Publishers: 91–103.

FAO Geospatial Unit - CBDS. 2021. "Agricultural Suitability and Potential Yields."

Fearon, James D. 1997. "The Offense-Defense Balance and War Since 1648." In *Annual Meeting of the International Studies Association, Chicago*, 379–414.

Freed, J.B. 2016. *Frederick Barbarossa: The Prince and the Myth*. Yale University Press. https://books.google.com/books?id=tng8DAAAQBAJ.

Gabaix, Xavier. 1999. "Zipf's Law for Cities: An Explanation." *The Quarterly Journal of Economics* 114 (3). MIT Press: 739–67.

Gennaioli, Nicola, and Hans-Joachim Voth. 2015. "State Capacity and Military Conflict." *The Review of Economic Studies* 82 (4). Oxford University Press: 1409–48.

Gortzak, Yoav, Yoram Z Haftel, and Kevin Sweeney. 2005. "Offense-Defense Theory: An Empirical Assessment." *Journal of Conflict Resolution* 49 (1). Sage Publications Sage CA: Thousand Oaks, CA: 67–89.

Gowa, Joanne. 1986. "Anarchy, Egoism, and Third Images: The Evolution of Cooperation and International Relations." JSTOR.

Greengrass, M., and B. Gordon. 2002. *The Swiss Reformation*. New Frontiers Series. Manchester University Press. https://books.google.com/books?id=M0W8AAAAIAAJ.

Hart, Marjolein 'T. 1989. "Cities and Statemaking in the Dutch Republic, 1580-1680." *Theory and Society* 18 (5). Springer: 663–87. http://www.jstor.org/stable/657615.

Herbst, Jeffrey. 2014. *States and Power in Africa: Comparative Lessons in Authority and Control*. Princeton University Press.

Hoffman, Philip T. 2015. *Why Did Europe Conquer the World?* Princeton University Press.

Hopf, Ted. 1991. "Polarity, the Offense-Defense Balance, and War." *American Political Science Review* 85 (2). Cambridge University Press: 475–93.

Hough, Peter. 2020. "Regional Security Organizations." *International Security Studies*. Routledge, 348–62.

Jervis, Robert. 1978. "Cooperation Under the Security Dilemma." *World Politics* 30 (2). Cambridge University Press: 167–214.

Kaspersen, Lars Bo, and Jeppe Strandsbjerg. 2017. *Does War Make States?: Investigations of Charles Tilly's Historical Sociology*. Cambridge University Press.

Kennard, Arthur Norris. 1986. *Gunfounding and Gunfounders: A Directory of Cannon Founders from Earliest Times to 1850*. Arms & Armour Press.

Keohane, Robert O. 1986. “Reciprocity in International Relations.” *International Organization*. JSTOR, 1–27.

Keohane, Robert O, and Joseph S Nye Jr. 1973. “Power and Interdependence.” *Survival* 15 (4). Taylor & Francis Group: 158–65.

Kupchan, Charles A, and Clifford A Kupchan. 1995. “The Promise of Collective Security.” *International Security* 20 (1). The MIT Press: 52–61.

Lepage, J.D.G.G. 2009. *Vauban and the French Military Under Louis Xiv: An Illustrated History of Fortifications and Strategies*. McFarland, Incorporated, Publishers. https://books.google.com/books?id=Fzp3MWRNPFAC.

Levy, Jack S. 1984. “The Offensive/Defensive Balance of Military Technology: A Theoretical and Historical Analysis.” *International Studies Quarterly* 28 (2). Blackwell Publishing Ltd Oxford, UK: 219–38.

Limberger, Michael. 2016. “‘The greatest marketplace in the world’. The role of Antwerp in the economic and financial network of the Habsburg Empire.” In *Les Villes Des Habsbourg Du Xve Au Xixe Siecle : Communication, Art et Pouvoir Dans Les Reseaux Urbains*, edited by Ludolf Pelizaeus, 45–62. Reims.

Mandelbrot, Benoit. 1967. “How Long Is the Coast of Britain? Statistical Self-Similarity and Fractional Dimension.” *Science* 156 (3775). American Association for the Advancement of Science: 636–38.

McCormick, Michael. 2021. “Mapping Past Societies.”

McNeill, William H. 1982. *The Pursuit of Power: Technology, Armed Force, and Society Since Ad 1000*. University of Chicago Press.

Meijer, Hugo, and Stephen G Brooks. 2021. “Illusions of Autonomy: Why Europe Cannot Provide for Its Security If the United States Pulls Back.” *International Security* 45 (4). MIT Press One Rogers Street, Cambridge, MA 02142-1209, USA journals-info …: 7–43.

Nunn, Nathan, and Diego Puga. 2012. “Ruggedness: The Blessing of Bad Geography in Africa.” *Review of Economics and Statistics* 94 (1). MIT Press: 20–36.

Parker, Geoffrey. 1976. “The "Military Revolution," 1560-1660–a Myth?” *The Journal of Modern History* 48 (2). The University of Chicago Press: 196–214.

———. 1996. *The Military Revolution: Military Innovation and the Rise of the West, 1500-1800*. Cambridge University Press.

Postel, Rainer. 1996. “The Hanseatic League and its Decline.” Central Connecticut State University, New Britain, CT.

Powell, Robert. 1991. “Absolute and Relative Gains in International Relations Theory.” *The American Political Science Review*. JSTOR, 1303–20.

