The Fractured-Land Hypothesis

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November 30, 2022

Abstract

Patterns of state formation have crucial implications for comparative economic development. Diamond (1997) famously argued that "fractured land" was responsible for China's tendency toward political unification and Europe's protracted polycentrism. We build a dynamic model with granular geographical information in terms of topographical features and the location of productive agricultural land to quantitatively gauge the effects of fractured land on state formation in Eurasia. We find that topography alone is sufficient, but not necessary, to explain polycentrism in Europe and unification in China. Differences in land productivity, in particular the existence of a core region of high land productivity in northern China, also deliver the same result. We discuss how our results map into observed historical outcomes, assess how robust our findings are, and analyze the differences between theory and data in Africa and the Americas.

Keywords: China; Europe; Great Divergence; State Capacity; Political Fragmentation; Political Centralization

JEL Codes: H56; N40; P48

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Here begins our tale. The empire, long divided, must unite; long united, must divide. Thus it has ever been.

Romance of the Three Kingdoms, Chapter 1.

1 Introduction

The economic rise of western Europe is often attributed to its polycentric state system (Jones, 2003, Mokyr, 2016, and Scheidel, 2019). In this reading of the historical record, the European state system a) fostered intellectual pluralism, which made a competitive market for ideas possible (and, with it, the Scientific and Industrial Revolutions); and b) created incentives for institutional innovation and incremental investment in state capacity. Correspondingly, many explanations of China's failure to achieve sustained economic growth focus on its long history as a centralized empire and the barriers to riches that such centralization induced. But what factors account for the prevalence of political polycentrism in Europe and the prominence of political centralization in China?

Researchers have proposed numerous mechanisms for the divergence in state systems across the two extremes of Eurasia. A popular mechanism, made famous by Diamond (1997, 1998), argues that "fractured land" such as mountain barriers, dense forests, indented coastlines, and rugged terrain impeded the development of large empires in Europe in comparison to other parts of Eurasia.

The fractured-land hypothesis is not without its critics. Hoffman (2015) points out that China is, in fact, more mountainous than Europe. Peter Turchin and Tanner Greer have advanced similar arguments.[1] Turchin goes so far as to claim that it is not Europe's fragmentation that needs explanation, but China's precocious and persistent unification. The fractured-land hypothesis has also been challenged for being static and overly deterministic. Hui (2005, p. 1) contests the idea that China was "destined to have authoritarian rule under a unified empire," while contending that Europe's political fragmentation was a highly contingent outcome. After all, China has not always been unified. As the opening lines of *Romance of the Three Kingdoms* above remind us, China has experienced long periods of fragmentation throughout its history.

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[1] See, for details, http://peterturchin.com/cliodynamica/why-europe-is-not-china/ and http://scholars-stage.blogspot.com/2013/06/geography-and-chinese-history-fractured.html.

Besides, the degree of fragmentation in Europe has varied over time.[2]

This paper has two goals. First, we provide a quantitative investigation of the fractured-land hypothesis. We gauge why China became a large state early in history, whereas Europe experienced protracted polycentrism, by modeling the dynamic process of state-building and exploring how fractured land shaped inter-state competition in non-linear ways. Second, we study state formation more generally. Using rich data on topography, climate, and land productivity, we simulate this model for the entire world, including Africa and the Americas, at a fine grid-cell geographical level and look at the resulting probability distributions of political structures.

Inspired by Crafts (1977) and Turchin et al. (2013), we focus on pattern predictions rather than replicating specific outcomes. We report probability distributions over outcomes because history is contingent. An independent event could interact with existing conditions to trigger unanticipated consequences. Absent that event, history may develop in a different direction. Our model allows for contingency in the outbreak and outcome of wars. Thus, our simulations are random, but with probabilities assigned by structural conditions. If and when a state emerges to dominate its neighbors is neither fluke nor destiny, but a balance of structure and contingency. Our model does not aim to capture the precise borders of specific countries—which are the product of chance events—but it *does* aim to generate patterns in border formation that correspond to what we observe historically.

We find that fractured land provides a robust explanation for the political divergence observed at the two ends of Eurasia: a unified China and a polycentric Europe. Also, our model allows us to distinguish between two versions of the fractured-land hypothesis. First, in a narrow sense, scholars have equated fractured land with mountainous and rugged topography. Second, a broader definition of fractured land considers the location of productive agricultural land.

We document that topography alone is sufficient, but not necessary, to explain polycentrism in Europe and unification in China. The location of Europe's mountain ranges ensured that several distinct geographical cores of equal size could provide the nuclei for future European states. In contrast, China was dominated by a single vast plain between the Yangtze and the

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[2] There is a question about how we measure political fragmentation before the rise of the modern nation-state. Can we consider the Holy Roman Empire as a unified polity? Under Otto I (r. 962–973, all dates are CE unless otherwise noted), perhaps yes. Under Francis I (r. 1745–1765), most likely no. For operational purposes, and following the Weberian tradition, we will call a "polity" or "state" an organization that keeps a quasi-monopoly of violence over a fixed territory (Weber, 1972; Tilly, 1990).

Yellow Rivers. But the presence of a dominant core region of high land productivity in China—in the form of the North China Plain—and the lack thereof in Europe can also explain political unification in China and division in Europe.

It is only when we neutralize the effects of fractured land in the broad sense that Europe and China cease to move at different paces toward political unification. Thus, geographical features that go beyond ruggedness are crucial to understanding why China unified and Europe remained polycentric. Our analysis highlights the importance of having core geographical regions of high land productivity unbroken by major mountain, desert, or sea barriers.

Importantly, we establish that fractured land can explain why Europe was fragmented into medium-sized states rather than into a large number of tiny and fragile polities as in Southeast Asia. Researchers have argued that this configuration of medium-sized polities is the one that played a critical role in developing European institutions. For instance, Mokyr (2016) has emphasized how a politically fragmented Europe fostered a competitive "market for ideas" that led to the intellectual milieu that made the Industrial Revolution possible. In other words, polycentrism can set up the pre-conditions required for the technological change highlighted in Galor and Weil (2000) and Galor (2011). Scheidel (2019) stresses the importance of fragmentation for preventing innovation from being shut down, while also highlighting the importance of military competition in generating institutional innovation.

In comparison, a centralized empire like China could more easily suppress ideas that challenged the status quo through many channels, such as the civil service exam that dominated elite selection (Lin, 1995), the limits to the development of "useful knowledge" (Mokyr, 2016), or the prevailing patterns of social cooperation (Greif and Tabellini, 2017). Jami (2012, p. 389) has even talked about "the continued imperial monopoly of 'science as action'." Thus, political centralization might account for the "Needham Paradox" of why China did not experience an indigenous industrial revolution despite having most of the pre-conditions that existed in Great Britain in the 18th century.[3] A critical insight of this interpretation is that the costs and benefits of China's state system varied with the overall level of technology. Civil service examinations based on the Confucian classics can create an efficient bureaucracy to run a pre-industrial society based on extensive Smithian division of labor, but it cannot spawn a scientific revolution.

We assess how our quantitative results depend on the assumptions and calibration of the

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[3] Mokyr (2016, ch. 16) reviews other proposed explanations of the "Needham Paradox."

model through an extensive battery of robustness tests. These tests confirm the key role of fractured land in the broad sense.

Next, we identify those dimensions where the simplest fractured-land hypothesis needs improvement. We discuss how the model misses the slow growth of a state system in Africa and the Americas and use the model as a measurement device to suggest possible channels (e.g., the disease environment in Africa, the slow diffusion of maize in the Americas) that can reconcile theory and data.

Our dynamic model of state-building is also of methodological interest because it would be easy to extend it to incorporate other factors—such as religious, linguistic, genetic, and ethnic diversity or technological and climatic change—that have played a role in state formation. Kung et al. (2022) examine the link between the timing of the adoption of agriculture and the emergence of the earliest states in China. Arbatli et al. (2020) and Spolaore and Wacziarg (2016) have documented the importance of diversity for the frequency of intrasocietal conflicts. Ashraf and Galor (2013) suggest that greater genetic diversity in Europe than in China may drive polycentricity. Conversely, the standardization of the Chinese characters by Qin Shi Huang has been a unifying force throughout China's history. Olsson and Hansson (2011) suggest that a long history of statehood is associated with less ethnolinguistic fractionalization.

Our model ignores the role of improvement in military technology through inter-state competition highlighted by Hoffman (2015). According to Hoffman, a political-military tournament eradicated polities that could not compete and accelerated military and political innovation through learning-by-doing. Our results show that this is not necessary to account for the comparative political structures of Europe and China. In a richer model, the political-military tournament could complement fractured land.

Our analysis contributes to several literatures. First, we build on Turchin et al. (2013), who pioneered using quantitative simulations to understand the causal link between geography and state fragmentation. However, both our questions and findings differ. Turchin et al. (2013) focus on the diffusion of cultural traits and military technology. They argue that the intensification of warfare—a process influenced by proximity to the Eurasian steppe and antagonistic relations between nomads and settled agriculturalists—selected for ultrasocial traits and large-scale states by pressuring premodern polities to strengthen and invest in state capacity. In comparison, we focus on the systematic differences in the size and pattern of state formation and offer a quantitative account of Europe's polycentricity.

Second, we complement a long-standing literature that attributes the rise of western Europe to its multi-state system by investigating the *causes* of Europe's political fragmentation. Without being exhaustive, the literature includes Hume (1752), Montesquieu (1989), Pirenne (1925), Hicks (1969), Baechler (1975), Jones (2003),Rosenberg and Birdzell (1986), Cowen (1990), Tilly (1990), Mokyr (2007), Karayalcin (2008), Chu (2010), Olsson and Hansson (2011), Voigtländer and Voth (2013a), and Lagerlöf (2014).

Third, we add to the literature on state formation in China and Europe. One strand emphasizes the importance of the threat from the steppe in Chinese state development (Lattimore, 1940; Huang, 1988; Barfield, 1989; Turchin, 2009; Bai and Kung, 2011; Chen, 2015; Ko, Koyama, and Sng, 2018). Other scholars contrast the greater absolutist power of Chinese rulers relative to their European counterparts (Fukuyama, 2011; Jia, Roland, and Xie, 2020). Another strand considers military competition in European state formation (Parker, 1988; Tilly, 1990; Voigtländer and Voth, 2013b; Gennaioli and Voth, 2015; Becker et al., 2020), or the relative dearth of inter-state conflicts as a hindrance to the rise of representative government in China (Dincecco and Wang, 2018). Finally, the literature on the size of nations pioneered by Alesina and Spolaore (1997, 2003, 2005) relates state size to both conflict and trade.

Fourth, our study is related to work that investigates the relationship between agricultural productivity, state formation, and conflict (Mayshar, Moav, and Pascali, 2022; Mayshar, Moav, and Neeman, 2017). For instance, Iyigun, Nunn, and Qian (2017) examine the link between a permanent rise in agricultural productivity and conflict between 1400 and 1900, while Acharya and Lee (2018) develop a model in which economic development generates rents that lead to the formation of territorial states.

Empirically, Kitamura and Lagerlöf (2019) find that mountain ranges and rivers influence the location of political boundaries in Europe and the Near East. Other empirical tests of other parts of Diamond's hypothesis include Turchin, Adams, and Hall (2006), Laitin, Moortgat, and Robinson (2012), and Pavlik and Young (2019).

Last, we contribute to the literature on the relationship between geography and economic and political outcomes. Geography can shape economic outcomes directly via access to trade routes or vulnerability to disease vectors (Sachs, 2001) or indirectly via its effect on ethnic fragmentation (Ahlerup and Olsson, 2012; Michalopoulos, 2012) or political institutions and social norms (Acemoglu, Johnson, and Robinson, 2001; Roland, 2020). We provide an example of the latter phenomenon: geography mattered because it gave rise to a centralized state in China and polycentrism in Europe.

The remainder of the paper is organized as follows. Section 2 outlines the fractured-land hypothesis. Section 3 builds a model of inter-state competition that integrates geographical characteristics. Section 4 calibrates the model and Section 5 presents the quantitative results. Section 6 discusses some aspects of Chinese and European history in light of our model. Section 7 looks at the implications of our model for Africa and the Americas. Section 8 discusses extensions of the model. Section 9 concludes.

2 Fractured Land?

Researchers have long argued that early states only formed when three conditions were satisfied. First, there was a sufficiently large area of productive agricultural land to generate the food surplus required to feed and clothe a political elite and its bureaucracy. Second, this food output needed to be appropriable (Mayshar, Moav, and Pascali, 2022). Third, there were geographical boundaries that made it possible to coerce the transfer of food surpluses to the political elite (Carneiro, 1970). Indeed, agrarian states struggled to project power into rugged, hilly, or mountainous lands where coercion was too costly (Mayshar, Moav, and Neeman, 2017; Scott, 2017).

Based on these ideas, geographers built the concept of a geographical core to describe the nucleus of successful states (Whittlesey, 1944; Pounds and Ball, 1964; Hechter and Brustein, 1980). The cores of most early states were centered around self-contained regions that had fertile agricultural land and good transport connections, and that were defensible from external invasion. Conversely, geographical cores that satisfied the above conditions experienced earlier and faster state formation.

Many authors (e.g., Hume, 1752; Jones, 2003; Kennedy, 1987) have postulated that since Europe's topographical peculiarities were less favorable to the formation of early states, the posterior history of the continent was plagued by fragmentation. The most influential formulation of this idea is the fractured-land hypothesis of Diamond (1997, 1998). Diamond makes three observations: (1) China was not threatened by the presence of large islands off its mainland

(Taiwan and Hainan were too small and Japan too far away); (2) the Chinese coastline was smooth compared to the European coastline; and (3) most importantly, unlike Europe, China was not fractured by high mountains and dense forests.

