Conflict Technology as a Catalyst of State Formation

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Abstract

We argue that the gunpowder revolution in medieval Europe encouraged the amalgamation of smaller polities into larger centralized states. The advance in military technology made existing fortifications obsolete and substantially raised the cost of defensive investments. Small polities lacked the fiscal capacity to make these investments, so they had either to ally or merge with others. Alliances created prospects of free-riding by interior cities on border cities. In contrast, centralized, territorial states benefited from geographic and fiscal economies of scale, facilitating defensive investments at the border that protected the interior while limiting free-riding and resource misallocation. Using a new dataset on fortifications in more than 6,000 European cities, we find that states made defensive investments in areas of territorial contestation, closer to borders, and farther from raw building materials. These findings are consistent with our theory that large centralized states arose in part as a consequence of changes in military technology.

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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 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. Advances in artillery rendered nearly all of Europe's urban defensive fortifications obsolete. The same period also saw the upheaval and evolution of the European political system. When Constantinople fell, most states in Europe were either small, autonomous polities or large ones without centralized, differentiated, and autonomous structures (Tilly 1990). Modern Europe, however, is characterized by states that use consolidated political authority to collect taxes, make laws, monopolize violence within their borders, and conquer weaker polities. 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 usually not be managed by cities acting on their own. Cities whose defenses had been effective protection for centuries became vulnerable to cannon fire. All but the wealthiest cities required external financing to construct the massively expensive new fortifications that were needed to resist artillery fire. In principle, cities could have drawn on existing alliances, such as networks of feudal patronage or trade confederations, for mutual support and assistance. However, defense could be provided more effectively and efficiently by a perimeter of walled cities that could protect interior cities. In the absence of a state's authority, cities had strong incentives to hoard resources rather than contribute to collective security 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 urban defensive investment and the rise of modern states in Europe. We generate a new dataset on the construction timelines of urban fortifications for over $6,000$ European population centers in the medieval and early modern periods by geolocating data originally presented in 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). Our first test compares the spatial distribution of sophisticated urban fortifications with a measure of territorial consolidation. Consistent with our theory, we find that fortifications capable of resisting artillery were more likely to be constructed near borders, while the most defensive resources in the pre-gunpowder period were more evenly spread across the interior of polities. Second, we find that upgrades to counter artillery were concentrated in places where states consolidated authority over territory. Finally, we find that location-specific costs of construction, measured by proximity to geological deposits of limestone (a key input for large-scale construction that is exogenous to other political considerations), explains new wall construction before, but not after, gunpowder became militarily relevant. Cities that leapt from lagging in defensive investment to the technological frontier tended to be closer to areas of territorial consolidation. This is consistent with increased state support for defense, concentrated in areas where it is strategically useful, rather than defensive investment as a function of cost.

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 describe state

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

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 provide evidence that helps 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 significant 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 work 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.[2] Our study partially reconciles Abramson's critique with the bellicist theory by explaining why some cities could remain independent as small city-states even while other cities were forced to agglomerate into states through bellicist mechanisms. Any cities rich enough to upgrade their defensive technology without outside help could retain their sovereignty for longer. We argue that both the classical bellicist theory of state-building and Abramson's critique have merit; the applicability of each theory to any particular case depends on the means to build cutting-edge fortifications.[3]

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

[2]See Appendix Figure A1 on p. A2 for changes in the size and number of states in Europe over time.

[3]Other critiques of the bellicist theory outlined by Grzymala-Busse (2020) argue that some institutions of the state had antecedents before the early modern period. For a comparative institutional analysis, see Stasavage (2014), which argues that the institutions of autonomous cities were better-suited to the pre-modern era.

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 theory also demonstrates how the political economy of security cooperation relates to the process of state formation. 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 argue that the costs of cooperation determine whether security is provided by alliances or by extending the state's borders. Cities agglomerate into states when the technology of conflict necessitate collective investments in security that cannot be provided by alliances due to the difficulty of collective action. 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 further develops the literature 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 heterogeneous populations. Our contention is that economies of scale in the provision of a particular public good – collective security – encouraged states to consolidate political authority. Dincecco and Onorato (2016) shows that populations gravitated 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. We find that the strength and boundaries of national states depend on the costs to enforcing inter-polity cooperation.

[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.

Some literature has previously considered the relationship between the military revolution and 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) 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 the timing of this agglomeration was influenced by 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 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, Barbarossa 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 1525 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

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

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 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).

[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.

3 Theory of Agglomeration and the Technology of Conflict

3.1 Theoretical Contribution

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. The second advantage is that 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).

Fortified border cities were an effective defense. In other contexts, territorial states like the Chinese Ming dynasty and Roman Empire have favored continuous border walls to defend borders. However, a series of individually hardened cities along a border still provided military protection to the interior in the context of early modern European military tactics that could not be easily reoriented to avoid defended cities (Tracy 2000). Two major factors ensured that attackers would need to defeat walled cities at borders. First, conquering cities was often itself an objective of invading forces who wanted access to their tax bases and economic assets, or who needed to supply and compensate soldiers with the proceeds of pillaging. Fortifying border cities, therefore, forced invaders to expend extra effort and stretch their campaigns further in search of softer cities. Second, cities could also act as garrisons for a state's armies from which they could mobilize defenses and counteroffensives against threats.

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.

The second obstacle is that border cities might underinvest 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.

Finally, 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.[7]

To see the benefits of centralized states in action, consider a possible alternative cost-smoothing mechanism that failed to adequately address the security crisis in early modern

[7] 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.

Europe: the defensive league of cities. 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.

Crucially, our theory does not necessarily predict whether cities would resist or embrace agglomeration, and this question is beyond the scope of our research focus in this article. 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 were either unable or unwilling to join states would be conquered and incorporated into stronger 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.

3.2 Relation to Other Theories

Our theory can partially reconcile the findings of Abramson (2017) with the bellicist paradigm. Abramson argues that the bellicist theory implies small states should be among the first conquered during the state formation process. His work finds that larger states were actually more likely to be conquered than smaller states, apparently contradicting the bellicists. In particular, he finds that the distribution of economically valuable resources is a better predictor for state development. Our theory allows some cities to resist agglomeration if they had the resources to construct a *trace italienne* without external financing. The wealthiest city-states were in position to maintain their security without ceding their autonomy throughout the gunpowder revolution. Our theory also explains why some larger states struggled to survive. 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.

Classically, the relationship between conflict and state formation in Europe is studied as a feedback loop (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 benefited 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. Blockmans (1989) attributes the decline of city autonomy in the 16th century to economic stagnation caused by increased conflict making it harder for cities to bear the burden of defense. This theory is not inconsistent with ours, particularly in light of the work of Tilly and others on the cyclical nature of conflict and state formation.

Onorato, Scheve, and Stasavage (2014) examines a more general "military revolution" beginning around the 17th century that drastically changed how wars were fought, particularly in terms of the increased size of standing armies. Tilly (1990), Dincecco and Prado (2012), Cantoni, Mohr, and Weigand (2019), and Queralt (2019) have suggested that the need to field and finance a standing army was a particularly important reason why states developed fiscal capacity. A series of recent papers ties the emergence of modern states and their institutions to the fiscal requirements of the military revolution. These papers argue that elites could not afford to finance a standing army without access to credit, but creditors were hesitant to lend without protections against expropriation.[8] When additional military investment became necessary, elites voluntarily submitted to institutional controls on their power to expropriate so that the necessary financing could be secured (Dincecco, Cox, and Onorato 2020, 2022; Cox and Dincecco 2021). We restrict our attention exclusively to the role of artillery and the consequent changes in urban defensive requirements and do not explicitly incorporate fiscal capacity into our empirical analysis; however, our theoretical and analytical conclusions are compatible with the findings of this literature. The *trace italienne* was not effective without soldiers to garrison the city, so the need to construct the new fortification also created a demand for soldiers. Furthermore, the same soldiers that

[8] This logic was first articulated in the context of the Glorious Revolution by North and Weingast (1989) but has since been applied more widely. See also Brewer (2002); Drelichman and Voth (2014); Cox (2016); and Cox (2020).

can defend a city can also be used in offensive operations. Thus, the need to construct and support defensive fortifications may have contributed to the proliferation of standing armies in Europe during this time.