———. 1993. “Guns, Butter, and Anarchy.” *American Political Science Review*. JSTOR, 115–32.

Reyerson, Kathryn L. 1999. *Commerce and Communications*. na.

Spruyt, Hendrik. 1996. *The Sovereign State and Its Competitors: An Analysis of Systems Change*. Princeton University Press.

———. 2017. “War and State Formation: Amending the Bellicist Theory of State Making.” In *Does War Make States?: Investigations of Charles Tilly’s Historical Sociology*, 73–97. Cambridge University Press.

Stoob, Heinz. 1988. “Die Stadtbefestigung: Vergleichende überlegungen Zur Bürgerlichen Siedlungs- Und Baugeschichte, Besonders Den Frühen Neuzeit.” In *Städteforschung: Europäische Städte Im Zeitalter Des Barock*, edited by Kersten Krüger. Böhlau.

Thakur, Ramesh. 2016. *The United Nations, Peace and Security: From Collective Security to the Responsibility to Protect*. Cambridge University Press.

Tilly, Charles. 1975. *The Formation of National States in Western Europe*. Princeton University Press. https://books.google.com/books?id=0u0jAQAAIAAJ.

———. 1990. *Coercion, Capital, and European States, Ad 990–1990*. Cambridge, Mass., USA: Basil Blackwell.

Tracy, James D. 2000. "To Wall or Not to Wall: Evidence from Medieval Germany." In *City Walls: The Urban Enceinte in Global Perspective*, edited by James D. Tracy. Cambridge University Press.

Van Evera, Stephen. 1998. "Offense, Defense, and the Causes of War." *International Security* 22 (4). MIT Press: 5–43.

Van Liedekerke, Marc. 2008. "Map of Soil pH in Europe." *Hamburger Beiträge Zur Physischen Geographie Und Landschaftsökologie* 19. Universität Hamburg, Institut für Geographie.

Voigtländer, Nico, and Hans-Joachim Voth. 2013. "The Three Horsemen of Riches: Plague, War, and Urbanization in Early Modern Europe." *Review of Economic Studies* 80 (2). Oxford University Press: 774–811.

Williamson, Oliver E. 1979. "Transaction-Cost Economics: The Governance of Contractual Relations." *Journal of Law and Economics* 22 (2): 233–61.

Wolfe, Michael. 2000. "Walled Towns During the French Wars of Religion (1560-1630)." In *City Walls: The Urban Enceinte in Global Perspective*, edited by James D. Tracy. Cambridge University Press.

Conflict Technology As a Catalyst of State Formation
Online Appendix

Michael-David Mangini and Casey Petroff

January 2022

A Count of States Over Time

Abramson (2017) documents the declining physical size of polities, and increasing number of polities, in Europe between the medieval and early modern periods. This broad pattern masks both substantial regional variation and variation in the trends of state geography over time, which Abramson (2017) explores in depth.[1] Figure A1 shows the number of states (top) and the average size of a state (bottom) existing on the continental European landmass in five-year intervals.[2] The graphs show the fragmentation of Europe through the High Middle Ages (pre-1250) and the beginning of the Late Middle Ages before stabilizing in the 1260s before consolidating again after 1500. The timing of the reconsolidation of Europe corresponds to the invention of the *trace italienne* and its counterparts in Northern Europe.