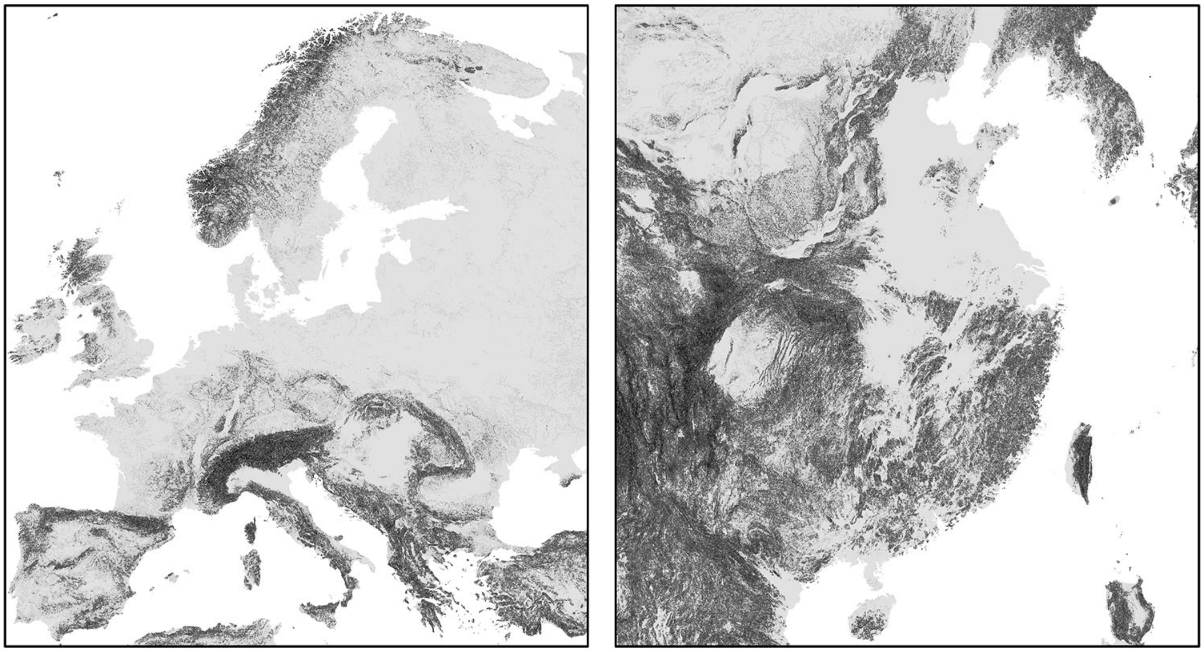

Figure 1: Ruggedness in Europe and China proper.

The claims of the fractured-land hypothesis have come under heavy criticism. Hoffman (2015, pp. 109–112) observes that China is significantly more mountainous than Europe (see Figure 1). Over 37% of modern China is defined as mountainous compared to little more than 10% of Europe. Even if one restricts attention to the so-called China proper, i.e., the traditionally agrarian part of China south of the Great Wall and east of the Tibetan plateau, more than 33% is elevated above 1,000 m. compared to only around 6% in Europe.

However, the crucial factor might not be the ruggedness of the terrain at large but the location of either continent's mountainous regions. Beyond the total amount of ruggedness, Figure 1 illustrates that mountain ranges at or near the center of western Europe play an important role in separating Italy and Spain from France and making core regions of central Europe (Switzerland, Austria) difficult to conquer.[4]

Consequently, Europe comprises several cores: the British Isles, Scandinavia, the Iberian

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[4] During World War II, Switzerland planned a retreat to a "réduit national" in the central part of Switzerland in case of a German invasion. The 12 Battles of the Isonzo during World War I between the Italian and Austro-Hungarian armies suggest that taking over such a redoubt is extremely costly, even for a modern army.

peninsula, and the Italian peninsula. France, the Low Countries, Germany, and Poland span what is known as the northern European Plain. The easternmost part of this plain borders the Russian forest in the northeast, the steppe in the east, and the Carpathian mountains in the south; it corresponds loosely to modern Poland and the territory controlled by the Polish-Lithuanian Commonwealth in the early modern period. The central part of the plain corresponds to modern Germany, while France occupies the western part of the plain.

Meanwhile, the most mountainous regions in China are in the south and west, and they do not intersect the Central Plain in the north that historically played a crucial role in China's early unification. The Central Plain, centered on the Yellow River basin, is blocked from Korea in the northeast by the Changbai Mountains and the Taihang Mountains in the west. The plain itself is flat, except for the Taishan Mountains in Shandong and the Dabie Mountains of Anhui. Southern China is more mountainous. The Yunnan-Guizhou plateau has a particularly high elevation. Mountains and dense forests divided Lingnan and Yunnan from Vietnam and Burma, respectively. Diamond (1997, p. 414) himself emphasizes the existence of a large core region capable of dominating the other regions in China:

> China's heartland is bound together from east to west by two long navigable river systems in rich alluvial valleys (the Yangtze and Yellow Rivers), and it is joined from north to south by relatively easy connections between these two river systems (eventually linked by canals). As a result, China very early became dominated by two huge geographic core areas of high productivity, themselves only weakly separated from each other and eventually fused into a single core.

The arguments in the previous pages are qualitative. As such, they cannot be assessed quantitatively (e.g., *how* rough must the terrain be to make a difference for political unification?) or used to measure the role of structure versus contingency in the observed outcomes (perhaps China's early leaders were luckier or better than their European counterparts?).

Can we bring quantitative data and a simple model of state formation and competition to the table and formally evaluate the fractured-land hypothesis and the range of distributions of probability that it can span? The following section introduces such a model.

3 Model

First, we describe how we divide the world into hexagonal cells. Second, we measure each cell's geographical, climatic, and resource availability characteristics. Third, we highlight Eurasia, the region we will focus on for our baseline exercises. Fourth, we present a formal model of how polities evolve through conflict and secession by gaining or losing cells.

3.1 The Geographical Space

Our first step is to divide the Earth's landmass (excluding Antarctica, which is largely uninhabited even today) into 65,641 hexagonal cells of radius 28 kilometers, each potentially capable of sustaining a polity and allowing armies to pass through it (Figure 2). This radius corresponds to the distance a healthy adult travels by foot per day on flat terrain.[5] As a result, a 28-kilometer hexagon roughly represents the surface that the simplest polities can monitor and defend with rudimentary Bronze Age technologies. Subsection 3.4 will motivate why we fill our geographical space with hexagons instead of other shapes.

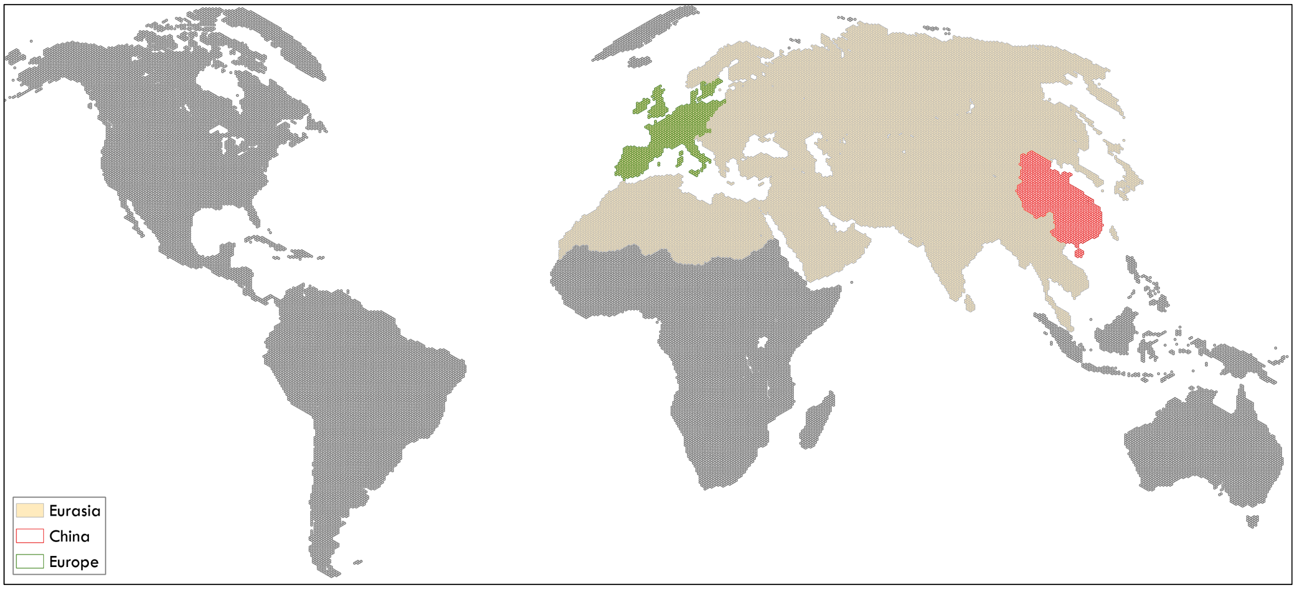

Figure 2: The world in hexagons.

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[5] This distance assumes a 7-hour march at a leisurely pace of 4 km/h. In Roman times, recruits were required to complete about 30 km in 6 hours in loaded marches. In the U.S. Army, the average march rate for foot soldiers is estimated to be between 20 to 30 km per day. See Headquarters, Department of the Army (2017, Figs. 1–2).

3.2 Geographical, Climatic, and Resource Availability Characteristics

Our second step is to measure, in each cell, a vector of geography and climate characteristics, $\mathbf{x}$, and historical resource availability, y.

Geography and Climate. We consider, first, terrain ruggedness, x_{rugged}. We measure ruggedness by the standard deviation of elevation within each cell, an index of topographic heterogeneity computed using the CGIAR-CSI dataset (see Appendix A.4). Plains and plateaus score low on this measure, while mountain ranges and valleys score high (Nunn and Puga, 2012). Figure 3 depicts x_{rugged}. There, we can see the high ruggedness of the Alps, the Balkans, the Caucasus, and the Himalayas, and the low ruggedness of the northern European Plain, much of Russia, the Indian subcontinent, and North China.

Second, we identify cells in hot and cold climates using the WorldClim 1.4 historical data on annual average monthly maximum and minimum temperatures during the mid-Holocene epoch (4000 BCE), which was relatively warm in historical context (in the appendix, as a robustness check, we rerun our simulations using climatic data from the 1960s). Hot and cold climates hinder the movement of large armies because exposure to extreme temperatures induces physiological stress that can impair body functions and cause death (Department of the Army, 2016; Sanford, Pottinger, and Jong, 2017) and change the behavior of insect vectors (Bellone, 2020).

We set $x_{hot} = \log(t_{max} - 21)$ for tropical cells with an annual average maximum temperature t_{max} of 22°C or above, and $x_{hot} = 0$ otherwise.[6] We set $x_{cold} = \log(9 - t_{min})$ if the annual average minimum temperature t_{min} of a cell is below 8°C, and $x_{cold} = 0$ otherwise.[7] In Figure 4, cells with a minimum temperature below 8°C are depicted in gray. Most of them are in the northern frontier of our study area or mountainous regions (the Himalayas, the Alps, and the Caucasus). Cells with a maximum temperature above 22°C appear in red. Most of those are in the Indian subcontinent and Southeast Asia.

We include these three geographical variables in the vector $\mathbf{x} = \{x_{rugged}, x_{hot}, x_{cold}\}$. The

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[6] According to the Wet Bulb Globe Temperature (WBGT) index, the most widely used measure of heat stress risk, a temperature of 22 °C is equivalent to a WBGT of 25°C (assuming a relative humidity of 85%, a humidity level often observed in the tropics). Beyond this level, it is advisable to adjust outdoor activities accordingly (Surgeon General, 2008; Department of the Army, 2016).

[7] A temperature of 8°C or below is defined as frigid under European Union regulations (see European Pharmacopoeia 10th Edition).

vector $\mathbf{x}$ could be enriched with further geographical, climatic, cultural, and technological variables. We will return to this point later on.

Resource Availability. Our primary measure of historical resource availability is drawn from the Food and Agriculture Organization's Global Agro-Ecological Zones database, version 4 (henceforth GAEZ v4). The database divides the world's land surface into grid-cells of size 5' latitude/longitude (approximately 75 km^2). The dataset publishes the hypothetical annual yields (in tons per hectare) of different crops for each grid-cell. We focus on cereal grains, which formed the basis of taxation in early states (Childe, 1936; Carneiro, 1970; Mayshar, Moav, and Neeman, 2017). Following Galor and Özak (2016), for each of our cells, we generate its highest attainable yield, y_{GAEZ}, in calories by (1) extracting the hypothetical yield of every cereal that existed in the continent where the cell is located before the Columbian Exchange, (2) converting the yields into calories, and (3) selecting the highest calorie-yielding cereal for the cell. Figure 5 shows the result of this exercise, with high densities in the Italian peninsula, India, and China and low densities in Russia, the Arabian peninsula, and inner Asia. In our model, productivity will determine the ability of the polity that controls it to mobilize resources for military purposes.

GAEZ v4 yields, however, might miss that agricultural states developed earlier along river corridors rich in alluvial soil, which is naturally irrigated by regular floods and not covered by thick forests (Scott, 2017). This soil is easy to work on with primitive tools and has the highest productivity among different soils (Fried, 1967; Driessen and Deckers, 2001). Indeed, the alluvium-rich regions of Mesopotamia (Tigris River), Egypt (Nile), the Indus Valley (Indus), and North China (Yellow River) were comparatively advanced in the exploitation of resources in 1000 BCE. To account for this phenomenon, we measure the percentage of alluvial soil in every cell based on the FAO Digital Soil Map of the World (DSMW) and denote it as r.