A complementary strain of literature focuses on the characteristics of early modern autonomous cities. Dincecco (2011) notes that modern states like France and Spain still struggled to develop efficient bureaucracies to collect and deploy taxes, while small self-governing polities could do so more efficiently. Stasavage (2014) attributes the decline of autonomous cities not to military obsolescence, since they had better access to credit on average than larger states, but rather to the eventual obsolescence of city institutions, particularly monopolistic guilds that became barriers to economic activity. This view, which complements Abramson (2017)'s work on the survival of small states, is also compatible with ours. Autonomous cities may have retained a financing advantage over large states but could not take advantage of geographic economies of scale to amortize the costs of defense over a larger area.[9]

4 Case Study: France

The case study of France's investments in urban defense provides intuitive evidence for the theory outlined in Section 3. Figure 1 compares the geographic distribution of cutting-edge defensive fortifications before vs. after gunpowder became militarily relevant. The top row shows new fortifications built in three different time periods alongside France's contemporaneous eastern border. The bottom row shows new fortifications built specifically with the intent of countering the new artillery threat alongside the evolution of France's post-medieval eastern border. Before the development of gunpowder, strong urban defenses were as likely to be located on France's interior as they were near the border. After gunpowder became a salient threat, necessitating new construction, that new construction was clustered near

[9] Bosker, Buringh, and Van Zanden (2013) points out that cities that were the capital cities of states typically experienced outsized growth relative, suggesting a complementarity between state and local governance.

France's expanding eastern border. These new investments were part of a comprehensive, centralized military plan executed by the engineer Vauban on behalf of King Louis XIV (J. D. G. G. Lepage 2009).

The example of France demonstrates that 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.[10] Walls required 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. Investments by occupiers and allies helped to keep fortifications current. 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. On the other hand, 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 Vauban's comprehensive plan of defenses along the new French border and upgraded yet again (J. D. G. G. Lepage 2009). The city of Dole was conquered by France while Spanish fortifications were literally under construction – not yet useful to the defender, but an investment on which the conqueror could build (Wolfe 2000).

Because of these diverse, complicated historical trajectories, and our data limitations, our following quantitative analyses do not differentiate between cities where locals initiated construction (perhaps at the expense of long-run fiscal and political stability, as in the case of Antwerp); cities where a single state initiated and completed the construction of a *trace italienne*; and cities where multiple states "collaborated" on construction. Instead, we our outcome captures only on whether a city ever successfully completed new construction of a

[10]Section 5.1.1 discusses our main data source, Stoob (1988), and its geographic and temporal limitations in detail. In particular, this source does not give the precise data in which city walls are constructed; we are limited to four categories that roughly correspond to the early (pre-1190), middle (1190-1250), and late (1250-1450) Middle Ages and the early modern period (post-1450).

trace italienne (or similar variants on the design) in response to the gunpowder threat.

5 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 new walls were constructed near the borders of states, where they were more strategically valuable for defense (Section 6.1). 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 first 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.

Second, we test whether localities that constructed walls in the post-gunpowder period were also places that saw the most political consolidation into states (Section 6.2). Our work introduces a 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.[11]

[11] We perform this analysis using a grid of 0.5×0.5 degree cells. See Section 5.1.2 for data construction details. Questions related to the precise timing of wall construction are additionally investigated in a case

Third, we test whether states were able to effectively redistribute resources for the purpose of coordinating defenses (Section 6.3). 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. Finally, we construct a panel dataset about historic defensive investments in each city over time. 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 cities that "caught up" to the technological frontier were located in places that experienced political consolidation.

5.1 Data

5.1.1 Technological Change

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 2 illustrates the spatial distribution of wall construction over time. Appendix Table A1 on p. A7 shows the number of walls by type and period.

Earthen fortifications were typically large defensive trenches dug around a town and only

study of France in Section 4.

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.[12]

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 4, it is usually unfeasible 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.

Our data covers Central Europe (the Holy Roman Empire) and adjacent portions of France and Eastern Europe. This limits our scope, precluding a comprehensive analysis of European state formation. For instance, we lack data on the western parts of France, all but the northernmost parts of the Italian peninsula, and the British Isles. However, we argue that our sample nevertheless contains sufficient useful variation in historical pre-conditions,

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

exposure to technological change, and political outcomes to shed meaningful light on our research question.

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 2 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.[13]

5.1.2 Outcomes

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 5.1.1). 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

[13] Appendix Figure A4 on p. A8 shows the number of new entrants into the European artillery industry by 50-year periods.

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.[14] 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.

To explore the relationship between the evolution of defensive technology and dynamic changes in the European political landscape, we need a measure that captures spatial variation associated with the rise of states and their conquest of weaker polities over time. To do so, we create a measurement based on the disappearance of political borders over time. Our reasoning for choosing this particular measurement is that states emerge as part of a competitive process by which smaller, weaker polities are absorbed into larger ones, or in which stronger states are able to conquer and absorb parts of weaker ones. Eventually, an equilibrium is reached in which strong states of roughly equal strength contest the same piece of territory but neither can definitively prevail, resulting in a draw (and the appearance of a stable border) or back-and-forth conquest and re-conquest of the same area). When a small polity is absorbed, it ceases to exist as an independent political entity and its border is dissolved, and when a strong polity conquers part (but not all) of an adjacent weaker one, it pushes its border into the territory of the loser, dissolving the old border. We operationalize this intuition as follows: we divide the sample space into grid cells and the length of borders eliminated across five-year periods in each cell is calculated.[15] From 1190-1450, the mean (median) amount of border eliminated in one grid cell is 49.16 km (41.86 km); for the post

[14] We demonstrate by simulation in Appendix D on p. A6.

[15] 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 on p. A3.

period, lasting from 1450 to 1790, the mean (median) is 87.08 km (66.06 km).

We focus on border disappearances as our measure rather than the creation of new borders (or the net difference between the two) because new borders are ambiguous: they might arise as part of the process of conquest, or they could result from the fragmentation of a previously coherent polity into multiple parts. We do not distinguish between borders that disappear because of conquest or the voluntary cessation of territory (for instance, via the formation of political unions or by transfer of territory due to marriage). The degree to which territorial changes were due to actual coercion vs. the implied threat of coercion (or non-coercive agglomeration) is outside of the scope of the present analysis, and we leave it to future work.

A heat map showing border changes is included in Figure 3 using the cells discussed in Appendix B on p. A3. Consistent with the literature, the map shows that states consolidated their territory much more aggressively after 1450.[16] 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 A2 on p. A5 shows an example of our methodology.

The use of the grid-cell approach to create arbitrary units of analysis has precedent for research questions in which states themselves are not an appropriate unit of analysis Abramson (2017). However, it is potentially sensitive to the modifiable areal unit problem, that is, results may be driven by the imposition of arbitrary geographic units. We therefore replicate relevant analyses using grid cells of larger and smaller sizes to confirm that our results are not spurious; see Appendix H.1.

[16] In particular, we can recreate figures similar to the key graphs of Abramson (2017) in our sample space. See Appendix Figure A1 on p. A2.

5.1.3 Geographic and Historical Covariates

Our analyses use a slate of control variables to account for geographic and historical preconditions 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).

6 Analysis

6.1 The Increasing Salience of National Borders

First, we address how defensive investments were distributed *within* polities 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. Figure 5 shows the distributions of the log border-centroid ratios of walls built before vs. after 1450 as described in Section 5.1.2. New defensive construction after 1450 is, on average, located nearer to polities' borders than to their centroids.