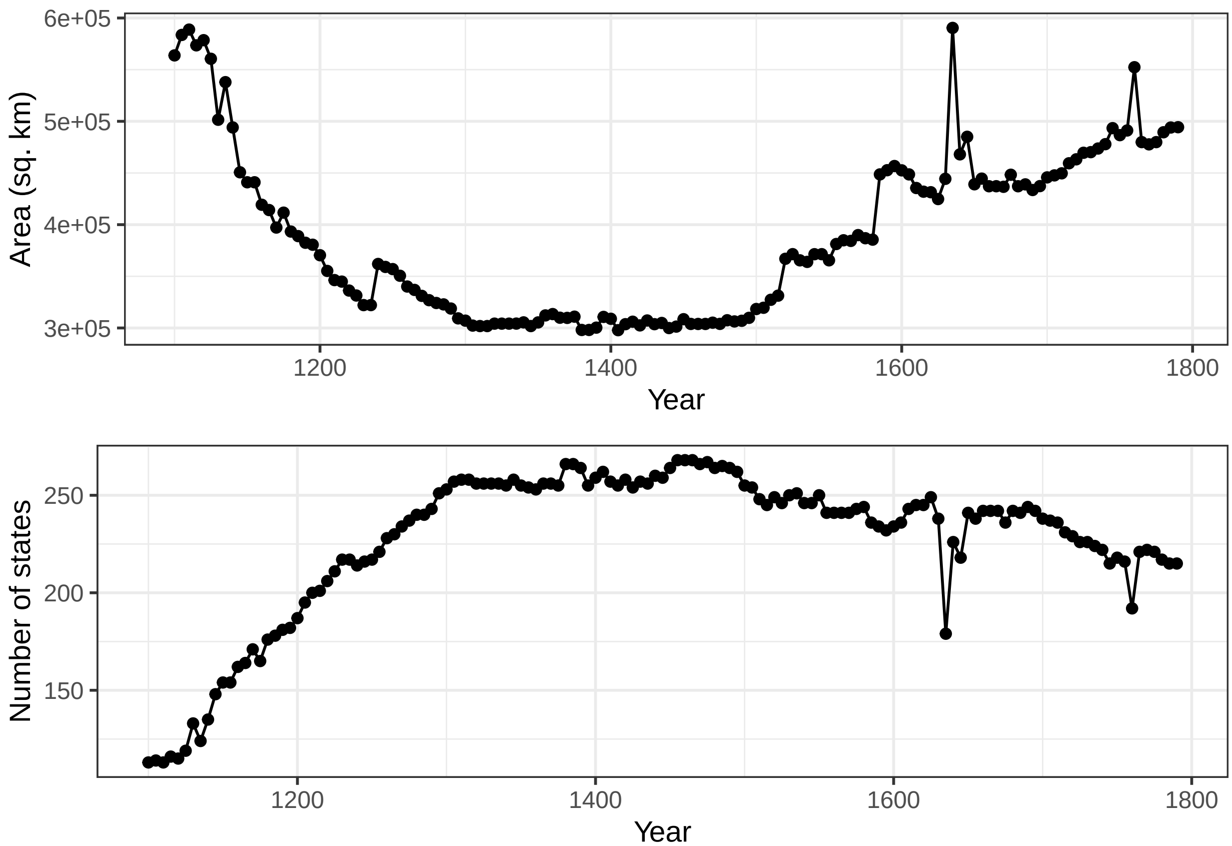

Figure A1

[1] We use the neutral noun "polity" to avoid conflating early medieval political units, which included city-states, feudal territories, and other entities, with modern nation-states.

[2] Territory held by Eurasian powers such as Russia on the Asian continent is excluded.

B Approaches to Spatial Analysis

The purposes of our analyses is to measure the spatial correlation, and to establish causality, between new offensive technology (artillery), new defensive technology (complex walls), and changes in political geography (for instance, the shifting of borders). This raises methodological questions about what units of analysis and measures of correlation are most appropriate. Other literature that examines the economic and political geography of the pre-modern world, for which data for clearly defined geographic units is unavailable, also faces this problem. One common solution (variations of which are used by Nunn and Puga (2012); Dincecco and Onorato (2016); and others) is to create arbitrary polygons by superimposing a grid onto the map and uses the resultant cells as units of analysis. In other analyses, we are interesting at comparing outcomes across individual cities. In this setting, we measure variables such as agricultural productivity and terrain ruggedness as average values over small polygons surrounding each city point feature. A key question raised by this approach is how to identify underlying clusters of city in the data in order to account for correlation of characteristics across neighboring cities. Since we are interested in examining the evolution of borders over time, we cannot cluster cities according to the state in which they lie. Instead, we use k-means clustering to identify natural groupings of cities according to their geographic proximity to one another. Formally, for each city, the k-mean assignment algorithm makes an initial, arbitrary assignment of each city $x^{(1)}, ..., x^{(m)}$ to a group characterized by one of k centroids (a cluster). Cities are then re-allocated to clusters such that

$$c^{(i)} := \arg\min_{j} ||x^{(i)} - \mu_j||^2 \tag{A1}$$

is minimized for each city i. Centroids are then re-calculated:

$$\mu_j := \frac{\sum_{i=1}^{m} 1\{c^{(i)} = j\} x^{(i)}}{\sum_{i=1}^{m} 1\{c^{(i)} = j\}} \tag{A2}$$

Convergence is reached when no improvement can be made to $c^{(i)}$ by re-allocating a city to a new cluster.

While this assignment process is dependent on the initial choice of the number of centroids and initial assignment of cities to clusters at the start of the algorithm, it has some attractive features. The resulting groups of cities are, conditional the initial assignment, are closer to the centroid of their group than they are to the centroids of other groups. This creates natural clusters of cities that, by reason of their relative proximity, are more likely to interact with one another than with other cities, and also takes into account parts map characterized by rough terrain or water features that block both the building of cities and the interaction of cities on either side of the feature, which then forms a natural border between clusters. (The grid-cell approach circumvents this problem with the assumption that each grid cell is a self-contained "cluster" with no spillover effects between neighboring cells.) We supplement with alternative robustness checks that calculate standard errors using the approach described in Conley (1999).

For the grid-cell approach, we use 0.5-by-0.5 degree square cells as the default unit of analysis, equivalent to roughly 55 square kilometers or 34 square miles, or approximately the amount of territory that could be covered on horseback within one day in the fourteenth century (Reyerson 1999). For the city-level approach, we use 400 clusters, a number chosen to roughly correspond to the number of states that existed in Europe in the the year 1200 (Abramson 2017).

For the panel of cities constructed for Section 5.3, we must match cities from one time period to another. This requires us to overcome some challenges stemming from the source data in Stoob

(1988), which is presented in its original form as a reprinted version of a physical map. Each city's new defensive construction is hand-stamped using a stamp of a different color and shape. This leads to noise in the geolocation process whenever stamps are slightly off-center from one another, introducing the risk of associating new construction to the wrong city if two cities are close to one another. We find that the distance between two cities is rarely smaller than 4 kilometers, and the distance between new build layers for each city is much smaller than that. We therefore create a panel dataset by overlaying a grid cell layer where each grid cell is 4 km^2. Each grid cell is a potential city site, and all new layers of wall construction falling within the grid cell polygon are assigned to one city.