In our baseline model, we set $y_0 = r \cdot y_{GAEZ}$ at $t = 0$ and $y_{500} = y_{GAEZ}$ at $t = 500$, with the assumption that y grows at a constant rate between $t = 0$ and $t = 500$ for every cell. Later, as a robustness check, we will measure r using estimates from the KK10 Anthropogenic Land Cover Change database. Separately, we will check if ignoring initial developmental differences by setting $r = 1$ affects our results. We will also show that our findings are robust to the use of alternative measures of resource availability, including agricultural productivity (Ramankutty et al., 2002) and historical population estimates (Goldewijk et al., 2017).

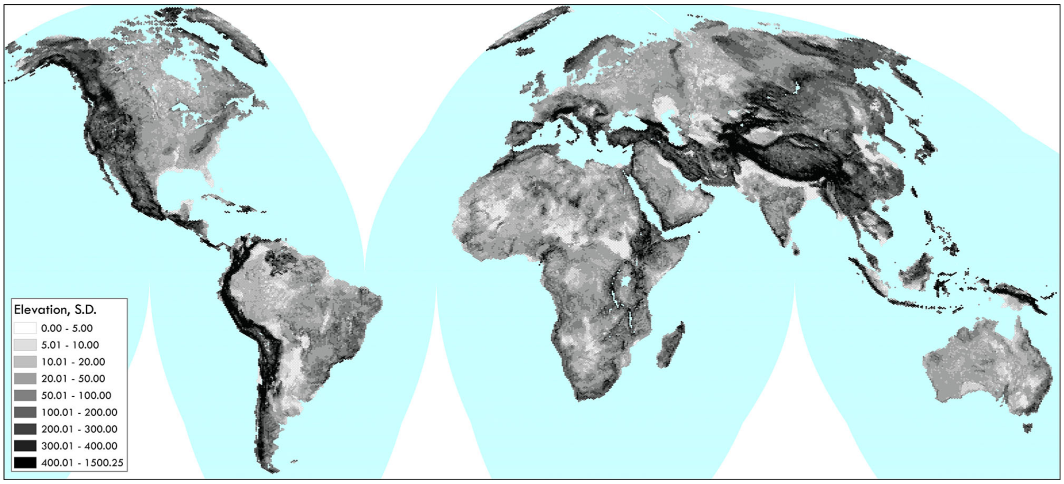

Figure 3: Terrain ruggedness (standard deviation of elevation).

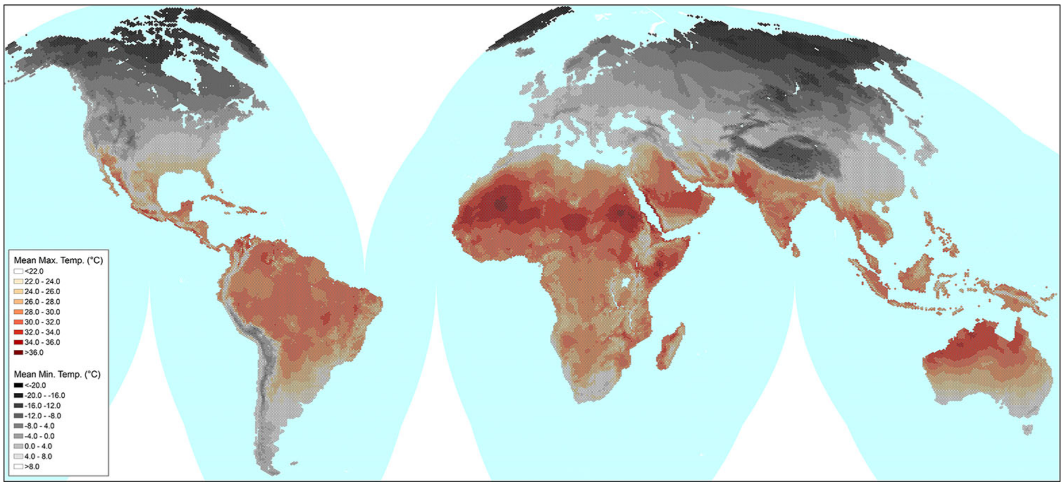

Figure 4: Annual average max. and min. Monthly temperatures.

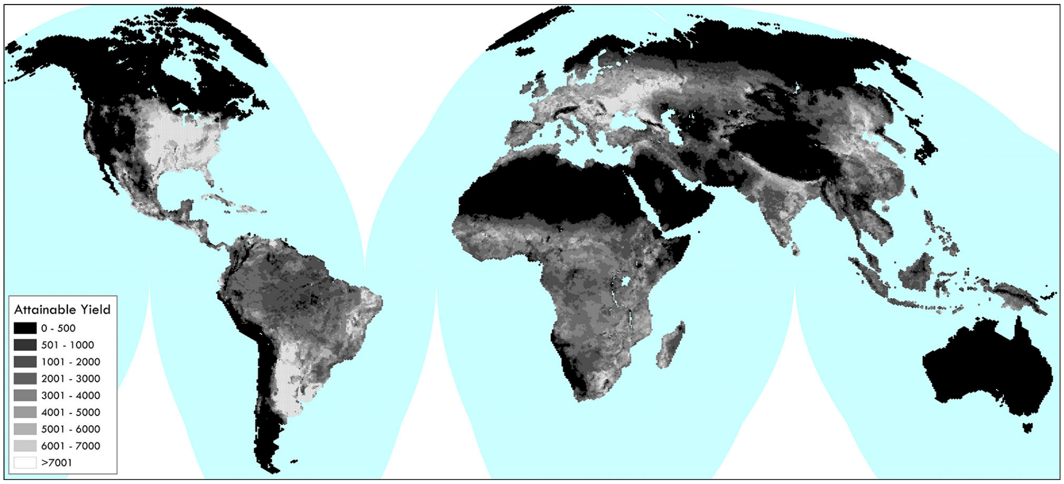

Figure 5: Attainable caloric yield based on pre-Columbian cereals (GAEZ v4).

3.3 Eurasia, China, and Europe

Our baseline exercises will report results from the 28,822 cells that include most of Europe, North Africa, the Middle East, Continental Asia, and Japan (cells with brown, red, and green borders in Figure 2). This area is often called Eurasia. We consider this space because intense political, trade, and cultural contacts across Eurasia took off after the beginning of the Iron Age (c. 1200–1000 BCE).[8]

As Hodgson (1954, p. 716) put it, our area of interest corresponds to:

> . . . the various lands of urbanized, literate, civilization in the Eastern Hemisphere, in a continuous zone from the Atlantic to the Pacific, [that] have been in commercial and commonly in intellectual contact with each other, mediately or immediately.

What phenomena did Hodgson have in mind? For instance, the Roman Empire and Han China traded indirectly and knew of each other's existence. A Roman delegation visited China in 166, and the Chinese historian Yu Huan wrote a description of the Roman Empire—named *Daqin*—sometime between 239 and 265. Roman commerce with the Indian subcontinent was lively, with the tariffs on it accounting for as much as one-third of the empire's revenue (McLaughlin, 2010). Roman coins made their way to Japan, and Buddhism was present in Rome.

Significantly, Eurasia has accumulated a large share of the world's population for most of history and has been the origin of many technological developments and social and political forms (Kremer, 1993; Diamond, 1997). Understanding the dynamics of the political forms that evolved in this space is critical for understanding global economic history.

Within the 28,822 Eurasian cells, 1,415 cells cover "China," defined as the lands south of the Great Wall (cells with red borders in Figure 2). This region corresponds to the historical core of Imperial China until the Qing expansion to the west (Perdue, 2005). Another 1,285 cells, highlighted with green borders in Figure 2, are in (western) "Europe," defined as the lands west of the line running from Saint Petersburg to Trieste and delimiting the region of the *European marriage pattern* (Hajnal, 1965). Many historians have used this marriage pattern as a proxy for close cultural and social similarities of the loosely called "western world."

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[8] The Iron Age starts at slightly different times over Eurasia, with the earliest transitions in the Middle East and the latest in northern Europe. For compactness of exposition, we ignore such heterogeneity.

Calling a cell "Eurasia," "China," or "Europe" has *no* implications for the model. It is just a label to build the statistics that summarize the outcomes from our simulations.

3.4 Evolution of Polities

We now take the hexagonal cells defined above, with their geographical, climatic, and resource availability characteristics, and consider how polities evolve in them over discrete periods $t = 0, 1, 2, \ldots$. At $t = 0$, each cell begins as an independent polity. Thus, the space is filled by a hexagonal tiling, with each cell bordering adjacent cells 1–6 (Figure 6). This setup is analogous to the hexagonal close-packing (HCP) system in crystallography. We consider a regular tiling to impose ex-ante homogeneity on the geographical shapes of polities. We prefer a hexagonal tiling to the other two regular tilings of the Euclidean plane because its vertex configuration is simpler than that of a triangular or square tiling. This simplicity better reflects the frontiers that most polities have had over time in our reading of the historical data.

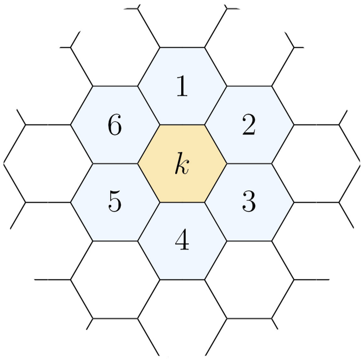

Figure 6: Cell k and adjacent cells.

Over time, some polities expand by conquering neighboring cells, while others lose control of cells. We describe now how the conquest and the secession of cells operate.

3.4.1 Conquest across land

In each period, a cell k finds itself in a border conflict with one of its adjacent cells with probability $\alpha \cdot y_k$, where $\alpha > 0$. For simplicity, we assume that, when a cell experiences a border conflict, only one of its six borders is affected. Relaxing this assumption is straightforward, but it makes the model less transparent with little additional insight.

The probability of a border conflict depending on the productivity of the cell embodies the notion that more productive cells are more tempting for neighbors to exploit. This idea is based on the Hobbesian thesis that the desire for gain, safety, and reputation drove warfare. Hence, productive lands are more likely to experience war.[9] The idea also builds upon the circumscription theory and the Malthusian argument, which both see warfare as an outcome of population pressure.

However, these conflicts face the so-called "Hicks Paradox." As Hicks (1932) first observed, it is hard to see how rational agents might fail to reach an efficient agreement that avoids a conflict and the subsequent deadweight loss. The literature has highlighted commitment problems due to time inconsistency as a fundamental obstacle to the peaceful resolution of political disputes (Fearon, 1995; Acemoglu, 2003; Monteiro and Debs, 2020). The anarchic nature of the international environment and the absence of a higher authority to adjudicate violations of an agreement imply that states often have the incentive to undertake preemptive strikes, especially if they have more to lose. In Appendix B, we present two empirical checks to show that our choice of a higher probability of border conflict in richer cells is consistent with historical data; later in Section 5.3, we conduct robustness tests based on alternative conflict mechanisms to verify that the assumption is not critical to the findings.

Most cells in our geographical space are inland. Conditional on inland cell k encountering a border conflict, the probability that its adversary is cell $\overline{k} \in \{1,2,3,4,5,6\}$ is:

$$\frac{y_{\overline{k}}}{y_1 + y_2 + y_3 + y_4 + y_5 + y_6},$$

where $y_1, ..., y_6$ are the respective productivities of the six adjacent cells (see Subsection 3.4.2 for the case where the cell has sea frontiers). This assumption follows the idea explained above: two highly productive cells are more likely to be tempted into a conflict with each other than one low- and one high-productivity cell.

A conflict between cells has two interpretations. If a different polity controls each cell (as occurs, for sure, in $t = 0$), we consider this conflict a war. The victor of this war, to be determined in the next paragraph, annexes the losing cell. If the cells are controlled by the

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[9] Studies of early states also suggest that the main objective of war was resources, including population and properties. States more eagerly sought control of productive lands than poor terrains. Military expeditions were expensive, and soldiers would not fight well if they expected meager rewards even in victory (Scott, 2017).

same polity (as may occur after previous annexations), we think about this conflict as a political struggle for resources within the polity. The unified government will resolve the conflict by reallocating resources or through other policies in a manner that is inconsequential to our model.

Victory in a war between two polities is given by a contest function that depends on (a) the aggregate productivity of the polities in conflict, and (b) the geographical characteristics $\mathbf{x}$ of the cells in conflict. Specifically, if a war takes place between polities i and j, which controlled cells k and $\overline{k}$, respectively, polity i wins with probability:

$$\pi_i = \frac{Y_{i,t}}{(Y_{i,t} + Y_{j,t}) \times (1 + max\{\Theta \cdot \mathbf{x}_k, \Theta \cdot \mathbf{x}_{\overline{k}}\}}, \tag{1}$$

where $Y_{i,t}$ $(Y_{j,t})$ denotes the sum of productivities of all cells controlled by polity i (j) at period t; $\mathbf{x}_k$ $(\mathbf{x}_{\overline{k}})$ denotes the geographical characteristics of cell k $(\overline{k})$; Θ is a parameter vector that controls the weights of each geographical and climatic characteristic, and $\Theta = \{\theta_{rugged}, \theta_{hot}, \theta_{cold}\}$.

The contest function (1) reflects two forces. First, more productive polities win more often, but the vagaries of war might bring victory to the weaker side. This may be due to factors we do not model, such as exceptional military leadership or strong state capability. Second, the relevant variable is the sum of the productivities of the cells of a polity, not the average productivity. Estonia, in 1939, had a higher income per capita than the Soviet Union (Norkus, 2019), but due to the difference in size, it could do next to nothing to resist annexation.