To adjust for potential observable confounding variables, 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 5.1.3. 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.[17]

To adjust standard errors for potential spatial correlation between nearby cities, we create artificial clusters of cities using Voronoi polygons and cluster standard errors at the polygon level. This flexible approach creates natural clusters that do not depend on an arbitrary distance cutoff, allowing us to adjust for potential correlation between further-apart cities in less densely populated regions of the map and *vice versa*. We discuss this approach further in Appendix B on p. A3 and replicate our analyses using Conley standard errors in Appendix H.2 on A13; results calculated using Conley standard errors are very similar to those calculated using Voronoi polygon clustering.

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

[17] We use the log of the border-centroid ratios because the distribution of border centroid ratios are log-normally distributed (see Appendix Table 5 on p. 44). Log-normal distributions are common in studies of economic geography; for instance, see Gabaix (1999) and Dittmar (2009).

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

6.2 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. Our next analysis demonstrates the corresponding link between defensive investment and agglomeration. We compare the amount of agglomeration (as defined in Section 5.1.2) in areas that did vs. did not eventually receive a *trace italienne.* There is no difference before 1600, but after 1600, areas that did receive the investment of at least one complex wall experience substantially more agglomeration.

This exercise departs somewhat from the classic difference-in-differences framework, in which treatment vs. control groups are compared before vs. after the treatment is assigned. As we discuss in our historical background and in the case study of France, there is no discrete artillery "treatment" that Europe received at a single point in time, and enacting a response of defensive investment was not an instantaneous decision. Instead, we are comparing the degree of territorial agglomeration in places where complex walls were built to establish that defensive were not simply built in areas that were historically prone to shifting borders; rather, they were built in places where polities were consolidating and contesting territory as modern states emerged.

We examine dynamic relationships between wall construction and agglomeration using a difference-in-differences estimator suggested by De Chaisemartin and d'Haultfoeuille (2020). For each cell i in fifty-year period t, we estimate the difference in summed border length eliminated in i during t as the weighted average difference-in-differences, which can be written as

$$DID_M = \sum_{t=2}^{T} (\frac{N_{1,0,t}}{N_S} DID_t) \tag{2}$$

where DID_t is defined as

$$DID_t = \sum_{g:D_{g,t}=1, D_{g,t-1}=0} \frac{N_{g,t}}{N_{1,0,t}} (Y_{g,t} - Y_{g,t-1}) - \sum_{g:D_{g,t}=0, D_{g,t-1}=0} \frac{N_{g,t}}{N_{0,0,t}} (Y_{g,t} - Y_{g,t-1})$$

and DID_M is the point estimate that measures the difference in summed border elimination in kilometers between cells containing at least one complex wall and those containing none; t indexes the period of observation; g indexes group (cells that did vs. did not build a complex wall post-1450); $N_{1,0,t}$ ($N_{0,0,t}$) is the number of cells that built (did not build) a complex wall post-1450 observed in period t; N_S is the total number of cells; and $Y_{g,t}$ and $Y_{g,t-1}$ are the sums of border length eliminated in group g periods t and $t-1$, respectively. This estimator, which we implement dynamically at fifty-year intervals, improves on other approaches to estimating a difference-in-differences model in the presence of heterogeneous effects, which can potentially assign negative weights to some observations when calculating the average treatment effect (ATE) in a standard difference-in-differences analysis.[18]

Figure 4 shows no evidence of any such relationship before the gunpowder era. In every fifty-year period before 1450, grid cells that eventually contain a complex wall experience roughly the same amount of agglomeration as those that never do. Before 1600, there is similarly little difference, but afterwards, there is a clear relationship between the elimination

[18] This could potentially lead 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 difference-in-differences specifications are available in Appendix H.1 on A10.

of national borders and the construction of walls that could withstand modern artillery.[19]

The onset of the observed effects during a period covering 1618 to 1648 suggests the importance of the Thirty Years' War to the agglomeration process although the significant, positive effect persists beyond the period of the war itself. As discussed in the historical background, the introduction of artillery occurred earlier and the *trace italienne* was developed by 1525. The lag between the maturation of the offensive and defensive technologies and the association between defensive investment and political agglomeration suggests that the mere existence of gunpowder was not sufficient to stimulate political consolidation; rather, what was important was how it changed the optimal defensive response to warfare. 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.

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).[20] 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 complements to fortifications. The star shape

[19] Appendix Section H.1 on p. A10 provides supplementary, qualitatively similar results for this exercise varying the size of grid cells to address concerns about the robustness of standard errors.

[20] 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.

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.[21] 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.[22]

6.3 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. 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 and local rulers were responsible for funding their own defense, cities located near building materials were

[21] 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.

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

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 that the link between proximity to building materials and wall construction should weaken after the gunpowder revolution.

Limestone was a premium 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) (Jean-Denis G. G. Lepage 2015, 134). While brick could be used when quarried stone was unavailable, 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. Archaeological studies of typical walled cities used limestone quarried from local areas (Kristin and Carl 2014; Steineke and Jensen 2017), and transportation of raw materials was a major component of construction costs of fortified structures (Meyer 2011). 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 5.1.3) as well as a measure of soil quality.[23] We run the following OLS regression specification:

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

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

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

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.

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:

$$\text{Border Change Distance} = \alpha + \text{pathway}\beta + \mathbf{X}\gamma + \varepsilon \tag{4}$$

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.[24]

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 4. As cities receive those investments they construct stronger defenses.

[24]The pathways "Progressive Development", "Catches Up", and "Falls Off" are represented in pathway. The residual category "Other" is the omitted category.

7 Conclusions

The central contention of our work is that the gunpowder revolution created a collective security crisis that most 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 and construction dates of urban fortifications, fine-grained data on border changes of territorial political entities, and the locations of artillery manufacturers. 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. 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 frequent 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. Proximity to raw materials mattered less to whether a city built permanent defensive infrastructure post-1450, when states could redistribute resources to key locations, and cities that suddenly leapt to the front of the defensive technological frontier were closer to sites of agglomeration.

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 therefore do not have the kind of positive externalities in growth and development that we observe in Europe. Gunpowder, which raised the returns to economies of scale in defense, made the relationship between conflict and political development in late medieval and early modern Europe a positive feedback cycle.

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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