C Agglomeration Measure Technical Details

We denote a substantial border change as one where a border moves at least X kilometers from its original location. For two maps dating from t_1 and t_2, we build X-km buffers around all national borders and then count a t_1 border as eliminated if its buffered region fails to intersect with any buffered border that exists in t_2. We simplify the resulting polylines and then measure the length of border eliminations per grid cell for the grid cell spatial approach; for the city-level spatial approach, we measure the distance from each city to the nearest border elimination. This outcome puts the focus not on individual expanding states *per se* but on regional trends in political change over time.

D Border-Centroid Measure Technical Details

To demonstrate that border-centroid ratios are not affected by the size of states, we simulate fields of randomly-placed points on polygons of different sizes. Figure A2 shows the distribution of border-centroid ratios of 10,000 points on polygons with radius 1, 10, and 100.

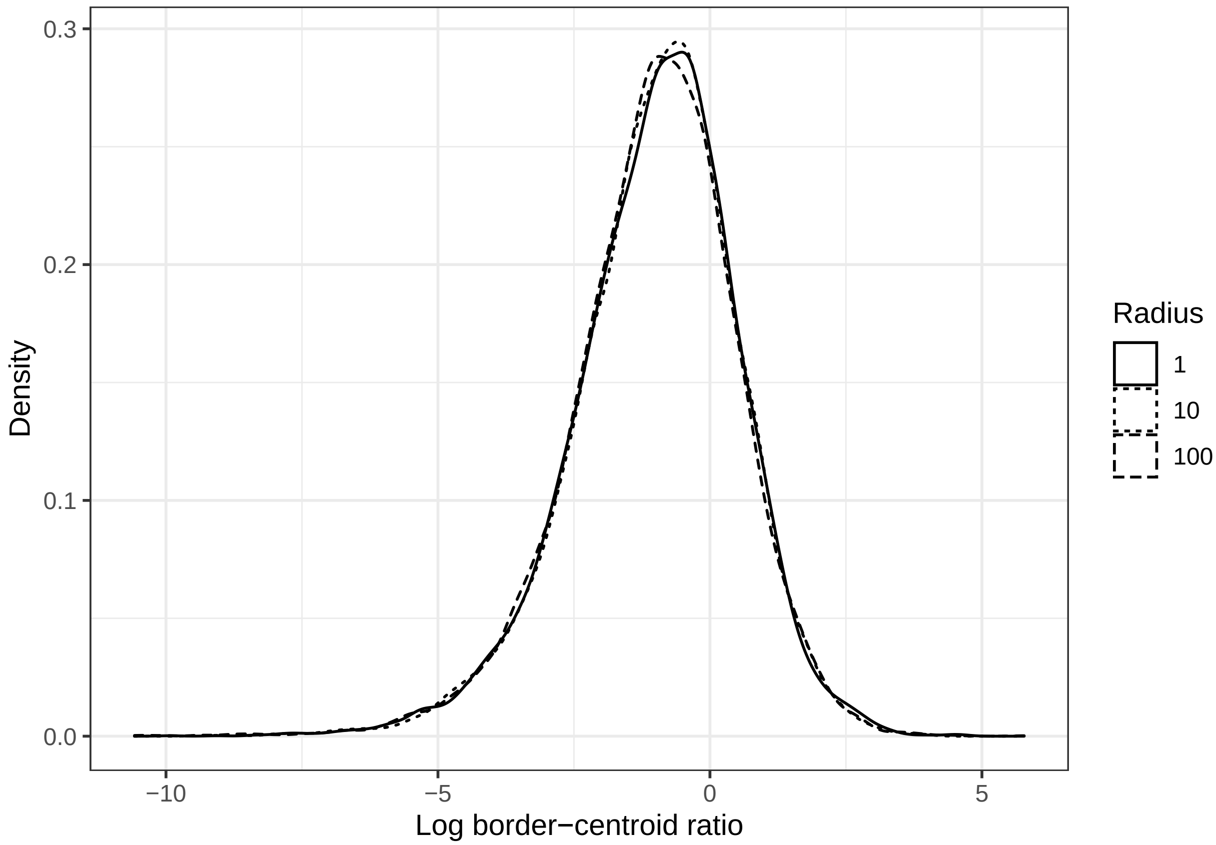

Figure A2: Border-centroid ratios of fields of simulated points on polygons of different size.

E Wall Construction by Type and Period

Table A1: Number of structures identified in Stoob 1988 by construction type and period. Many cities build multiple defensive structures over time.

Type	Pre-1190	1190-1250	1250-1450	Post-1450
Earthen	1463	0	0	0
Wooden	255	398	614	59
Stone	158	491	1982	122
Reinforced	3	104	450	76
Bulwarks	0	0	60	56
Bastions	0	0	5	377