Second, the geographical and climatic variables make conquest harder or easier depending on the values of Θ, which mediate the probability of victory. The probability of the war ending with no victor and, thus, no annexation is:

$$1 - \pi_i - \pi_j = 1 - \frac{1}{1 + max\{\Theta \cdot \mathbf{x}_k, \Theta \cdot \mathbf{x}_{\overline{k}}\}},$$

which is strictly positive and is increasing in $max\{\Theta \cdot \mathbf{x}_k, \Theta \cdot \mathbf{x}_{\overline{k}}\}$. If $\theta_{rugged} \gg 0$ (i.e., conquering very rough terrain is daunting, as scores of armies over millennia have discovered in Afghanistan), the probability of no annexation after a war that involves a cell with rough terrain is high.

Two secondary assumptions deserve further discussion. First, we assume that only the cell of the losing polity in the conflict is annexed, not the whole polity. While complete conquest sometimes occurs in history (e.g., the fall of the Sasanian Empire to the Arab invaders between

642 and 651), most conflicts end up by trading small pieces of land (recall the dynastic struggles that plagued Europe during the early modern period and the subsequent small exchanges of territories).

Second, since a polity may share borders with multiple polities, it may face simultaneous wars with several of them. We assume that a polity fighting more than one war will channel its resources proportionately according to the strengths of its adversaries. Otherwise, these wars are independent of each other. A good example of simultaneous struggles, albeit a little later than the period for which our model is most appropriate, is the wars of Charles V, Holy Roman Emperor (r. 1519–1556), against his many enemies. The emperor always carefully weighed where to allocate his resources. His strategic choices were lamented by Francis I of France (r. 1515–1547) during his captivity in Madrid, but thoroughly enjoyed by the Elector John of Saxony (r. 1525–1532) while organizing the Schmalkaldic League.

We could generalize the previous two assumptions by allowing the annexation of larger parts (or the totality) of a polity and the correlation of wars across frontiers. In our example above, Francis I and Suleiman the Magnificent (r. 1520–1566) signed an improbable alliance in 1536 against Charles V. However, these generalizations require the introduction of many free parameters and we prefer to keep our model tightly parameterized. We could also introduce strategic considerations (e.g., alliances and strategic conquests). Section 6 discusses these issues.

3.4.2 Conquest across the sea

Our model allows for conquest to take place across the sea. For our period of study (1000 BCE to 1500, see Section 4 for an explanation), invasions via the sea occasionally took place (e.g., the Roman conquest of Britain). Still, they were much less common than conquest over land for at least two reasons. First, ships were not stout enough for long-distance power projection across rough seas until the early 15th century, which saw the emergence of bigger, full-rigged ships with three masts (Clowes, 1932; Woodward, 2021). Second, until the development of better boats and more powerful guns, *and* the synthesis of the two into a new form of assault employed by the European powers against the non-Europeans during the Age of Sail, naval battles were essentially infantry battles fought on water or beach.[10] This setting disadvantaged the aggressor,

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[10] For example, the Battle of Sluys in 1344 was one of the largest naval battles of the Middle Ages. It took place at the port of Sluys and was contested by men-at-arms fighting from the platforms of static cogs.

whose capacity to conquer was constrained by the number of ships it could gather and that could survive the journey to the opposite shore (Padfield, 1979). While extensive maritime trade existed, there were no navies to dominate the oceans until the 16th century. Historically, no major naval battles were fought in the Indian, the Pacific, or the Atlantic Oceans before 1500. The exceptions were the straits and the Mediterranean Sea, almost entirely enclosed by land and, thus, calmer and less dangerous to traverse than other seas. Even an invasion across a narrow strait was militarily risky and logistically challenging (see Koyama, Rahman, and Sng, 2021).

We incorporate this "stopping power of water" for military conquest (Mearsheimer, 2001, p. 84) in two ways. First, consider a coastal cell k, which borders $l \in \{1, \ldots 5\}$ cells by land and $6 - l$ by sea. Let L denote the set of cells that border cell k by land, and let S denote the set of cells that lie no more than six cells ($\sim$330 km) from cell k by sea. We assume that, conditional on cell k encountering a border conflict, the probability that its adversary is cell $\overline{k}$ is:

$$\frac{y_{\overline{k}}}{\sum_{i \in L} y_i} \cdot \frac{l}{6}, \tag{2}$$

if $\overline{k} \in L$ and:

$$\frac{y_{\overline{k}}}{\sum_{i \in S} y_i} \cdot \frac{6-l}{6} \cdot \alpha_{sea}, \tag{3}$$

if $\overline{k} \in S$. In other words, we do not allow sea conquests in the model over more than $\sim$330 km.[11]

The parameter $\alpha_{sea} \in [0, 1]$ measures the likelihood of wars arising across the sea relative to land conflicts. For completeness, we will consider both the case $\alpha_{sea} < 1$, i.e., conflicts across the sea are less likely to take place than conflicts over land, and the case of $\alpha_{sea} = 1$, i.e., conflicts are as likely to take place across the sea as over land.

Second, if a polity controls two or more clusters of cells that are separated by sea, when a war involving one of these clusters breaks out, the polity can mobilize the full resources of that cluster and a fraction $\sigma \in [0, 1]$ of the resources of the other clusters to fight the war. This accounts for the fact that moving large armies and supplies across a sea strait is capital-intensive and depends on factors such as the possession of a large navy or the ability to mobilize a large

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[11] This upper limit is wider than the English Channel, the Irish Sea, the Sound, the Bosporus, the Strait of Sicily, the Red Sea, the Palk Strait, the Indonesian Straits, and the Korea and Taiwan Straits—the straits that witnessed sea conquests before 1500. It also allows for conquest through the Mediterranean Sea via island or coast hopping. As Abulafia (2011, loc. 412) puts it: "Conflicts for control of the Mediterranean thus have to be seen as struggles for mastery over its coasts, ports and islands rather than as battles over open spaces."

merchant fleet and the availability of good harbors for loading and unloading. Circumstances such as unpredictable sea weather or changes in wind direction also affect the ability of troops and supplies to arrive promptly (recall the "Protestant Wind" that favored William of Orange's invasion of England in 1688 while keeping James II's fleet in port). Again, for completeness, we will consider both the case $\sigma < 1$ and $\sigma = 1$.

3.4.3 Secession

To reflect the historical tendency for border regions in large states to seek secession, we allow border cells to secede from the polity they belong to with strictly positive probability in each period. A border cell is one that shares an edge with one or more cells ruled by another polity.

The border cell k's probability of secession is high if (a) the cell has a high $\Theta \cdot \mathbf{x}_k$ (i.e., geographical and climatic characteristics that make secession hard to suppress), (b) if the parent polity i controls a large number of cells (and is therefore heterogeneous), or (c) if polity i has a long frontier relative to its interior (which increases the difficulty of monitoring and controlling the population). Specifically, the probability of border cell k seceding from polity i is:

$$\beta \times \Theta \cdot \mathbf{x}_k \times \sum_{m}^{65,641} \mathbb{1}_i(m) \times \frac{\sum_m^{65,641} (\mathbb{1}_i(m) \cap \mathbb{1}_B(m))}{\sum_m^{65,641} \mathbb{1}_i(m)} = \beta \times \Theta \cdot \mathbf{x}_k \times \sum_{m}^{65,641} (\mathbb{1}_i(m) \cap \mathbb{1}_B(m)), \quad (4)$$

where $\beta > 0$ is a constant determining the likelihood of secession, $\mathbb{1}_i(m) = 1$ if cell m is ruled by polity i and $\mathbb{1}_i(m) = 0$ otherwise, and $\mathbb{1}_B(m) = 1$ if cell m is a border cell and $\mathbb{1}_B(m) = 0$ otherwise.

To simplify, we assume that if a polity is cut into disjoint parts due to war or secession, each part becomes a separate polity. The exception is when the disjoint parts are separated by sea by a distance no further than six cells (Subsection 3.4.2), in which case the polity survives. Geographically divided polities such as Pakistan between 1947 and 1971 seldom live long.

As before, we consider that each cell separates independently from other cells for simplicity. However, since a polity might have several cells sharing edges with other polities, it may suffer the separation of several cells in the same period.

3.4.4 Summary

As conflicts between polities and unrest within polities occur, states consolidate over time if the probability of secession is not too high. Larger states have access to more resources, and, hence, are likely to consolidate further. However, it is more challenging to conquer some cells than others due to their geographical and climatic characteristics. These features will lead to regular patterns of state formation.

To summarize, the timing of events is as follows:

1. At $t = 0$, each cell is a separate polity (i.e., zero-state consolidation).
2. At each t, the probability of conflict breaking out in cell k is $\alpha \cdot y_k$, where $\alpha > 0$ and y_k is the productivity of cell k.
3. If cell k encounters a border conflict, only one of its six borders is affected. The conditional probability that its adversary is cell $\overline{k}$ is given by equation (2) if $\overline{k}$ borders k by land, and by equation (3) if $\overline{k}$ is connected to k by sea.
4. If there is a conflict between cells controlled by different polities, a war occurs.
5. In a war between cells k and $\overline{k}$, controlled, respectively, by polity i and polity j, polity i wins and annexes cell $\overline{k}$ with the probability given by the contest function (1).
6. A polity may fight no war, one war, or multiple wars in any period. If it fights multiple wars, it splits its resources proportionally according to the resources of its adversaries.
7. Cell k secedes from polity i with the probability given by equation (4).

4 Calibration

To calibrate our model, we need to pick an initial and endpoint of the simulation, a time unit, and the values of seven parameters: α, α_{sea}, σ, θ_{rugged}, θ_{hot}, θ_{cold}, and β.

For the initial and endpoint of the simulation, our baseline exercises gauge whether our model can account for the evolution of the Eurasia polity structure between the beginning of the

Iron Age (c. 1200–1000 BCE) and the dawn of the Age of Exploration in the second half of the 15th century. Thus, we pick 1000 BCE to 1500. These points give us a total of 2,500 years.[12]

At the start of the Iron Age, Eurasia was nearly entirely fragmented. Even areas where larger polities existed previously, such as the Fertile Crescent, were recovering from the Late Bronze Age collapse: Egypt was transitioning through its third intermediate period, the palace economies of the Aegean had crumbled, and the Kassite dynasty of Babylonia and the Hittite Empire had disappeared (see Drews, 1993, and Cline, 2014). The Shang in China had somewhat progressed toward unification, but the documentary record of how effective their territorial control was is scant (Campbell, 2018, ch. 4).

The Age of Exploration quickly integrated the whole world. Juan Sebastián Elcano completed the first circumnavigation of the globe in 1522, only 103 years after the Portuguese started systematically exploring the West African coast. And by 1565, the Manila galleons had opened a regular trade route between Europe, Asia, and the Americas.

Our choice of time unit must balance the need to have a detailed account of the evolution of political forms and the computational burden. Hence, we pick five years to get 500 simulation periods (2,500 years divided by 5). This time unit is also a reasonable approximation to the median length of many conflicts, which, in the data, have a huge variation.[13]

Fortunately, the values of all parameters in the model, except β, are time-independent. They represent the geographical relative attractiveness or difficulties of conquest, which are static properties.[14] Thus, our pick of an initial and end period and a five-year time unit only matters when mapping the lengths of outcomes in the model with the lengths of outcomes in the data.

We can move now to calibrate our seven parameters. Since $\alpha \cdot y_k$ determines the probability of conflict occurring in cell k, we set $\alpha = \frac{1}{y_{max}}$, where y_{max} is the productivity of the cell with the most resources in our dataset. In such a way, $\alpha \cdot y = 1$ for the cell with the highest value of y and $0 \leq \alpha \cdot y \leq 1$ for all other cells. We pick $\sigma = 0.33$, based on Dupuy (1979), a well-regarded source among military scholars and historians. Dupuy (1979) uses military history statistics to weight variables that predict war outcomes (these weights are used, for example, to calibrate

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[12] Later, we will discuss the implications of our model for Africa and the Americas during this period.

[13] Computing this variance becomes even more challenging once one realizes it is hard to agree on what constitutes a war. Think about the long conflict between the Spanish Empire and the Provinces of the Netherlands (1568–1648): Was it one long war or several consecutive ones?

[14] We do not model changes in military technology. Although some of those changes could be biased toward one geographical feature, there is not much evidence of this bias in the data (Dupuy, 1979).

war games at general staff colleges). We set $\alpha_{sea} = 0.1$ to account for the observation that about 10% of the historical battles listed on Wikipedia were sea battles.[15]

Drawing again from Dupuy (1979), we pick θ_{rugged} so that $\theta_{rugged} \cdot x_{rugged} = 2$ for the cell at the 90th percentile of the ruggedness ranking.[16] At this value, a war between two adversaries of equal strength fighting in this cell will end in a stalemate with a probability of $\frac{2}{3}$. Likewise, we pick θ_{hot} and θ_{cold} so that $\theta_{hot} \cdot x_{hot} = \theta_{cold} \cdot x_{cold} = 2$ for the respective cells at the 90th percentile of the annual average monthly maximum and minimum temperature rankings.

Finally, we set $\beta = 1 \times 10^{-5}$. Given Europe's long coastline compared with China's, European states tend to be non-compact in our simulation. Our low β prevents secession from being the main cause of Europe's fragmentation. At the calibrated β, a polity that comprises Europe's cells would have to annex territories at a rate of 90 cells (approximately the size of two Austrias) every 50 periods (250 years) to compensate for the loss of cells through secession. In comparison, a polity that controls China's cells would only need to annex approximately 22 cells (approximately half the size of Austria) every 50 periods to maintain its territorial size.

Parameter	Value
α	$\frac{1}{y_{max}}$
α_{sea}	0.1
σ	0.33
θ_{rugged}	$\frac{2}{x_{rugged}=90th \text{ percentile}}$
θ_{hot}	$\frac{2}{x_{hot}=90th \text{ percentile}}$
θ_{cold}	$\frac{2}{x_{cold}=90th \text{ percentile}}$
β	1×10^{-5}

Table 1: Baseline calibration of the model.

Table 1 summarizes the calibration. We will call this calibration our "baseline calibration."