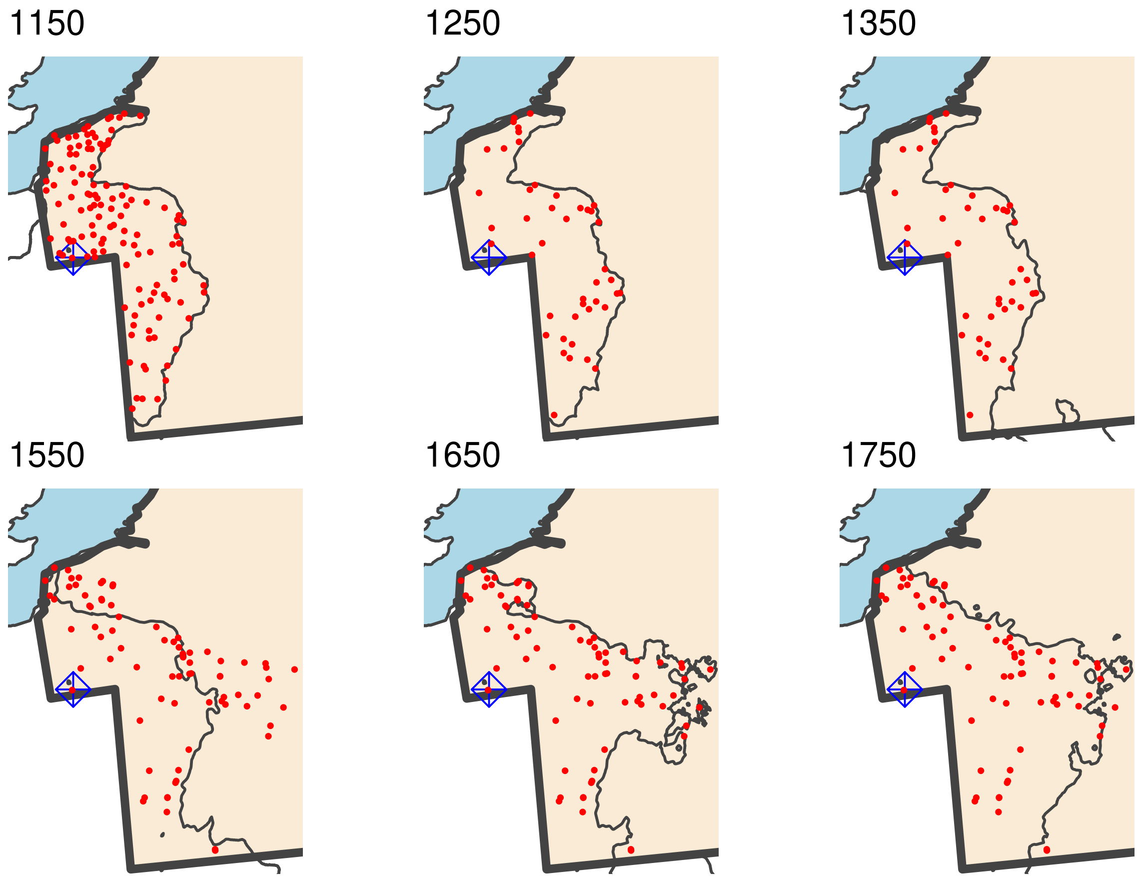

Figure 1: These maps show the shift of new wall construction from the interior of France to the border after the development of gunpowder for areas in which data is available (denoted by a thick grey line). The top row shows new wall construction (red points) juxtaposed with contemporaneous borders (thin black lines; dates are approximate due to data limitations on the dates of wall construction). The blue diamond shows the location of Paris. We show only walls that are militarily advanced for their time period (stone and reinforced pre-1450 and bulwarks and bastions post-1450). From left to right, the top row of maps show pre-1190 construction alongside 1150 borders; 1190-1250 construction alongside 1250 borders; and 1250-1450 construction alongside 1350 borders. The bottom row shows borders as they stood in 1550, 1650, and 1750, juxtaposed with all post-1450 wall construction. We omit 1450 due to the small number of complex walls that were likely completed by that date. Before the gunpowder era, walls are likely to be built relatively far from the borders of France. Afterwards, they are more concentrated near France's expanding border.

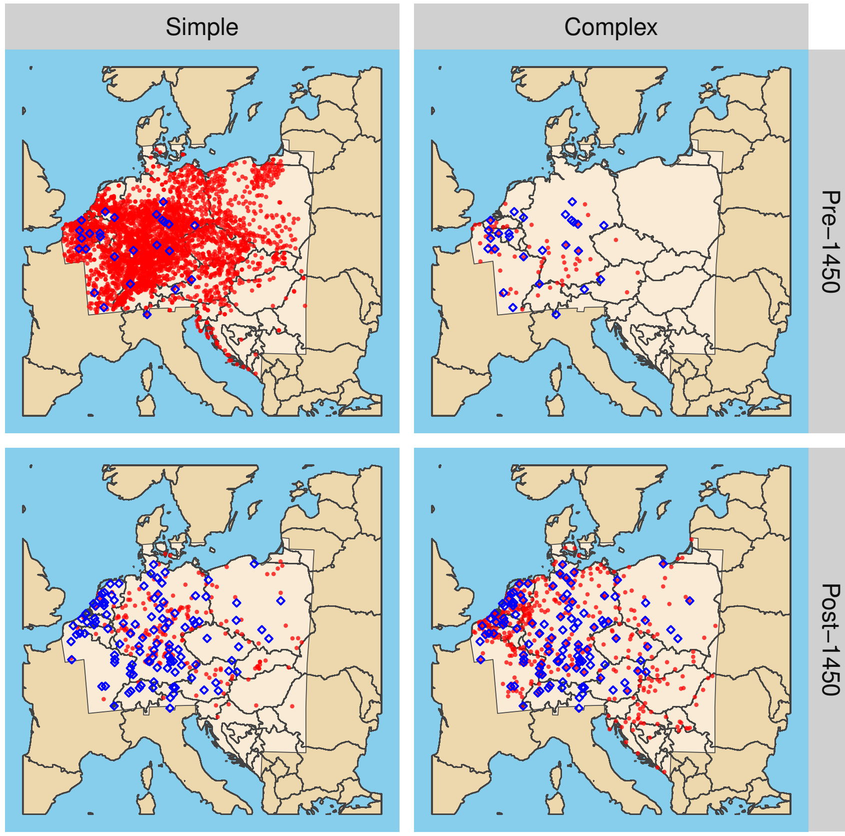

Figure 2: Each small point represents new simple (stone or reinforced) and complex (bulwarks and bastions) wall construction in that period for the specified wall type. Definitions for each construction type can be found in the text. While Stoob (1988) originally reported the data in four periods (pre-1190, 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 larger diamond represents the location of a gunmaker (Kennard 1986). The light-colored area represents the part of the map for which fortification data is available. Modern borders are shown for reference.

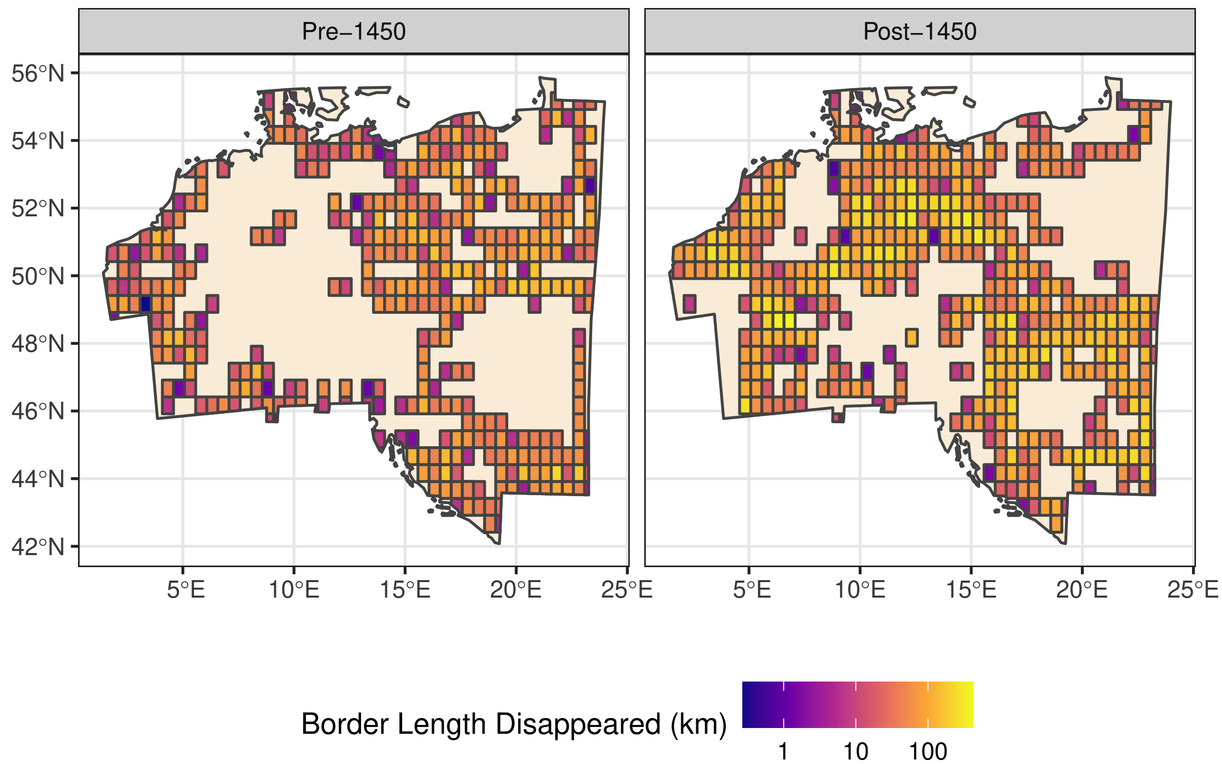

Figure 3: Heatmaps of border changes. The scale corresponds to the summed length of smoothed border that disappears within each cell.