F Gunmakers Over Time

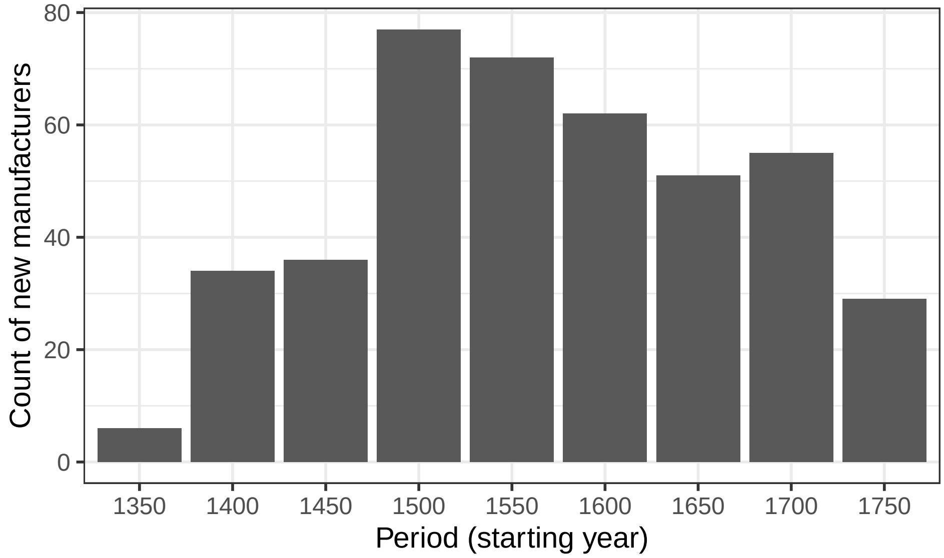

Figure A3: Number of unique artillery manufacturers by period of first known operation (Kennard 1986).

G Summary Statistics of Covariates

Table A2 shows city-level summary statistics (relevant for Sections 5.2 and 5.3) for the covariates discussed in Section 4.1.4. All distances are given in kilometers. The ruggedness index provided by Nunn and Puga (2012) is divided by 1000 for interpretability when reporting regression results. City-level measures for the ruggedness, agricultural productivity, and soil quality measures are constructed by taking the raster value at the point where a city is geolocated.

Table A2: Summary statistics of city-level covariates.

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Atlantic coastline	6,559	0.022	0.148	0	0	0	1
Distance to large river	6,559	54.361	45.523	0.008	16.370	81.764	218.548
Agricultural productivity	6,559	5,913.376	621.486	0	5,684	6,201	7,167
Distance to major Roman road	6,559	146.178	171.192	0.027	11.851	234.355	828.142
Soil quality index	6,559	5,894.224	616.954	0.000	5,682.500	6,192.000	7,048.250
Terrain ruggedness index	6,559	76.788	98.977	0.000	19.961	94.288	901.970
Distance to limestone deposit	6,559	32.514	56.224	0.000	1.311	37.919	411.365

H Additional Analyses and Robustness Checks

H.1 Border Disappearance

Figure A4 compares the point estimates and 95% confidence intervals for a naive linear regression of agglomeration and complex wall construction, a standard two-way fixed-effects specification that controls for grid cell and time period, and the de Chaisemartin-d'Haultfoeuille estimator. The regression shows a positive correlation consistent with the theory. However, this specification is vulnerable to a host of confounding variables. Perhaps the most serious confounder among these is the *initial* distribution of population and wealth: large, wealthy cities have the resources to construct sophisticated fortifications but are also more valuable targets for nascent states. (It is important to emphasize that we only consider the initial distribution as a possible confounder. Wealth and population are endogenous to security, so it would not be appropriate to include time varying measures as control variables because the regressions would be subject to post-treatment bias.) Even without precise measures of historical wealth and population it is possible to control for these unobserved time-invariant confounders when estimating the model by differences-in-differences (shown in the middle of the figure). The technique controls for time invariant confounders because all effects are found using within grid cell variation over time. Note that the de Chaisemartin-d'Haultfoeuille estimator is a different estimator than the classic two-way fixed-effects estimator and will thus not have the same point estimate.

Figure A5 shows a different visualization of the intuition conveyed in the other analyses. It compares the distribution of the log km of borders eliminated before vs. after 1450 in grid cells that did vs. did not eventually receive complex fortification investments. Before 1450, the outcomes for each type of cell was almost precisely the same; after 1450, grid cells with complex walls experienced significantly more major eliminations.