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[15] While Wikipedia data might have biases in its coverage, we checked that other sources, such as Phillips and Axelrod (2005), do not have more comprehensive datasets. Fortunately, our robustness exercises document that the model's results do *not* depend materially on the value of α_{sea}.

[16] According to Dupuy (1979), a formula that fits the historical data well is c (combat power) $= s$ (military strength and other factors) $\times$ r (role, either attack or defense) $\times$ w (weather/terrain obstacles), where $r = 1$ for attack, $r = 1.3$ for defense, $w = 1$ for attack, and $w = 1.5$ for defense when obstacles are present. All else equal, this formula implies that the combat power of defense is approximately twice ($1.3 \times 1.5 \approx 2$) that of attack under unfavorable weather/terrain obstacles. This power of defense translates into a $\frac{2}{3}$ probability that the war ends with no conquest. An alternative approach is to incorporate topographical features in the Lanchester equations, a popular set of ODEs used to compare military forces (see Przemieniecki, 2000, ch. 4). Following this strategy, Engel (1954)—using combat data from the battle of Iwo Jima—and Weiss (1966)—using combat data from the U.S. Civil War—also estimate that weather/terrain obstacles roughly double the effectiveness of the defense.

We will also have a "preferred specification," with the same parameter values, but we make our model more realistic by adding the roles of rivers, steppes, loess soil, and climate in state formation. Section 5 will show that both specifications deliver nearly the same quantitative results regarding the speed of state consolidation. But since the preferred specification requires additional discussion, we delay the presentation of its details until Subsection 5.4 and focus, first, on the more parsimonious and easier-to-analyze baseline calibration.

In Subsection 5.3 and Appendix D, we conduct many sensitivity tests to document that our results are robust not only to changes in the values of the parameters in Table 1, but also to the use of alternative datasets and modifications to the conflict mechanism.

5 Quantitative Results

We are ready to simulate our model: we divide the world into hexagonal cells, feed in each cell's geographical and climate characteristics and historical resource availability, and draw random paths of conflicts and secession. Since the evolution of the model is stochastic, replicating the idea that history is a mix of structure and contingency, we simulate the model 30 times.[17] Based on this sample, we conduct bootstrap analysis to compute the mean Herfindahl indices of the areas we called "China" and "Europe" and their confidence intervals by drawing a sample of 30 simulations with replacement for 10,000 times. Our simulations cover the whole world. But for now, and only for *reporting* purposes, we will focus on the results for Eurasia. We will discuss the results on Africa and the Americas in Section 7.

Despite its simplicity (and the omission of many plausible mechanisms of state formation), our model generates patterns of political consolidation that resemble those observed in history. Panel A of Figure 7 depicts Eurasia in a representative simulation from our preferred specification in period 50 (i.e., 750 BCE). While nearly every cell is still an independent polity, we start seeing a consolidation of power in northern China resembling the core areas of the Shang and the Zhou dynasties. In comparison, no large polities appear in Europe.

Panel B of Figure 7 depicts the same simulation after 300 periods (i.e., 500 CE). In the east, a large polity has unified northern China, but has yet to control the southern half fully. In

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[17] A short movie with a representative simulation can be seen here: `https://www.dropbox.com/s/ftgcjqpetm2291l/FracturedLandMovie220101.mp4?dl=0`.

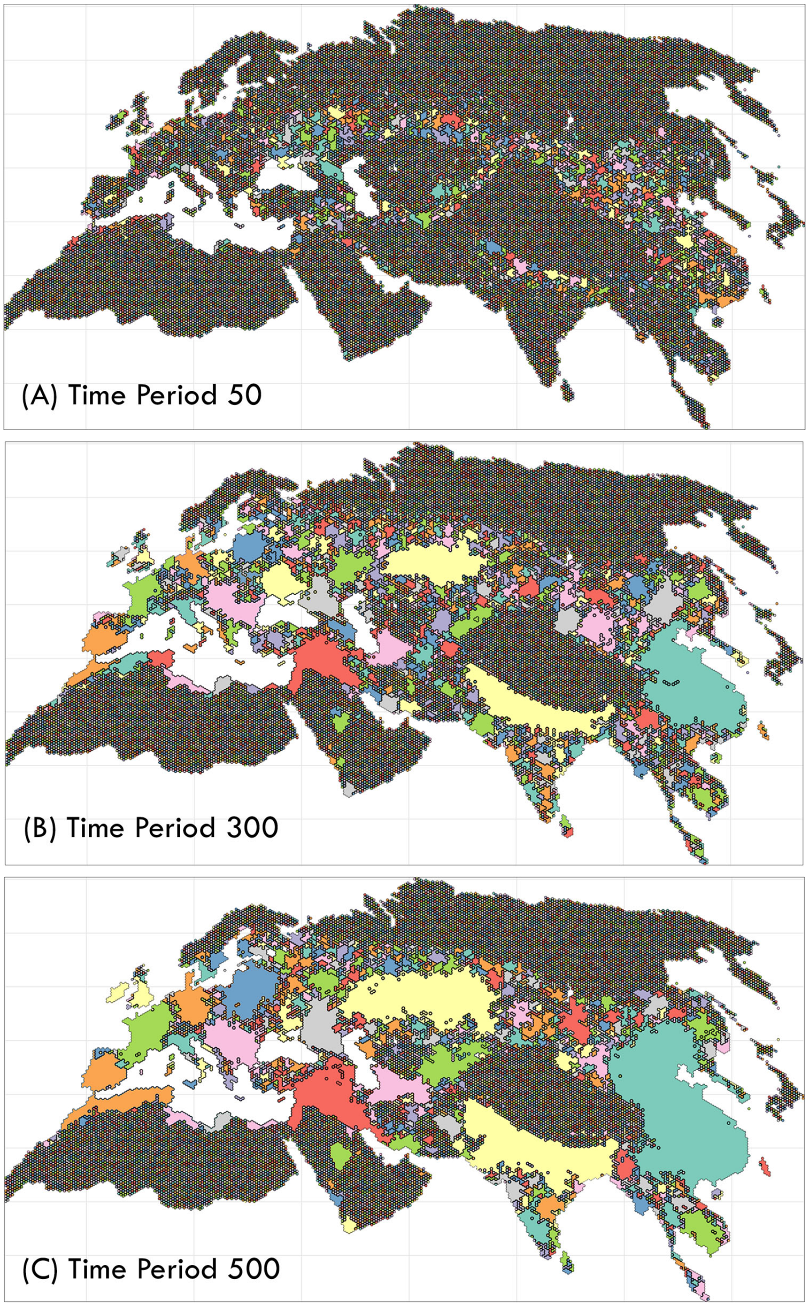

Figure 7: One representative simulation run.

the west, we see polities roughly resembling Spain or France (including a polity very similar to the Kingdom of the Suebi in the northwest of the Iberian peninsula, which existed between 409–585). The year 500 is around the time when the Germanic kingdoms that inherited the western Roman Empire were formed. The Indian subcontinent is divided into many polities (with an emerging power in the north), while the Arabian peninsula, given the low productivity of its land, is fragmented (we will revisit this point in Section 8 and Appendix E.6).

Panel C of Figure 7 depicts the same simulation at the end of the simulation after 500 periods (i.e., 1500). The large polity occupying China and dominating East Asia has expanded to the south toward Vietnam and Yunnan. The polity controlling India has expanded toward the south, occupying an area similar to the Delhi Sultanate (1206–1526) at its peak. In Europe, we see a nearly unified Iberian peninsula (as happened between 1580 and 1640), polities resembling England, Scotland, and Ireland, a larger France, and the Ottoman Empire.

At the end of the simulation, European Russia and (in particular) Siberia are highly fragmented. Both observations match the historical record during the period we consider. The Grand Duchy of Moscow only started to grow quickly after 1300, and the conquest of Siberia did not commence until the 16th century and the arrival of gunpowder. However, our simulation misses anything resembling the Mongol Empire and its successor states, such as the Golden Horde, even if these unification processes were transient. Appendix E.2 discusses what we need to change in the model to generate states resembling the Mongol Empire.

5.1 Chinese Unification, European Polycentrism

Figure 7 is not an anomaly. The central result of our model is that larger polities emerge early in China and that this part of the world tends to become unified under a single state. In contrast, polycentrism is persistent in Europe. Figures 8 and 9 depict the evolution of the Herfindahl indices of political unification for China and Europe over 500 periods for the 10,000 bootstrap samples based on the 30 simulations under the baseline calibration.[18] We start with the baseline calibration to have the simplest scenario. The colored intervals denote the 95% confidence intervals of the estimated indices in each period.

Across all simulations, China centralizes quickly. The Herfindahl index for China crosses 0.5 after around 300 periods and converges to 1 toward the end of the 500 periods. In history, China was first unified in 221 BCE when the armies of Qin Shi Huang conquered the state of Qi, the last independent kingdom in northern China. Still, much of southern China continued to be occupied by minorities such as the Yue and Man (Twitchett and Fairbank, 1986; Dien and Knapp, 2019). When the Han dynasty replaced the Qin, the present-day provinces of Fujian, Guangdong, Guangxi, Guizhou, and Yunnan were outside Chinese control (notice the similarities

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[18] We define the Herfindahl index of political unification of a region as $H_{pc} = \sum_{i=1}^{N} s_i^2$, where N is the number of polities existing in the region, and s_i is the percentage of the cells in the region controlled by polity i.

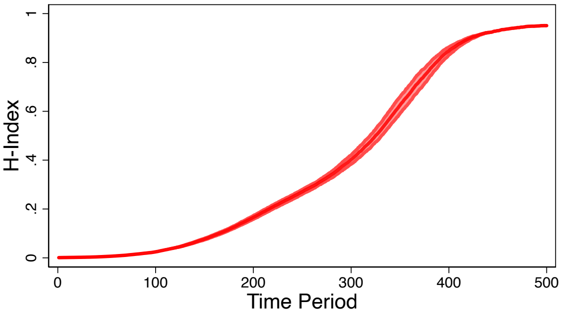

Figure 8: China. Fan chart for 30 simulations of the baseline specification.

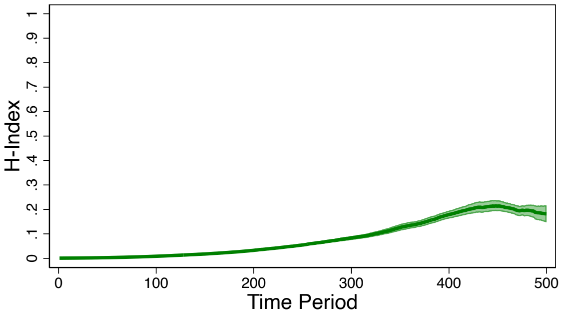

Figure 9: Europe. Fan chart for 30 simulations of the baseline specification.

between Figure 37 in Appendix F and Panel B in Figure 7). Over time, the Chinese set up an increasing number of new counties in the south and replaced nominal suzerainty with actual bureaucratic control. Yunnan, the last of the provinces above to be brought under Chinese rule, was officially incorporated into China only in 1276, close to the end of our study period. Hence, our model captures China's political consolidation and its speed. In comparison, Europe always remains fragmented. The Herfindahl index for Europe stays as low as 0.2 as late as 500 periods into the simulations.

5.2 Inspecting the Mechanism

We inspect the mechanism behind Figures 8 and 9 by varying the parameter values of the obstacles and the productivities of the cells. First, we eliminate the role of climate in making conquest difficult by setting $\theta_{hot} = \theta_{cold} = 0$. This exercise, which we call "minimum set of obstacles," is motivated by Diamond (1997), who focuses on mountain ranges and seas, and irregular coastlines as barriers to conquest.[19] Panel A of Figure 10 shows that China unifies more rapidly than Europe. The main difference with respect to Figures 8 and 9 is that Europe unifies more by the end of the simulation.

We push the previous argument to its limit by eliminating the sea and geoclimatic obstacles to conquest: $\alpha_{sea} = 1$, $\sigma = 1$, and $\Theta = \mathbf{0}$. We call this exercise "no obstacles." In this case, cells will no longer secede as the probability of secession given by equation (4) is now always zero. Furthermore, indented coastlines no longer slow political consolidation as a war between two coastal cells across the sea is now as likely to occur and end up in annexation as a war between

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[19] Table 6 in Appendix C summarizes all the specifications reported by Figures 8–12. The two regions are comparable in resource availability across our different specifications.