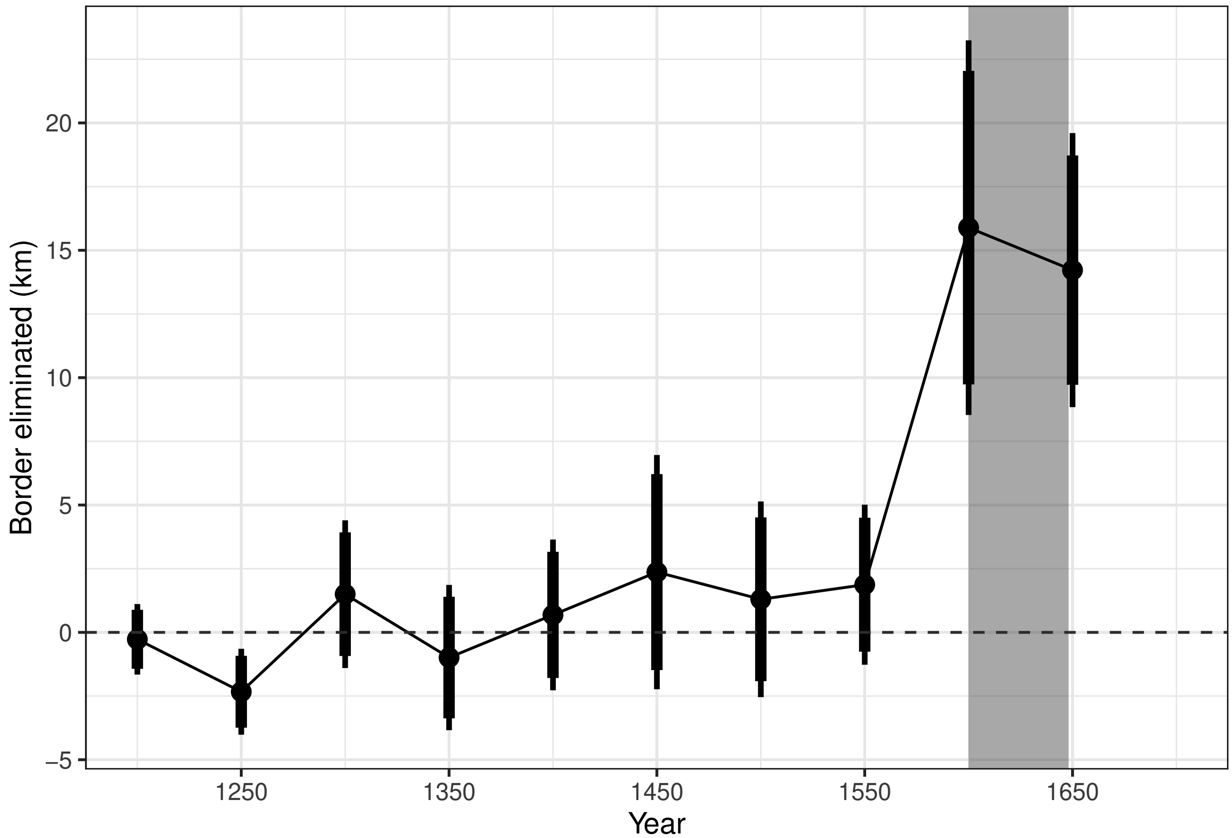

Figure 4: The dynamic relationship between complex wall construction and agglomeration at the grid cell level. Agglomeration is measured by meters of border eliminated from the grid cell. Complex walls include points marked as either bastions or bulwarks in Stoob (1988). The placebo tests show that grid 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).

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		

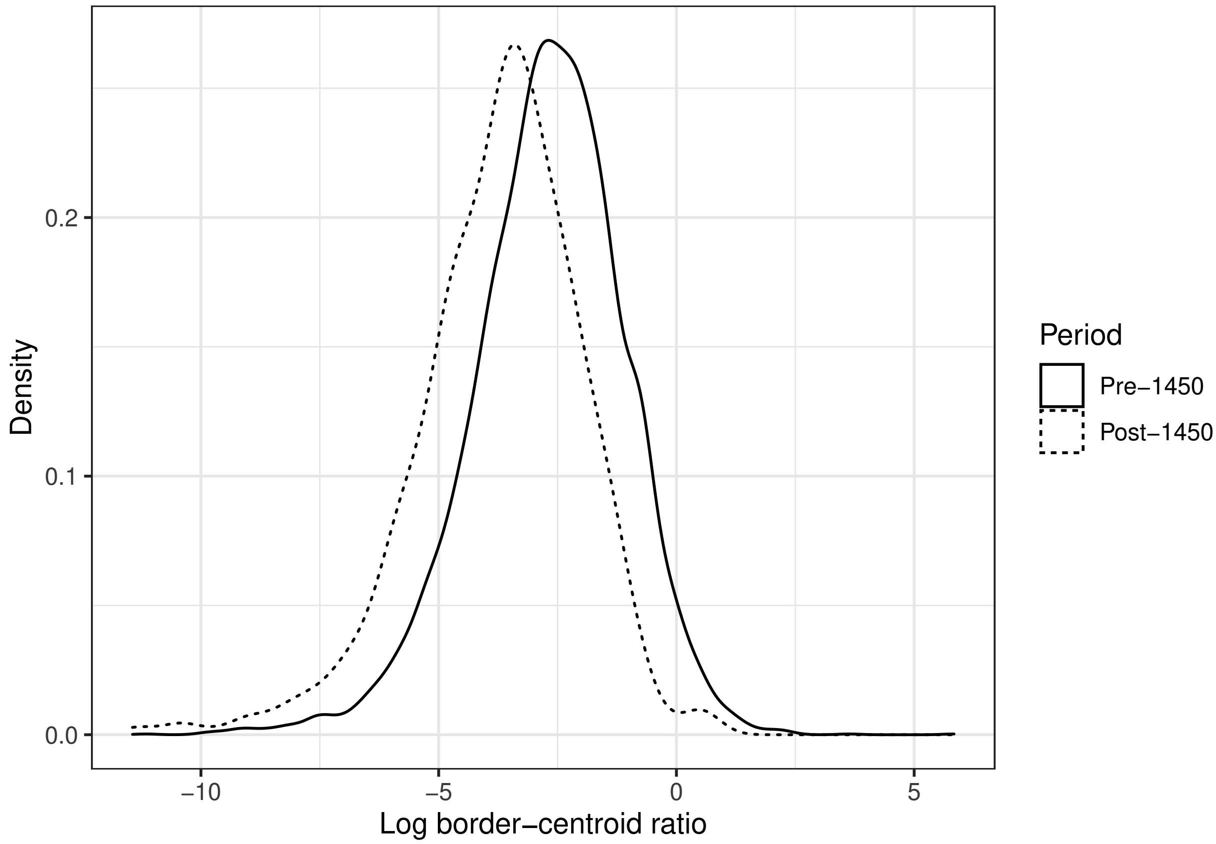

Figure 5: Density graphs of minimum log border-centroid ratios pre- and post-1450.