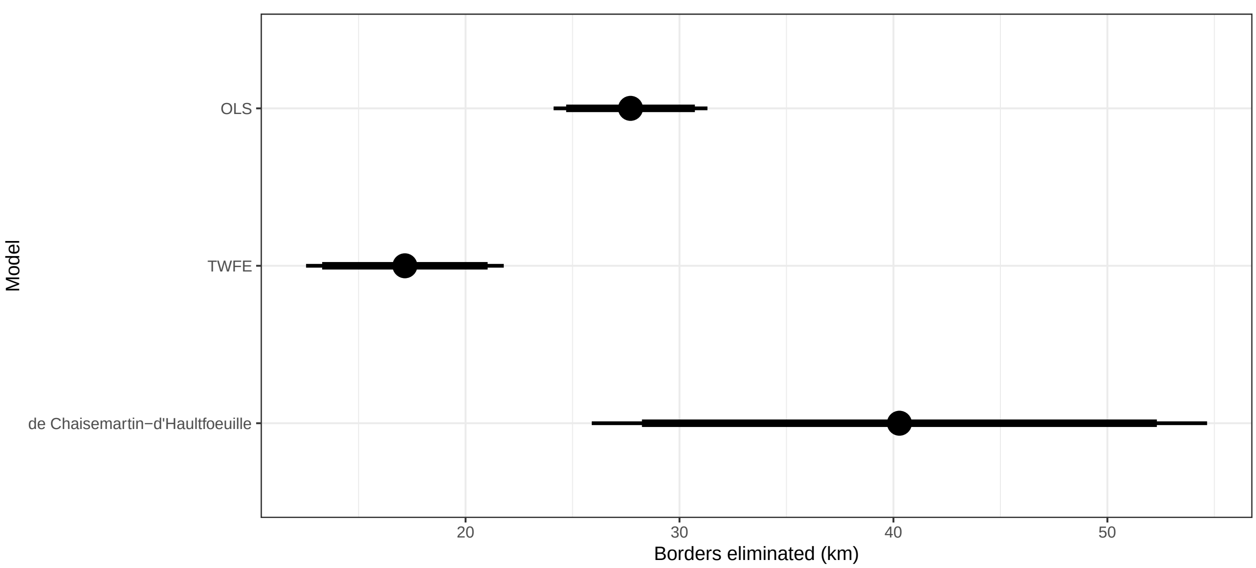

Figure A4

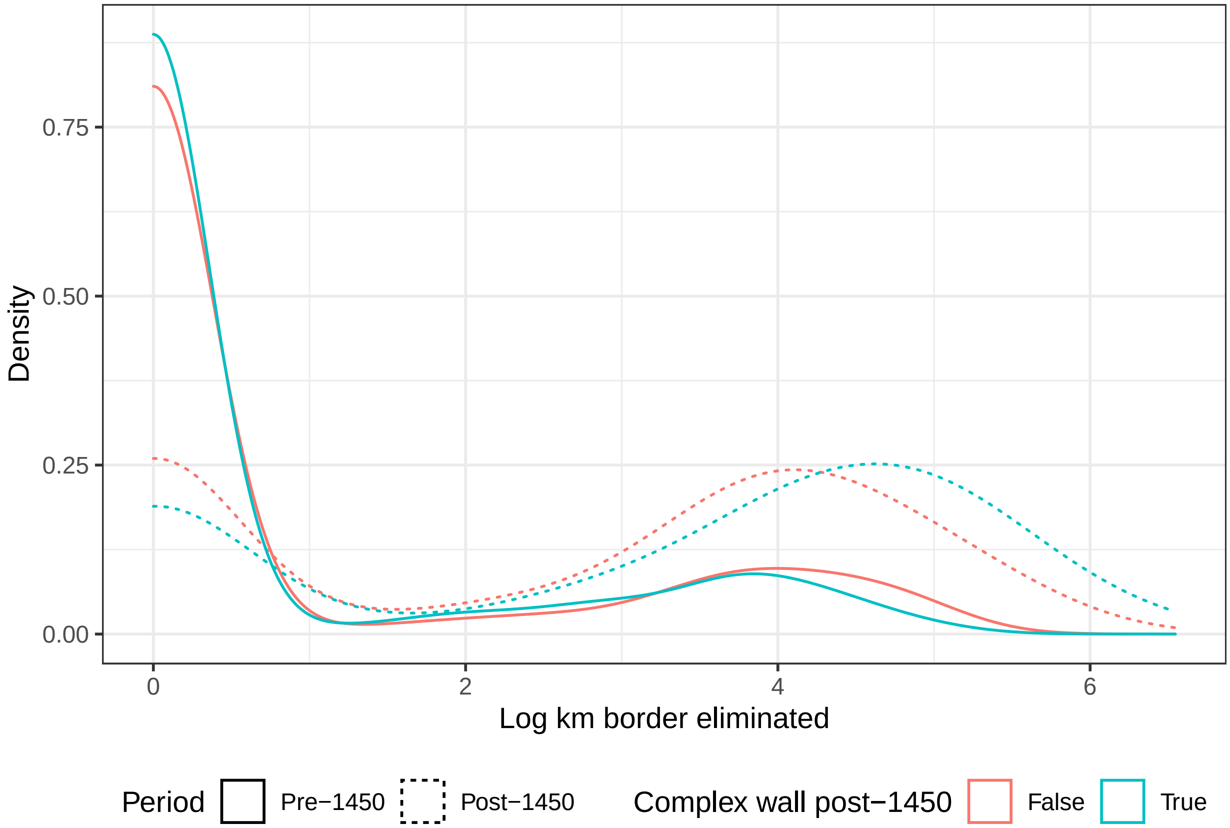

Figure A5

To ensure that the results from Section 5.1 are not an artifact of our arbitrarily chosen grid cell size, we provide robustness checks that vary the size of the cells. Figures A6 replicates Figure 4 using grid cells that are 0.25-by-0.25 degrees (or approximately 27.75 sq. mi.) and 1-by-1 degree (or approximately 111 sq. mi.).