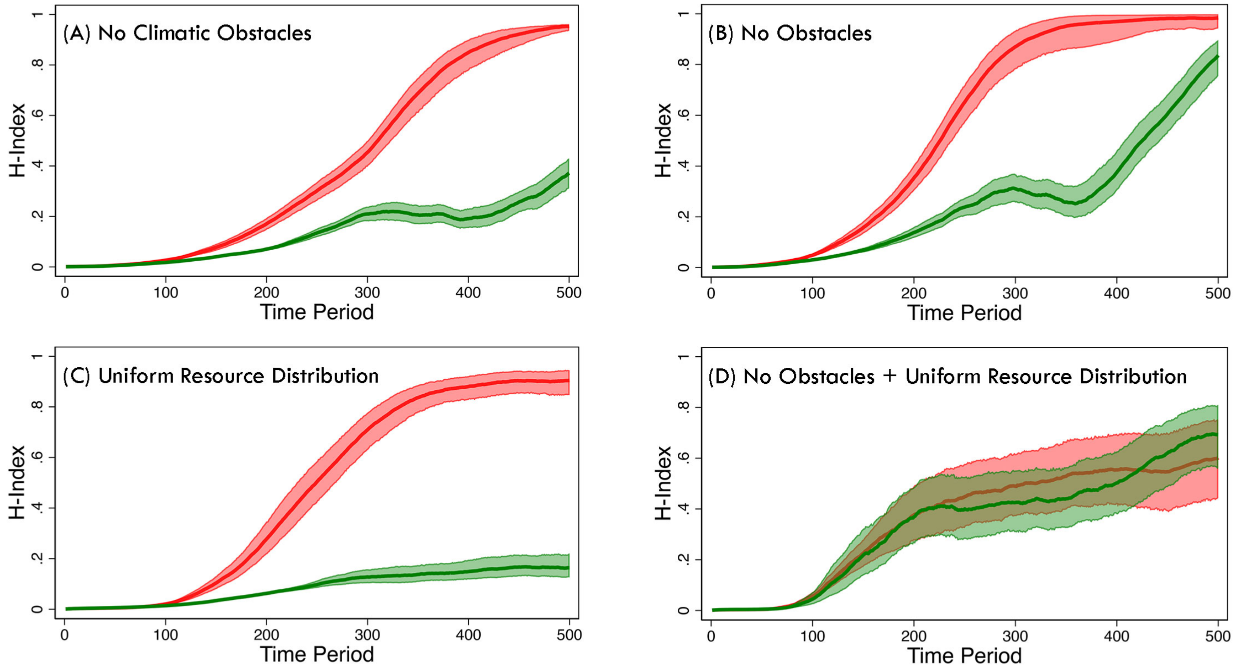

Figure 10: Varying parameter and productivity values. For each specification, we conduct the simulation exercise 30 times and display the average Herfindahl (unification) indices for China (red) and Europe (green). The shaded intervals depict the 0.95 bootstrap confidence interval.

two neighboring cells on a flat plain. Panel B of Figure 10 shows that, absent geographical and climatic barriers to conquest, Europe still unifies later than China, but will end up in a similar situation a few centuries later as an empire from Eastern Europe emerges to conquer the West. European unification remains sluggish because China's core productive areas are more compact, facilitating early consolidation.

Next, we assume that attainable caloric yield is uniform across our study area, with $y = 0.5$ for all cells. Thus, every cell is equally likely to engage in conflict. We call the third alternative exercise "uniform resource distribution." Panel C of Figure 10 is nearly the same as Figures 8 and 9, our baseline calibration.

Panel D of Figure 10 combines "no obstacles" and "uniform resource distribution." In this counterfactual, our geographical space is neither "fractured" by geographical and climatic obstacles, nor separated into land clusters of varying productivity levels. Panel D of Figure 10 shows that China no longer unifies earlier once we neutralize both aspects of fractured land. Panel D is a key result in our paper. It indicates that non-linearities play a central role in accounting for patterns of state formation: only when we remove both geographical obstacles *and* differences in resources do China and Europe unify at a comparable pace.

5.3 Robustness

How robust to the details of our exercise is our central finding of fast Chinese unification and persistent European polycentrism? In the next pages, we conduct two sets of robustness tests, but Appendix D reports the results of many additional tests.

Alternative Datasets. We choose the GAEZ v4 attainable caloric yields as our primary measure of productivity and the percentage of alluvial soil to account for early state formation because they are transparent and objective. However, they are not perfect (see Appendix A for details). Also, focusing on alluvium overlooks a vital source of China's early agricultural advantage: the deep loess deposits along the upper reaches of the Yellow River (see Subsection 5.4). These issues suggest that, under a better measurement, China's unification might be faster than in our baseline model.

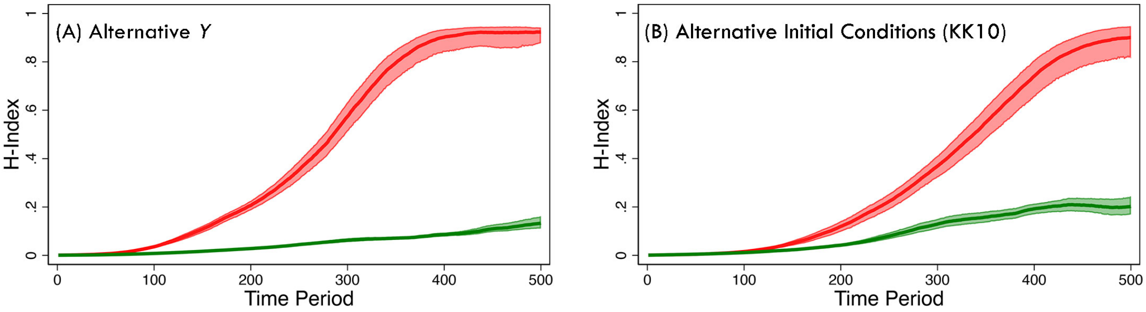

Figure 11: Alternative datasets. For each specification, we conduct the simulation exercise 30 times and display the average Herfindahl (unification) indices for China (red) and Europe (green). The shaded intervals depict the 0.95 bootstrap confidence interval.

Hence, we undertake two robustness checks. First, we replace the highest attainable yield based on the GAEZ v4 database with the Cropland Suitability Index computed by Ramankutty et al. (2002) as our y variable. The result is reported in Panel A of Figure 11. Under this alternative measurement, China completes its unification a bit earlier, while the consolidation of polities in Europe is even slower than in the baseline results in Figures 8 and 9.

Second, we use the KK10 Anthropogenic Land Cover Change dataset (henceforth KK10) in 1000 BCE (our $t = 0$) constructed by Kaplan and Krumhardt (2011) in place of the percentage of alluvial soil to capture the early lead that some areas enjoyed. The KK10 dataset estimates the fraction of land under human use in 1000 BCE (see Appendix A.2 for some potential problems with the KK10 dataset). Panel B of Figure 11 shows that China unifies even faster than in the baseline specification.

Appendix D.2 presents more checks using alternative datasets, including the History Database of the Global Environment (HYDE) version 3.1, the FAO Harmonized World Soil Database version 1.2, and temperature data of the 1960s drawn from WorldClim 1.4. In each case, we see China unifying much faster than Europe.

Alternative Conflict Mechanisms. Our second set of robustness tests modifies how wars occur in our model. In the baseline model, a cell enters into a war with one of its neighbors with a probability that depends on the relative productivities of the neighboring cells: the more productive a neighbor, the higher the probability that conflicts arise along its border.

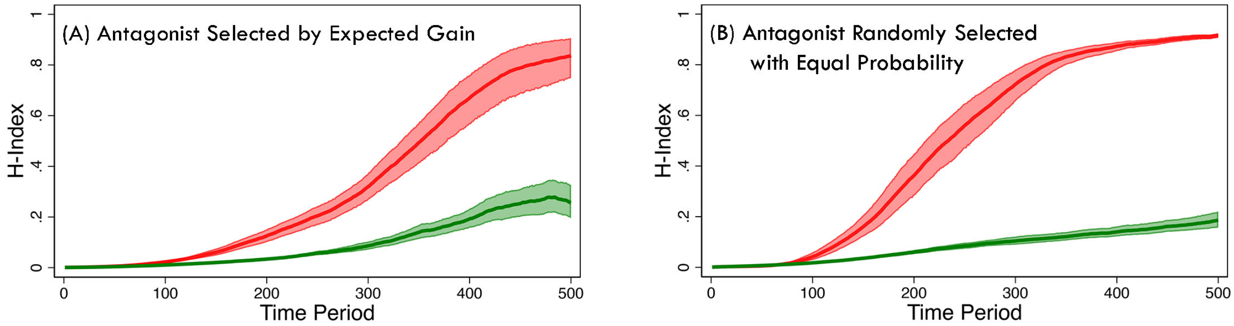

Figure 12: Alternative Conflict Mechanisms. For each specification, we conduct the simulation exercise 30 times and display the average Herfindahl (unification) indices for China (red) and Europe (green). The shaded intervals depict the 0.95 bootstrap confidence interval.

Figure 12 changes this probability. In Panel A, the adversary of the cell is the neighboring cell that offers the highest expected gain of conquest to the regime that controls cell k. In panel B, all the adjacent cells are potential adversaries with equal probability. In both instances, we continue to observe faster unification in China. Appendix D.3 implements two more alternative conflict mechanisms that consider the cost of transporting resources from where they originate to the location of fighting. The results are qualitatively the same.

5.4 Enriching the Model

Next, we add more realism to our model by considering the roles of rivers, the steppe, nomadic pastoralism, loess soils, the disease environment in the tropics, and the risk of hypothermia in cold regions. We first consider these enrichments separately before taking them jointly into account. This last case will constitute our preferred specification mentioned in Section 4.

Scholars have linked riverine connectivity and state-building. Diamond (1997, p. 331) noticed that "China's long east-west rivers (the Yellow River in the north, the Yangtze River in the south) facilitated diffusion of crops and technology between the coast and inland." The role of rivers in England's early development is widely discussed by medievalists and geographers (see Langdon, 1993; Jones, 2000). Armies used major rivers as a source of supply. For example, the Roman invasions of Persia often followed the Euphrates. Even as recently as the U.S. Civil War, most operations in the West followed rivers (the Mississippi, the Cumberland, etc.). At the same time, rivers separate basins and can impede movement between left and right banks. Historically, numerous battles took place by the crossing of an important river.[20]

Panel A of Figure 13 captures the role of rivers by increasing the probability of conquest when cells along the same river come into conflict and decreasing the probability of conquest when a riverine cell fights a non-riverine cell. The extension yields results similar to our baseline calibration, with only slightly slower political unification in China (see Appendix E for details about this and the following exercises in this subsection).

Panel B considers the early agricultural advantage enjoyed by areas with rich loess deposits and easy access to water (Scott, 2017). One such area is the loess plateau in the middle reaches of the Yellow River. This plateau was an important source—if not the crucial source—of Chinese civilization (Ho, 1975). Twenty thousand years ago, the region was covered mainly by grass (Jiang et al., 2013). This, coupled with the nature of loess soil—soft and stoneless—and easy access to water, made agriculture extremely rewarding even with primitive tools. Thus, we give cells with deep loess deposits a higher r, equivalent to alluvial areas having a head start in our baseline specification. While China unifies faster, the main findings remain unchanged.

The next two exercises focus on the Eurasian steppe as depicted in Ramankutty and Foley (2014). The first exercise (Panel C, Figure 13) considers the role of the steppe as a "highway of grass," i.e., a network of overland routes that facilitated the movement of caravans, pack animals, and people between Europe and Asia (Frachetti, 2008). We also engage with Turchin et al. (2013), who note that the Eurasian steppe influenced state-building both directly, because steppe nomads eliminated weaker and less cohesive polities, and indirectly, by developing and

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[20] Some notable examples include the Battle of Granicus (334 BCE), the Battle of Rhone Crossing (218 BCE), the Battle of the Medway (43), the Battle of Red Cliffs (208), the Battle of the Milvian Bridge (312), the Battle of Fei River (383), the Battle of Stamford Bridge (1066), and the Battle of Stirling Bridge (1297).

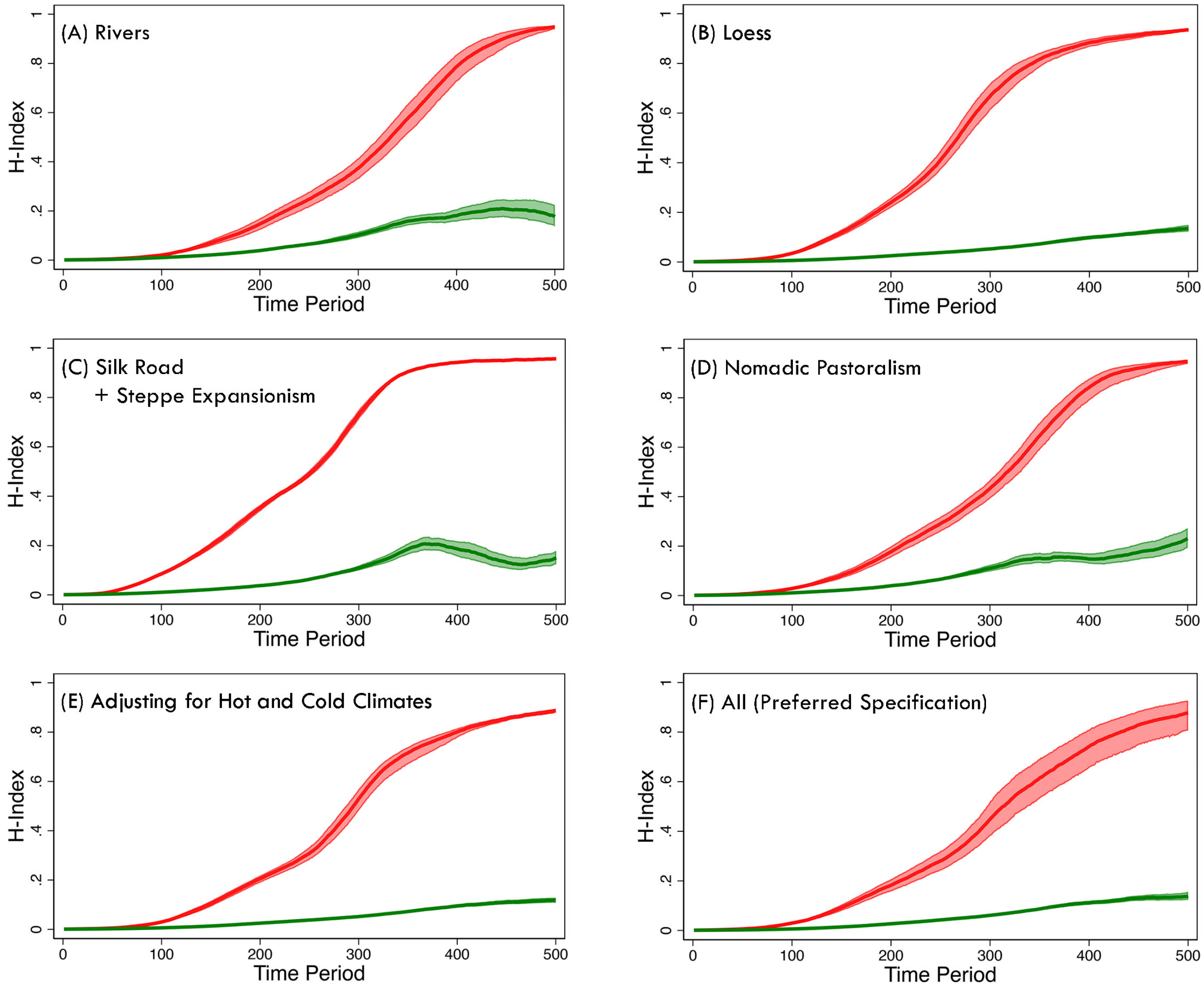

Figure 13: Enriching the model. For each specification, we conduct the simulation exercise 30 times and display the average Herfindahl (unification) indices for China (red) and Europe (green). The shaded intervals depict the 0.95 bootstrap confidence interval.