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 on p. A3. Appendix Table A3 on p. A13 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

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 on p. A3. Appendix Table A4 on p. A14 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	−0.085	0.072	0.105
	(0.125)	(0.120)	(0.112)
Catches up	−0.286**	−0.165	−0.246**
	(0.116)	(0.120)	(0.110)
Progressive development	−0.245	−0.068	−0.114
	(0.203)	(0.187)	(0.180)
Atlantic coastline			1.049***
			(0.164)
Log dist. to river			−0.069*
			(0.041)
Ag. prod.			−0.0005
			(0.001)
Ruggedness			−0.045
			(0.041)
Log dist. to Roman road			−0.0002***
			(0.0001)
Lat-lon	No	Yes	Yes
Observations	4,489	4,489	4,489
R^2	0.004	0.032	0.059
Adjusted R^2	0.003	0.031	0.057
Residual Std. Error	1.421	1.401	1.382
F Statistic	5.468***	29.919***	28.058***
Note:			*p<0.1; **p<0.05; ***p<0.01

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 on p. A3. Appendix Table A5 on p. A15 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
			(0.038)
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

Conflict Technology As a Catalyst of State Formation
Online Appendix

Michael-David Mangini and Casey Petroff

September 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. The large spike in the 17th century corresponds to instability caused by the Thirty Years' War.

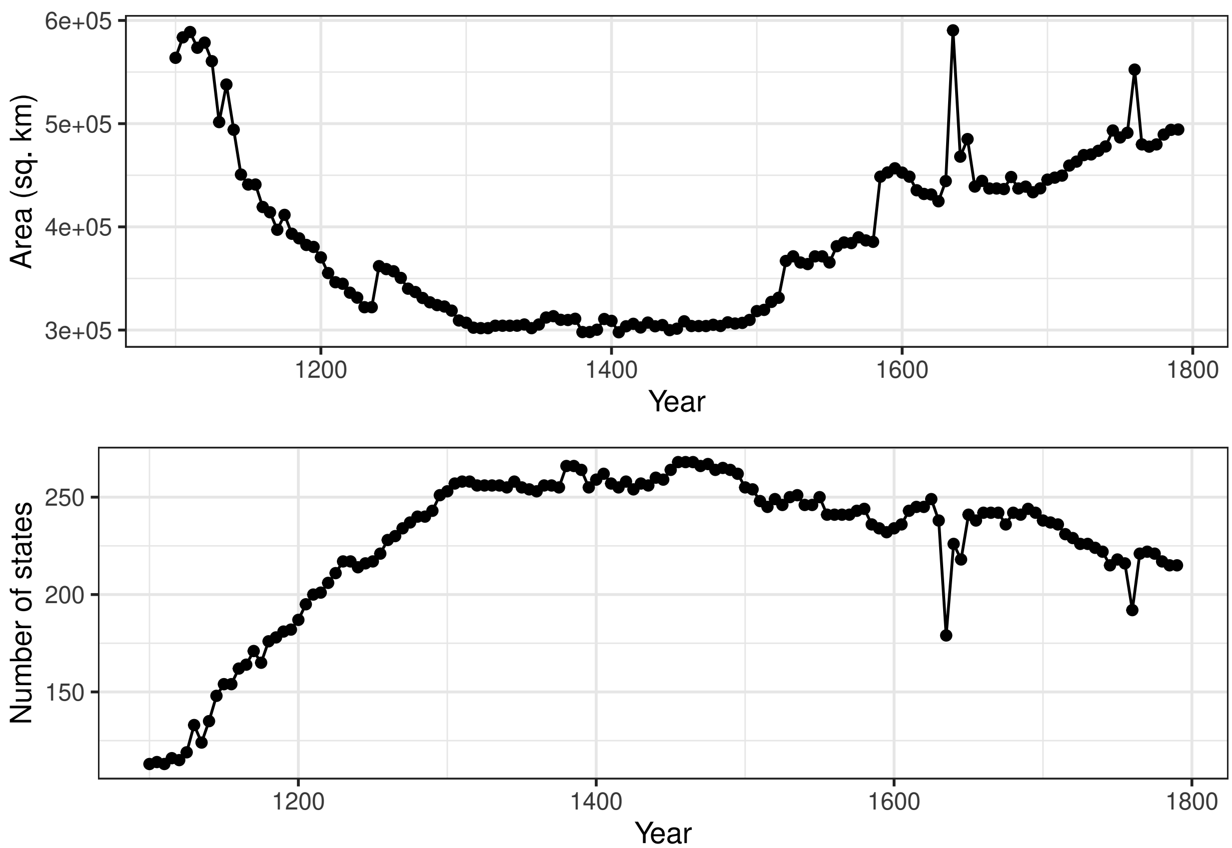

Figure A1

[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 6.3, 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. Figure A2 shows an example of our measure 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.

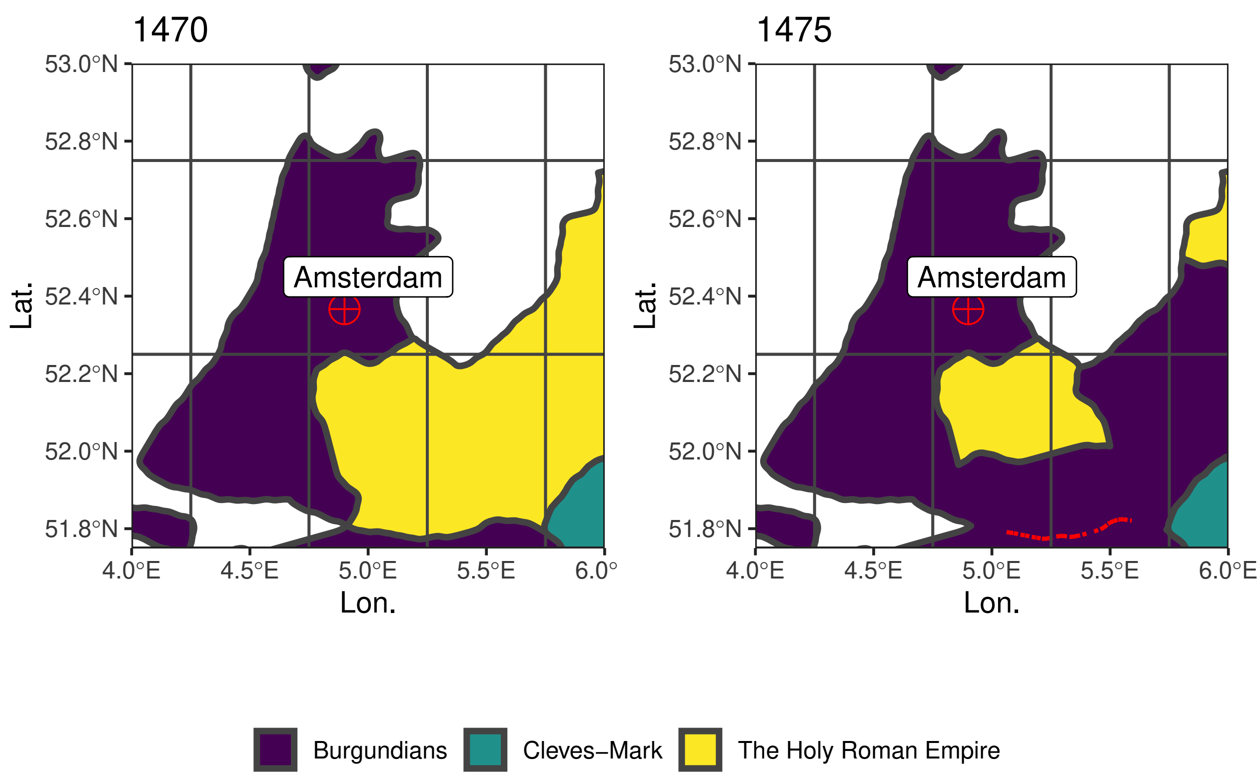

Figure A2: This example shows an example of our border elimination measure. The left-hand figure shows borders around the city of Amsterdam as they stood in 1470. The right-hand figure shows borders five years later, in 1475. The red line in the bottom right-hand corner of 1475 image shows a border that 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.

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 A3 shows the distribution of border-centroid ratios of 10,000 points on polygons with radius 1, 10, and 100.