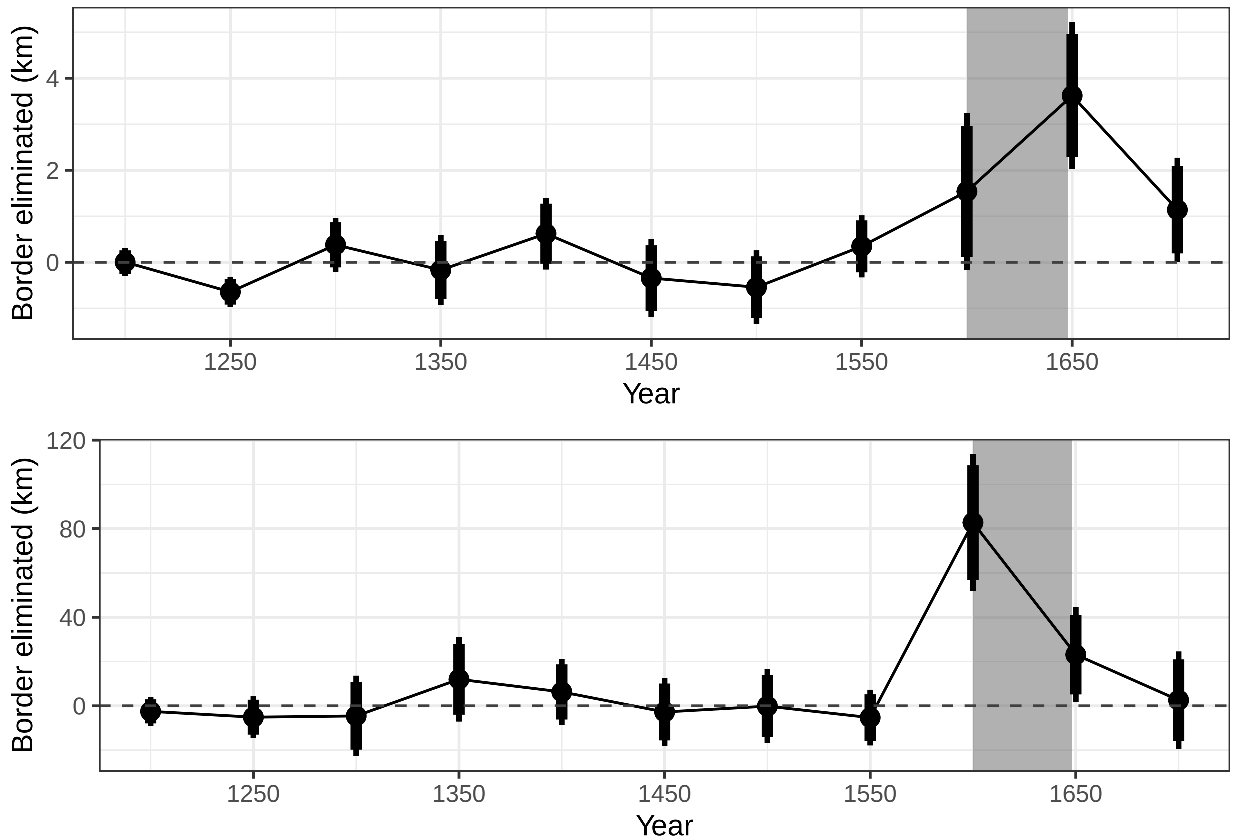

Figure A6: These figures replicate figure 4 using 0.25-by-0.25 (top) and 1-by-1 degree (bottom) grid cells.