spreading technologies that intensified warfare. Barfield (1989) observed that the fragile ecology of the steppe helped shape a culture and practice of military expansionism.[21] The steppe east of the Altai Mountains, where temperature swings are greater than in any other part of the world, was especially prone to outward expansionism (Gibbon, 2003; Neparáczki, Maróti, and Kalmár, 2019; McNeill, 2021). Our second steppe exercise in Panel D adjusts the productivity of cells belonging to the Eurasian steppe to acknowledge that nomadic pastoralism, rather than cereal

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[21] Lattimore (1940) emphasizes the ecological foundation of the struggle between the pastoral herders in the steppe and the settled populations in China. Geography created a natural divide between the river basins of China and the Eurasian steppe. In the Chinese river basins, fertile alluvial soil, sufficient rainfall, and moderate temperatures encouraged the early development of intensive agriculture. In the steppe, pastoralism emerged as an adaptation to the arid environment. During periods of cold temperatures, when droughts led to catastrophic deaths among animal herds, the steppe nomads were often impelled to invade their settled neighbors for food (Bai and Kung, 2011).

cultivation, was the primary mode of livelihood in the steppe. In both exercises, we observe a slightly faster pace of unification in China, but no qualitative impact on our main findings. These modifications do not affect the productivity and barriers to conquering the core areas of state formation.

Panel E of Figure 13 allows for the influence of climate on pathogens and production. Historically, in tropical regions, diseases limited the use of farm animals and lowered human health and capital. In cold areas, land must be set aside for firewood in the winter and for pastoral activities, e.g., for meat (heme iron), fur, or wool to keep warm (Rosenzweig and Volpe, 1999). We discount the historical productivity values of cells in hot (>22°C for average monthly maximum temperature) and cold (<8°C for average monthly minimum temperature) regions by $\chi_{hot} \cdot \log(t_{max} - 21)$ and $\chi_{hot} \cdot \log(9 - t_{min})$ respectively. The formulas ensure that cells with more extreme temperatures are discounted more heavily. We set χ_{hot} and χ_{cold} so that cells at the 25th (-4°C) and 75th (29.5°C) percentile average temperature values have their productivities discounted by approximately 75%.[22] In this exercise, Europe's pace of political consolidation is somewhat slower, but the main results are unchanged.

Finally, in Panel F, we consolidate the modifications in Panels A–E to construct our preferred specification. Comparing this panel with Figures 8 and 9 shows that our central result is roughly the same as with the baseline calibration and the preferred specification. The former is more transparent, the latter richer in details and, thus, our favorite choice.

5.5 Taking Stock

This section has demonstrated that it is insufficient to compare average levels of ruggedness between China and Europe. Instead, what matters is the *distribution* of mountains and other geographical obstacles. While China is, indeed, more rugged than Europe, the location of geographical barriers promoted faster political unification in China. Furthermore, while topography alone is a sufficient condition to explain China's recurring unification and Europe's persistent polycentrism, it is not necessary. Take away topography, and we continue to observe more rapid unification in China. Only removing *both* geographical barriers and land productivity ensures that China and Europe unify at a comparable pace.

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[22] This is a very cautious correction. Cells at the 25th and 75th percentile temperature scales are mostly marginal lands for cultivation. Only 38% of the global land surface is arable (cropland and pastures).

6 Historical Discussion Informed by the Model

We can now use our model to discuss China and Europe, the role of the balance of powers, and the feedback between economic prosperity and political polycentrism.

China. At first glance, it is not obvious why geography should contribute to China's recurring political unification. China's terrain is significantly more rugged than Europe's (Hoffman, 2015). Also, the climatic distinction between China's temperate north and subtropical south is stark. Different climatic conditions divided China into two agricultural zones: historically, millet, sorghum, and wheat were the staple crops in northern China, while rice was dominant in the south. Different crops, in turn, encouraged the development of different social organizations and cultural norms (Talhelm et al., 2014).

China's political unification intrigued the Chinese themselves. During the late Warring States period, Lü Buwei, the chancellor of the Qin kingdom, asked why the number of states in China had decreased from tens of thousands c. 2200 BCE to three thousand c. 1600 BCE to only a handful in his time (Sellmann, 2002). Not long after Lü's death, all but one of the remaining surviving states would perish as Qin built China's first unified empire in 221 BCE. While the Qin dynasty lasted only 15 years, it marked a watershed. From 221 BCE to the founding of the Chinese Republic in 1911, China was unified for 1142 out of 2132 years (Ko and Sng, 2013). The record is unparalleled in world history.

Our model highlights the role of North China, referred to as the "Central Plain" in historical records, in driving these phenomena. While North China is only one of several macroregions of China (Figure 14), it has played an outsized role in Chinese history. The silty and flood-prone Yellow River, China's "mother river," runs through the region. Regularly inundated by flooding, which replenished the soil, North China was agriculturally precocious and productive even with primitive agricultural tools (Huang, 1988). Notably, North China is close to the flat cores of Northwest China (Guanzhong Plain), Middle Yangzi (Jianghan Plain), and Lower Yangtze (Yangtze Delta), which, together with the Central Plain, form the heartland of traditional China. In 1943, Sha Xuejun, one of the first modern political geographers in China, used the term "the hub of China" to describe the centrality of North China and its contiguous plains (Sha, 1972). Paraphrasing Mackinder (1942), he remarked: "To control China, one needs to first control its

Figure 14: China's macroregions as defined by Skinner (1977).

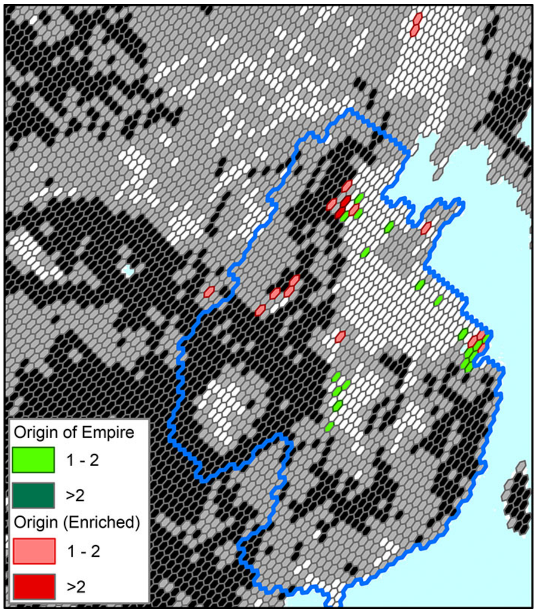

Figure 15: Flatness & centrality of North China (Background: Ruggedness).

heartland; To control China's heartland, one needs to first control its hub."

In our simulations, North China stands out for its flat terrain and high agricultural productivity. Its flatness facilitates military conquest and political consolidation (Figure 15 plots the cells from where the empire originates in each simulation). And once a unified state emerges in North China, the wealth of resources at its disposal makes it nearly impossible for the other Chinese regions—which find internal unification harder to achieve due to their rugged terrains—to resist conquest. This explains why the states of Qin and Jin could unify China despite its adversaries' attempts to maintain a balance of power during the Warring States and the Three Kingdoms periods (see Section 6 for a discussion of balancing and bandwagoning).[23]

Unlike the northern European Plain, which is non-compact and open to being invaded from multiple directions, North China was shielded by the Tibetan plateau and the Pacific Ocean on its two flanks. Meanwhile, the steppe and deserts north of China limited the expansion of the Chinese state in that direction. In our simulations, the North Chinese state typically expands in a southerly direction until it hits the tropical rainforests of Indochina, and an increased probability of secession hinders further expansion. Thus, the resulting empire often approximates the shape of China proper.

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[23] The historical literature points to the reforms enacted by the Qin state, notably by Shang Yang. These included conscription, large-scale irrigation projects, and a system of land registration (Hui, 2005). However, other warring states also pursued these reforms.

Besides the size and flatness of North China, its proximity to the core areas of Northwest China, Middle Yangtze, and Lower Yangtze also allowed a single powerful state to overcome its rivals and build a centralized polity. In our baseline simulation run, all unifications of China originate from three contiguous plains: the Central Plain, the Jianghan Plain, and the Lower Yangtze Delta (Figure 15). The proximity of North China to the Mongolian steppe likely provided a further martial impetus to China's unification. When we enrich the model by incorporating the roles of the steppe and the loess plateau, the Guanzhong Plain of Northwest China and Eastern Mongolia-Manchuria are added to the list of origins of the Chinese empire. This is broadly consistent with the historical record summarized in Table 3 of Appendix F. All ten dynasties that controlled most or all of China proper at their peaks originated north of the Yangtze River, and all had their capital cities in the north (except for the Ming dynasty for several decades). Historically, there were long periods of political fragmentation in China: the Warring States period (475 BCE–221 BCE), the Six Dynasties period (220–589), the Five Dynasties and Ten Kingdoms period (907–960), and the Southern Song period (1127–1279). However, if a powerful Chinese state arose to establish stable rule in North China, it would often subdue rival kingdoms and unify "all under heaven."

Europe. Figure 16 shows the evolution of the average size of the five largest polities in China and Europe in our preferred specification. In contrast to China, where one polity quickly dominates the rest, in Europe (including or excluding Eastern Europe), we typically observe the simultaneous emergence of several middle-sized polities. The size gap between the largest and fifth-largest European polities is never of the same magnitude as in China. In other words, Europe is distinctively polycentric and develops into a series of medium-sized states surrounded by small polities.

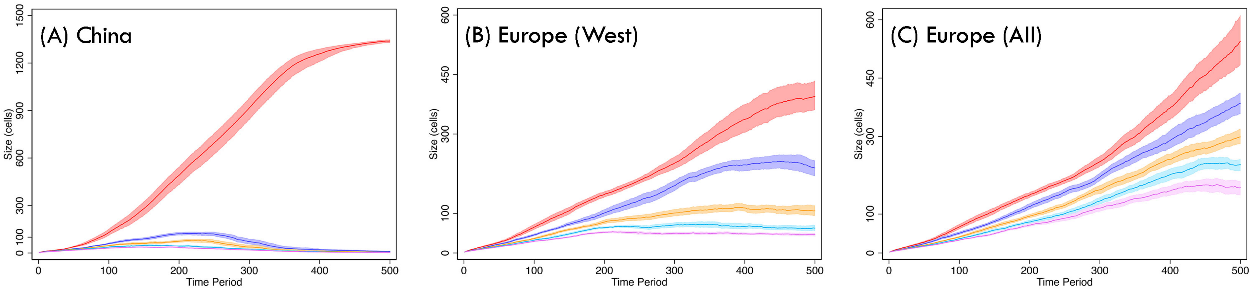

Figure 16: Land Area of the Five Largest Regimes in China and Europe (West, All).

This result is in line with European history from the Middle Ages onward. Scheidel (2019, pp. 338–339) notes that after the fall of Rome, Europe was composed of "multiple states that did not dramatically differ in terms of capabilities." This had significant implications for the balance of power (discussed below).

The closest Europe came to being ruled by a single polity was during the Roman Empire. This was a unique development in European history; at no other point did a single polity come close to establishing stable rule over the majority of Europe. Numerous factors are important in explaining the rise of Rome: the Mediterranean Sea as a conduit to empire, Rome's peripheral position on the edge of the Eastern Mediterranean state system based around the Fertile Crescent, its early ability to incorporate nearby populations and to build an alliance system of Italian cities, its unusual bellicosity (Harris, 1979, 1984), and favorable climatic conditions during the classical period (Braudel, 1972, 1949; Horden and Purcell, 2000; Harper, 2017; Scheidel, 2019). In Subsection 8, we use our model to study under what conditions a Mediterranean empire could emerge. We find that the rise of Rome likely depended on the highly contingent factors for which these historians have argued.

After the fall of the Roman Empire, the closest Europe came to being unified by a single ruler was during the 16th century under the Habsburg emperor Charles V. Importantly, for our purposes, Charles V did not acquire this empire by conquest, but by generations of successful marriages and dynastic luck. He also did not create a unified state, but ruled his disparate kingdoms as separate entities. Our model does not directly speak to how the Habsburgs chanced on a European-wide empire. However, it speaks to the difficulties Charles V had in managing his domains. Geography prevented Charles V from focusing on facing the Ottomans in the Mediterranean, driving France out of Italy, or subduing Protestant German princes. The final admission of the power of geography came when, upon his abdication, Charles divided his territories between his son Philip II of Spain (r. 1556–1598) and his brother Ferdinand I (r. 1556–July 1564).

Beyond accounting for the Habsburgs' experience, our model also speaks to the failures of Louis XIV and Napoleon to successfully build a hegemonic state in Europe against a combination of several medium-sized states led by Great Britain. Our model delivers many medium-sized states not only because of the presence of mountain barriers in Europe but also because the most productive agricultural land in Europe is dispersed rather than concentrated as in China.