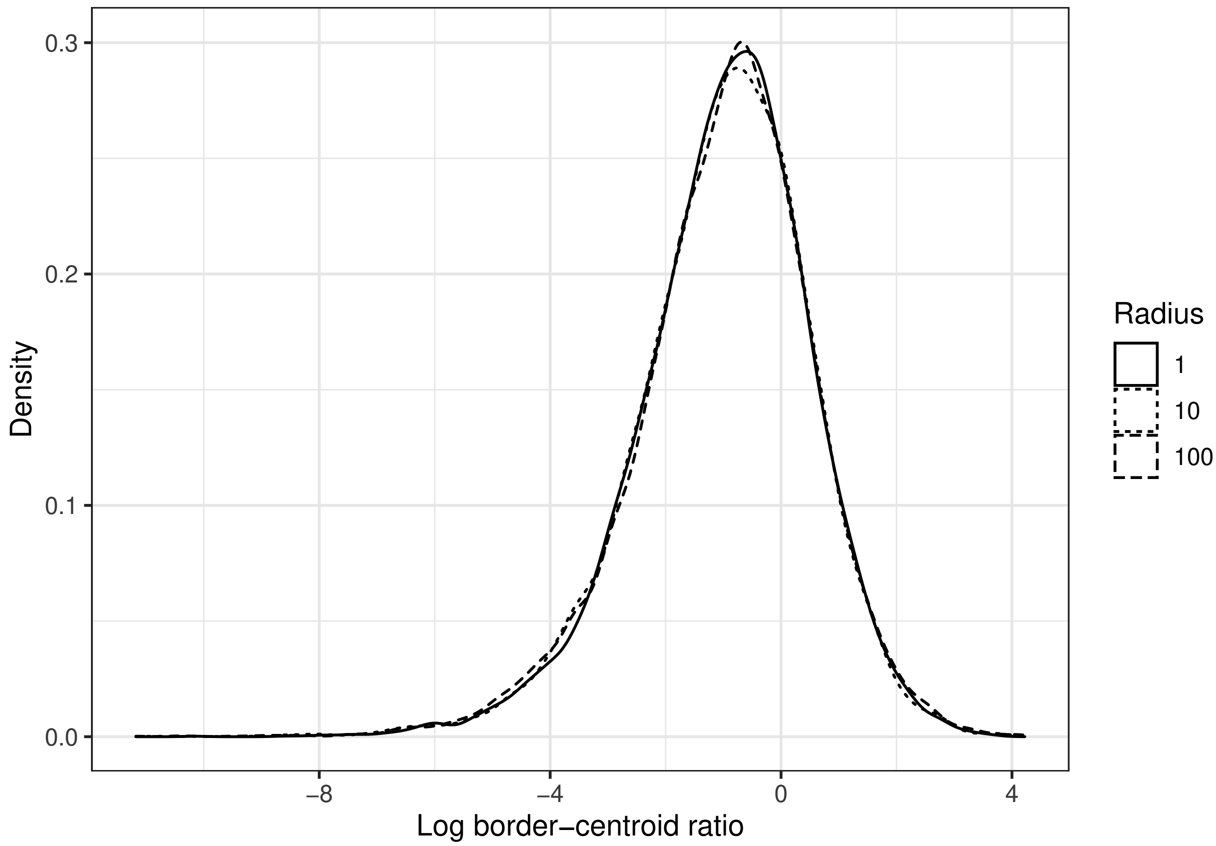

Figure A3: Border-centroid ratios of fields of simulated points on polygons of different size.

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

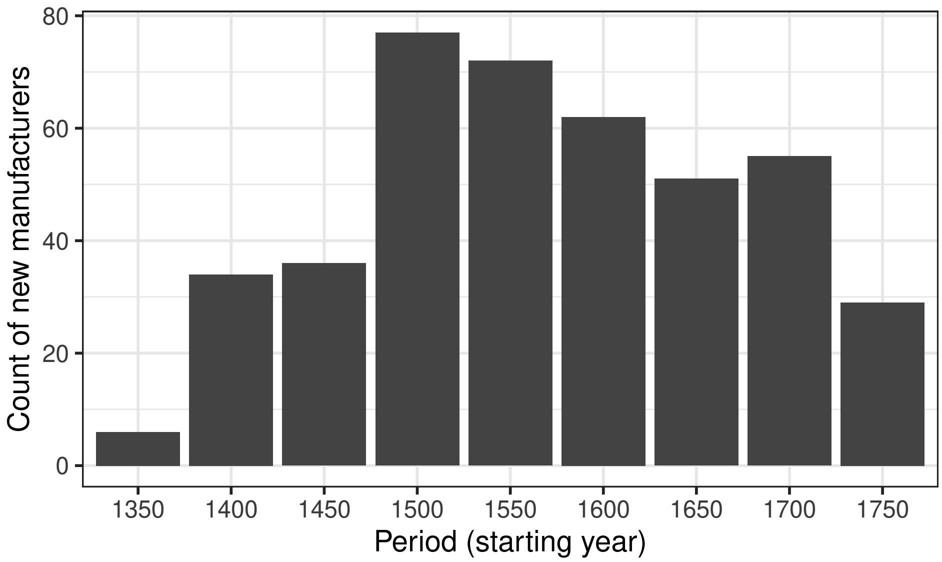

Figure A4: Number of unique artillery manufacturers by period of first known operation (Kennard 1986).

G Summary Statistics of Covariates

Table A2 shows city-level summary statistics (relevant for Sections 6.1 and 6.3) for the covariates discussed in Section 5.1.3. 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 A5 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 difference-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 A6 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.