H.2 Border-Centroid Ratios

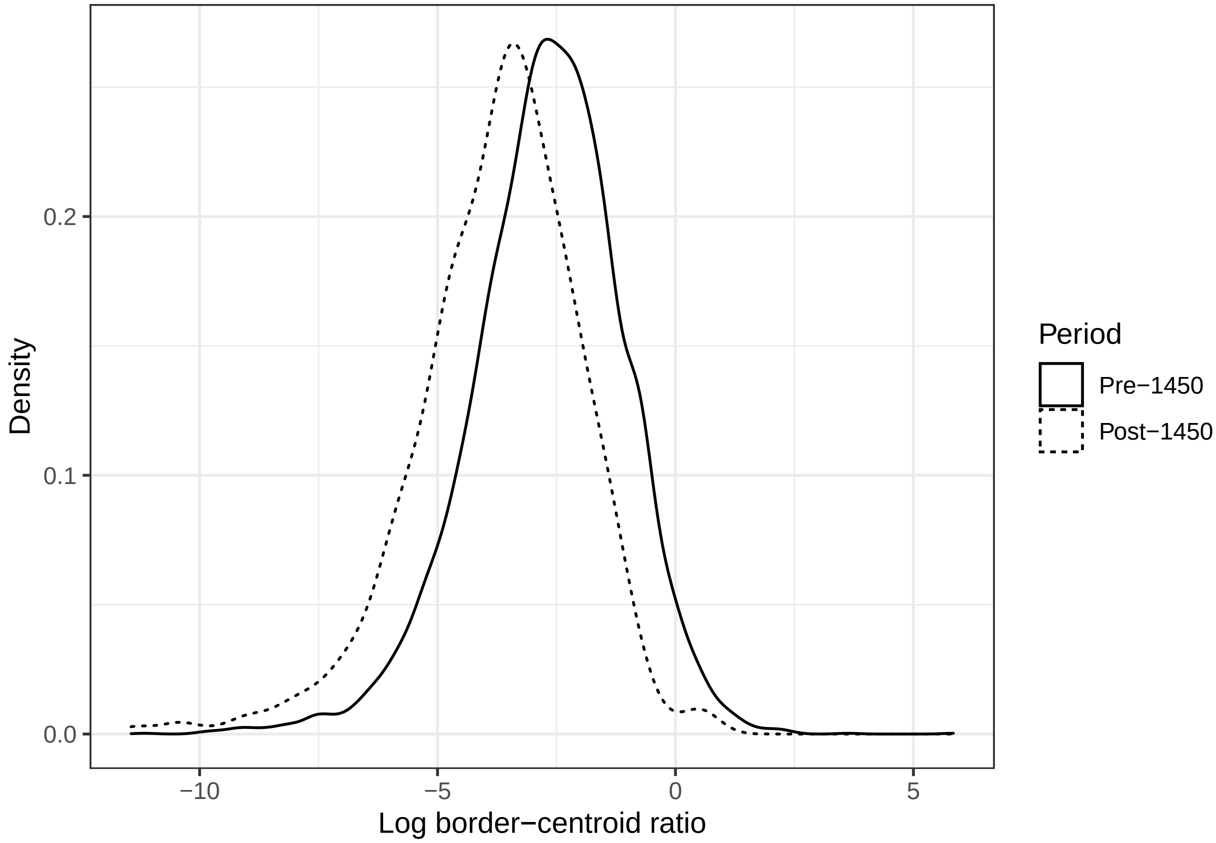

Figure A7: Density graphs of minimum log border centroid ratios pre- and post-1450 as described in Section 5.2.

Table A3: This table replicates Table 3 using Conley standard errors with a radius of 100 km.

	Dependent variable:								
	Log border-centroid ratio								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Post-1450 (v. pre-1450)	-1.041^{***}	-1.021^{***}	-1.032^{***}						
	(0.116)	(0.113)	(0.117)						
Complex post-1450 (v. simple post-1450)				-0.154	-0.269^{*}	-0.346^{**}			
				(0.156)	(0.154)	(0.141)			
Bastion post-1450 (v. bulwark post-1450)							-0.374^{*}	-0.363^{*}	-0.394^{**}
							(0.193)	(0.194)	(0.200)
Atlantic coastline			-0.594^{***}			-0.661^{**}			-0.772^{**}
			(0.195)			(0.310)			(0.321)
Log dist to river			-0.051			-0.120^{***}			-0.128^{**}
			(0.037)			(0.046)			(0.050)
Soil quality			-0.0001			0.0004			0.001
Ruggedness			-0.001			-0.002			0.0002
			(0.001)			(0.002)			(0.002)
Log dist. to Roman road			-0.047			0.119^{**}			0.089
			(0.043)			(0.056)			(0.060)
Lat-lon	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Observations	6,559	6,559	6,559	735	735	735	483	483	483
R^2	0.040	0.042	0.050	0.002	0.031	0.073	0.009	0.021	0.073
Adjusted R^2	0.040	0.042	0.049	0.0004	0.027	0.063	0.007	0.015	0.057
Residual Std. Error	1.611	1.609	1.603	1.725	1.702	1.670	1.696	1.690	1.653
F Statistic	272.607^{***}	96.414^{***}	43.479^{***}	1.326	7.785^{***}	7.195^{***}	4.227^{**}	3.369^{**}	4.633^{***}

Note: *p<0.1; **p<0.05; ***p<0.01

H.3 Spatial Patterns of Investment

Table A4: This table replicates Table 4 using Conley standard errors with a radius of 100 km.

	Dependent variable:		
	Log dist. to border eliminiation post-1450		
	(1)	(2)	(3)
Falls behind	0.100	0.040	0.079
	(0.148)	(0.127)	(0.128)
Catches up	−0.161	−0.136	-0.223^{**}
	(0.105)	(0.111)	(0.097)
Progressive development	−0.036	−0.041	−0.100
	(0.207)	(0.182)	(0.179)
Atlantic coastline			1.216^{***}
			(0.220)
Log dist. to river			−0.023
			(0.040)
Ag. prod.			−0.001
			(0.001)
Ruggedness			−0.071
			(0.055)
Log dist. to Roman road			-0.0003^{***}
			(0.0001)
Lat-lon	No	Yes	Yes
Observations	4,489	4,489	4,489
R^2	0.002	0.026	0.059
Adjusted R^2	0.001	0.025	0.057
Residual Std. Error	1.382	1.366	1.343
F Statistic	2.327^{*}	23.808^{***}	27.894^{***}
Note:			*p<0.1; **p<0.05; ***p<0.01

Table A5: This table replicates Table 5 using Conley standard errors with a radius of 100 km.

	Dependent variable:		
	Builds any stone-and-mortar wall		
	(1)	(2)	(3)
Log dist. to limestone	-0.007^{***}	-0.004^{**}	-0.004^{**}
	(0.002)	(0.002)	(0.001)
Post-1450	-0.315^{***}	-0.319^{***}	-0.321^{***}
	(0.024)	(0.024)	(0.024)
Log dist. to limestone x post-1450	0.007^{***}	0.006^{***}	0.006^{***}
	(0.002)	(0.002)	(0.002)
Atlantic coastline			0.028
			(0.046)
Log dist. to river			0.007
			(0.005)
Ag. prod.			0.00001
			(0.00001)
Ruggedness			-0.0002^{**}
			(0.0001)
Log dist. to Roman road			-0.021^{***}
			(0.007)
Soil quality			0.00005^{**}
			(0.00002)
Lat-lon	No	Yes	Yes
Observations	10,893	10,893	10,893
R^2	0.092	0.142	0.160
Adjusted R^2	0.092	0.142	0.159
Residual Std. Error	0.435	0.422	0.418
F Statistic	367.737^{***}	361.709^{***}	188.340^{***}
Note:			*p<0.1; **p<0.05; ***p<0.01