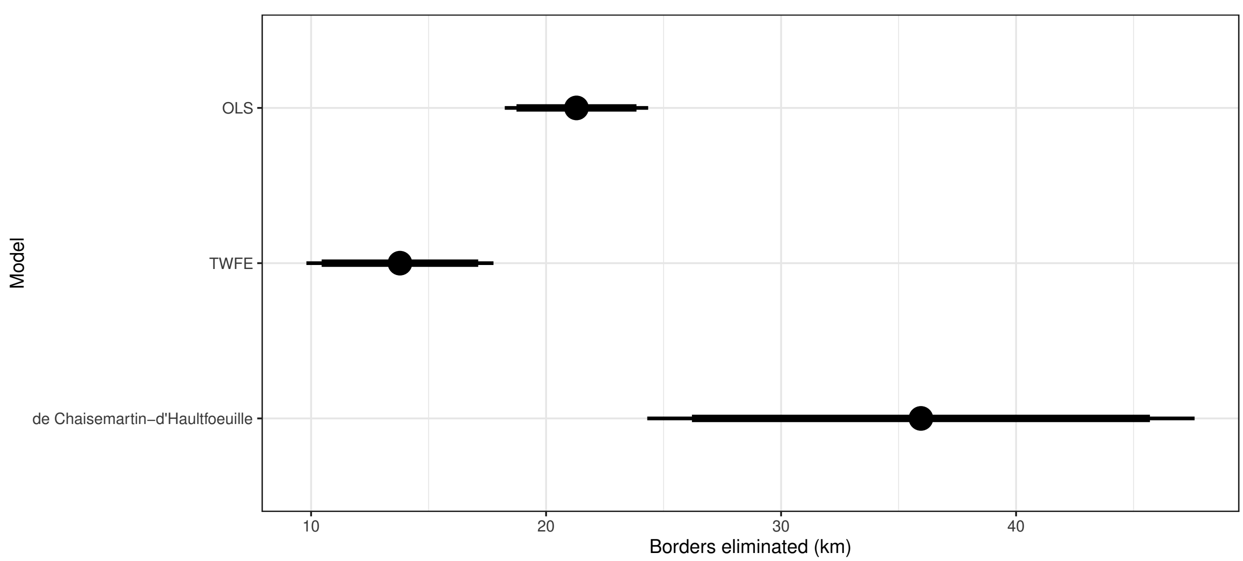

Figure A5

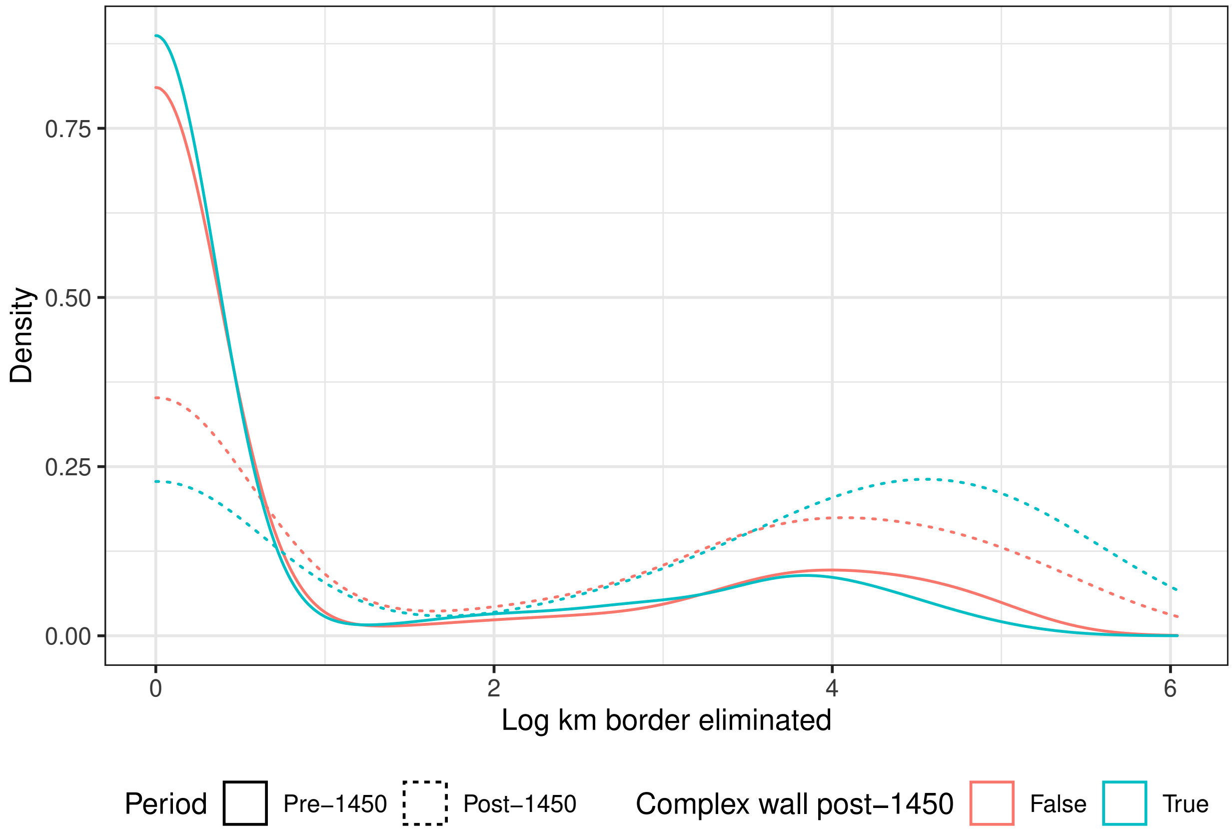

Figure A6

To ensure that the results from Section 6.2 are not an artifact of our arbitrarily chosen grid cell size, we provide robustness checks that vary the size of the cells. Figures A7 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.).

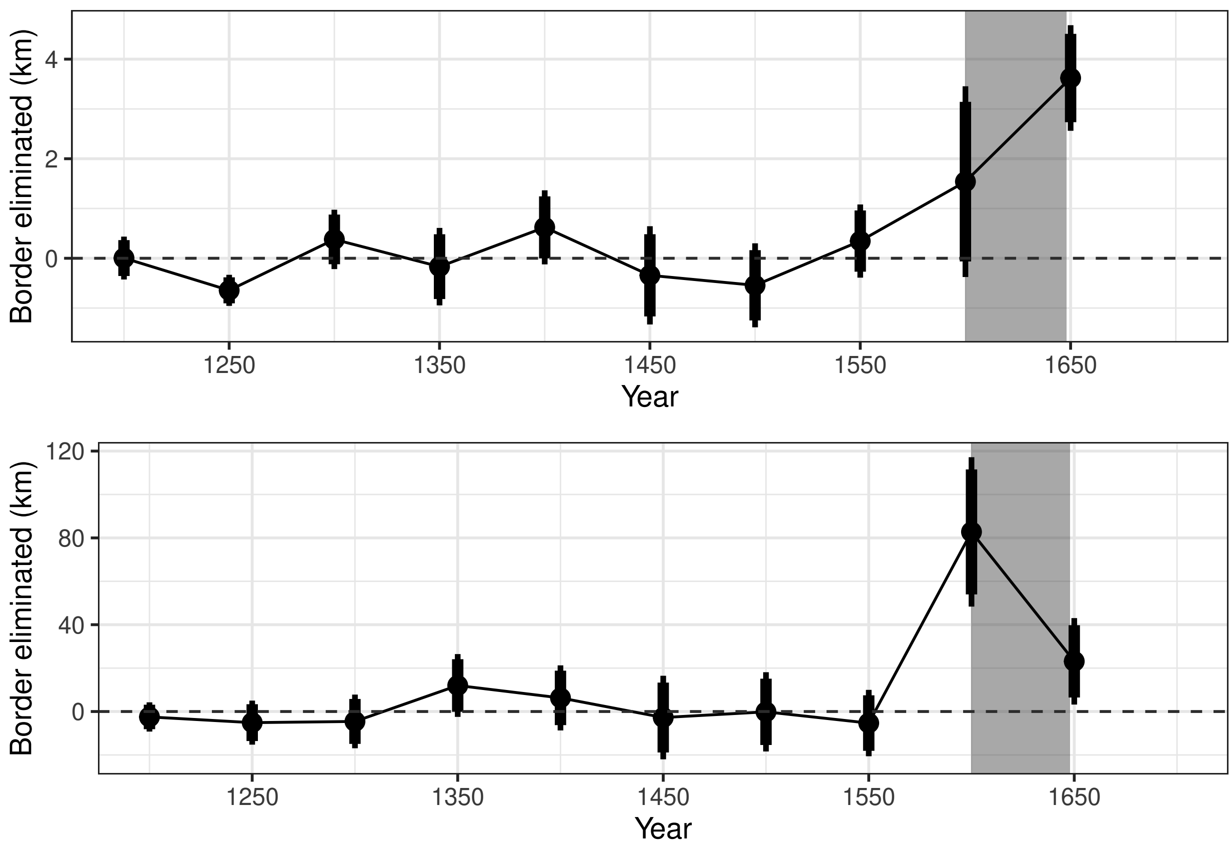

Figure A7: These figures replicate figure 4 using 0.25-by-0.25 (top) and 1-by-1 degree (bottom) grid cells.

H.2 Border-Centroid Ratios

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	−0.085	0.072	0.105
	(0.148)	(0.132)	(0.131)
Catches up	−0.286***	−0.165	−0.246**
	(0.110)	(0.115)	(0.099)
Progressive development	−0.245	−0.068	−0.114
	(0.211)	(0.183)	(0.176)
Atlantic coastline			1.049***
			(0.215)
Log dist. to river			−0.069
			(0.046)
Ag. prod.			−0.0005
			(0.001)
Ruggedness			−0.045
			(0.058)
Log dist. to Roman road			−0.0002***
			(0.0001)
Lat-lon	No	Yes	Yes
Observations	4,489	4,489	4,489
R^2	0.004	0.032	0.059
Adjusted R^2	0.003	0.031	0.057
Residual Std. Error	1.421	1.401	1.382
F Statistic	5.468***	29.919***	28.058***
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