The Balance of Power. Our model lacks strategic interactions: polities enter into conflicts and win or lose them based on exogenous probability distributions. For instance, we do not allow polities to think about issues such as state power investment, a dynamic path of conquest, or the formation of alliances—for instance, through strategic marriages, a common form of political consolidation in European history (Levine and Modica, 2013; Dziubinski, Goyal, and Minarsch, 2017).

The most important reason why we do this is computational. Introducing even a minimum of strategic thinking will complicate the model so much that simulations would become unfeasible given computing power and current algorithms.

However, we conjecture that strategic interactions will likely strengthen our results. A key idea in international relations is the balance of power (Morgenthau, 1948; Waltz, 1979; Mearsheimer, 2001). States form alliances against potential hegemons, limiting their expansion. Examples of balancing in European history include the shifting compositions of the Greek poleis leagues,[24] the polyhedric structure of arrangements in the Italian peninsula during the Middle Ages and early modern period, or the alliances in Europe first against the Habsburgs and later against the House of Bourbon. More recently, balancing explains why the French Third Republic, probably the most democratic nation in Europe around 1914, could be the staunchest ally of Tsarist Russia, the epicenter of reaction, or why Churchill wrote: “If Hitler invaded Hell I would make at least a favourable reference to the Devil in the House of Commons” (Churchill, 1950, p. 370). Because Europe had different nuclei for forming states that could form the seed of multi-faced balancing coalitions, the balance of power was the predominant structure of international relations for much of its history, reinforcing the mechanisms in our model.

Why did the same balancing logic not prevail in China? Because the early formation of a large polity in northern China, illustrated by our simulation, triggered the opposite force to balancing: bandwagoning. In this situation, weaker states align themselves with the hegemon (or integrate), as resistance is futile without alternative nuclei. The Three Kingdoms period (220–280), which opened at the end of the Han dynasty, shows this point. The alliance between Wu and Shu could only resist Wei until the northern kingdom regained its strength. But Wu and Shu were doomed once Wei could mobilize the northern plain’s resources. Our model

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[24] The oligarchic Corinth is a textbook example of a balancer, deftly switching between its alliances with Sparta, Athens, and Thebes to ensure none of its rivals became too powerful.

suggests that the lack of geographical barriers in northern China and the potential for cumulative conquests in this core region of historical China as the reasons for bandwagoning. In other words, given the geographical features of China, balancing was likely never a feasible Nash equilibrium, but bandwagoning was, reinforcing the mechanisms in our model.

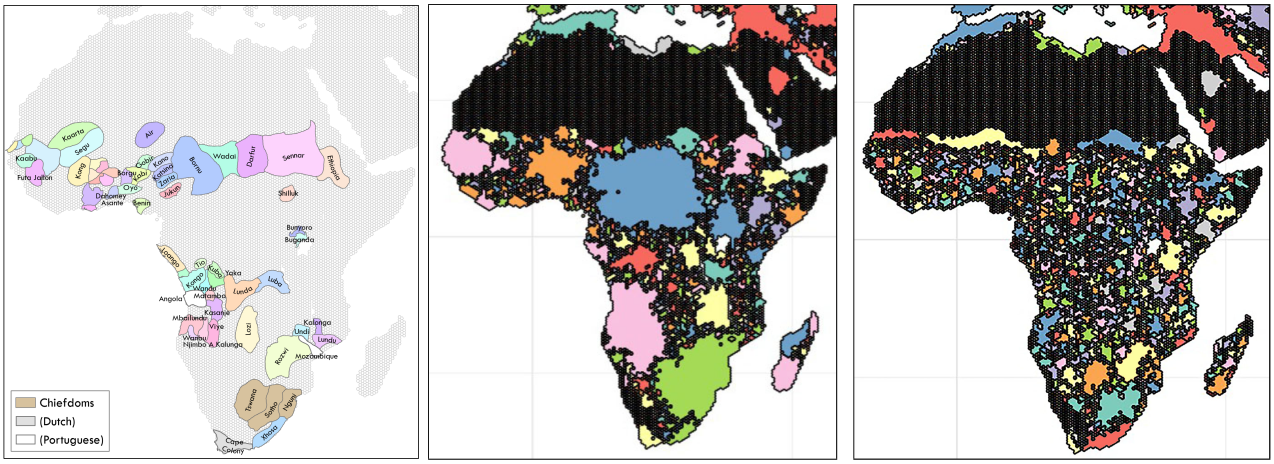
Feedback between Economic Growth and Political Fragmentation. To keep the model simple, we also abstract from how political fragmentation or unification might feed back into economic growth and, through it, into the power of different polities to conquer or defend. Abramson (2017) has argued that the economic prosperity that small independent polities, such as Venice or the United Provinces of the Netherlands, enjoyed thanks to Europe's polycentrism allowed them to punch above their weight militarily and survive for centuries. Eisenstadt and Rokkan (1973) argue that the core of the modern European states appeared where no large urban centers could assert their independence. Conversely, once a sufficiently large polity has emerged, its urban structure and the transportation network built around it can further unify the country (think about London in England). Thus, these feedback channels will likely reinforce the main mechanisms in our simulations.

7 Africa and the Americas

In this section, we investigate the predictions of our model for state formation in Africa and the Americas. Due to length constraints, we discuss these results briefly here and leave their detailed assessment to the appendix.

Africa. Historically, state formation in Africa differed from state formation on other continents. No large, sustained agrarian state had emerged in sub-Saharan Africa outside Ethiopia before 1500, the calibrated end of our simulation (many states rose and disappeared without long persistence over time). Panel A of Figure 17 shows how, by 1750, the region was still composed of many small states and communities.

Our baseline simulations, however, suggest that Africa should be home to several large states (Panel B of Figure 17). While the prediction is off the mark, it is unsurprising. As we discussed earlier, the GAEZ v4 dataset overestimates agricultural productivity in hot regions like sub-Saharan Africa. Because of this, in our baseline simulations, we observe political



(A) Distribution of states in 1750 (Overy, 2004).

(B) Baseline specification: representative output ($t = 500$).

(C) Climate & timing adjusted: representative output ($t = 500$).

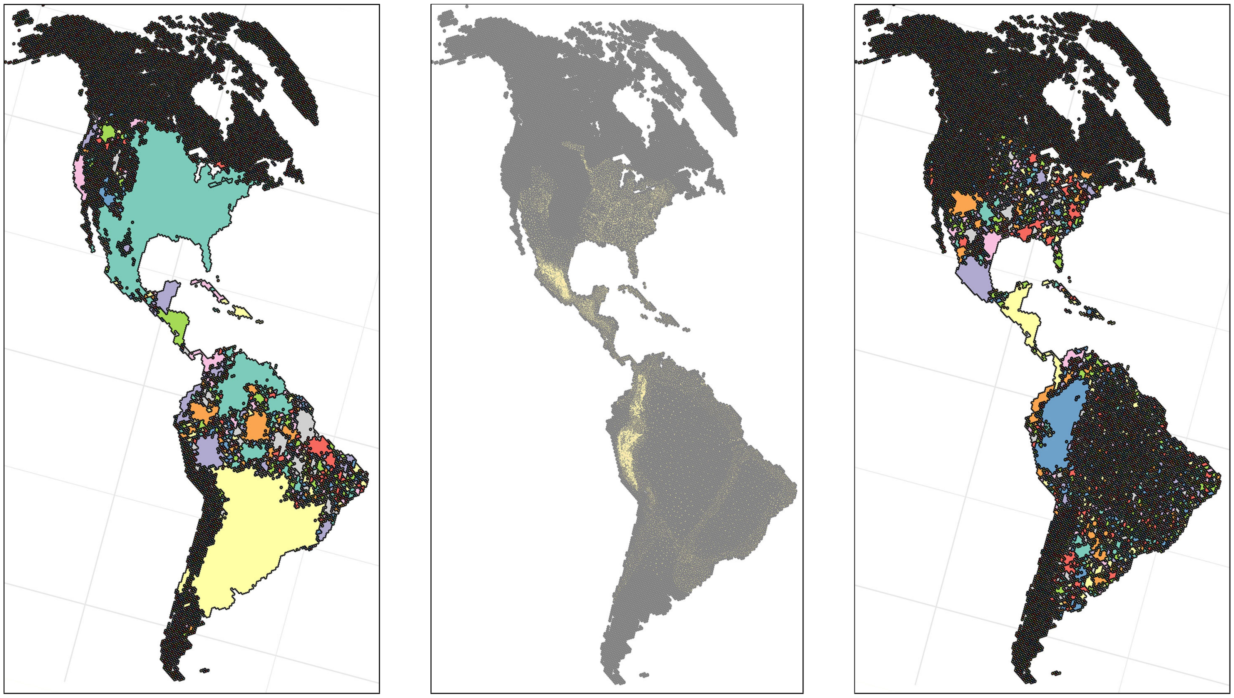
Figure 17: Accounting for the relative absence of large-scale states in Sub-Saharan Africa.

consolidation in every part of sub-Saharan Africa.

How can we make progress reconciling theory and data? Scholars have highlighted sub-Saharan Africa's relative isolation from the rest of Eurasia in leading it onto a path of technological and agricultural development that was less conducive to state formation (Childe, 1957; Goody, 1971; Diamond, 1997), and a climate-enabled disease environment that slowed growth (Weil, 2014; Alsan, 2015; Bellone, 2020). We consider these factors by delaying the start of the cells' ability to conquer other cells to $t = 150$ and by correcting the GAEZ v4 productivity as in our preferred specification (see Appendix G for details). When we do so, Panel C of Figure 17 shows results that look much closer to what we observed historically (without impacting state formation in Eurasia due to geographical distance).

Our results also suggest other possibilities to improve the model. For example, it might be the case that social structures in Africa mean that small rulers were less willing to go to war with their neighbors, which might have slowed the formation of large states (see, for some intriguing evidence, Moscona, Nunn, and Robinson 2018).

The Americas. According to GAEZ v4, the Americas are home to the world's most productive lands. Each of the 50 hexagons with the highest attainable caloric yields in the world is in present-day Argentina or the United States. As a result, in our baseline simulations, we generally observe empires emerging in Argentina and the eastern United States (Panel A of Figure 18), which is inconsistent with the historical observation that pre-contact state formation was most advanced in Mesoamerica and the Andes.



(A) Baseline specification: representative output ($t = 500$).

(B) Maize cultivation in 1500 (adapted from Fig. 1, Goodman and Galinat, 1988).

(C) Accounting for maize and guano: representative output ($t = 500$).

Figure 18: Locating the large states in pre-Columbian Americas.

This counterfactual result is driven by the fact that our use of GAEZ v4 assumes that maize, the major indigenous crop in the Americas, is available throughout the continent from $t = 0$. Historically, this is inaccurate. While maize was domesticated from Balsas teosinte, a wild grass, in the Mexican plateau about 9000 years ago, its spread across the Americas was slow (Staller, Tykot, and Benz, 2006). Possible reasons include the wide climate and terrain variability across the vertically oriented American continent, which created obstacles to its adaptation across latitude and elevation. Also, the lack of iron tools in the Americas to deal with the prairie sod might have restricted maize cultivation in the fertile plains of the Midwest United States and northern Argentina (Hudson, 2004; Bamforth, 2021). For example, the earliest evidence of maize consumption in the middle Ohio Valley is as late as 900 (Staller, Tykot, and Benz, 2006, p. 230). On the eve of the Columbian Exchange, the crop was most intensely cultivated in the Mexican plateau and neighboring Guatemala and Yucatán, as well as Peru (Panel B of Figure 18).

Furthermore, in the case of Peru, scholars have highlighted the role of guano, the accumulated feces of marine birds and bats. Guano was the richest organic source of nitrogen compounds known in the premodern world. Archaeological evidence suggests that Andean inhabitants understood the use of guano as a natural fertilizer as early as 2,000 BCE (Poulson et al., 2013). This was made possible by an abundance of guano-producing birds, including the Peruvian cormorant, the Peruvian pelican, and the Peruvian booby. Guano turned the relatively infertile Andean highlands and coastlines into some of the most productive fields in pre-contact America (Cushman, 2014) and, thus, it enabled the agricultural development and political ascendancy of the Inca Empire and its predecessors (Santana-Sagredo, 2021; Rodrigues and Micael, 2021).

We incorporate these insights by accounting for (1) the timing and spread of maize cultivation in the Americas and (2) the use of guano in the Cusco basin and its surroundings. As Panel C of Figure 18 illustrates, once we consider these factors in our simulations, the Americas cease to produce supersized polities. Now, relatively large states typically emerge on the Pacific coast and in the Andean highlands, as well as in Mesoamerica, states that resemble the Triple Alliance and the Inca Empire. As in the case of Africa, these modifications do not change the results of the simulations in Eurasia. See also Figure 35 in Appendix G.

During the last decades, we have learned much about the pre-contact Americas, with the consensus among researchers tilting toward the Americas being more populated and having more sophisticated state structures than previously thought (Mann, 2006). Our results in Panel C of Figure 18, with a wide variety of emerging polities, can be interpreted as providing additional support to this emerging consensus and hint that there are still complex societal structures, such as those uncovered in Llanos de Moxos (North Bolivia), that remain to be discovered.

Taking stock. The study of Africa and the Americas shows that the simplest fractured-land hypothesis falls short in these two regions and that it requires additional mechanisms to account for state formation. We have used our model to suggest which of these additional mechanisms one needs to reconcile theory and data.

8 Extensions

This section considers several extensions of our model as external validity checks.

Exogenous Shocks and Dynastic Cycles. Introducing exogenous shocks allows us to probe path dependence. Are the patterns of state formation observed in the model generated by initial conditions? Or, on the contrary, can the introduction of large-scale shocks create changes in the overall distribution of polities?

The idea that external shocks explain the rise and fall of particular polities is a popular thread in Chinese historiography, where the rise of empires is often interpreted through the lens of dynastic cycles (Usher, 1989; Chu and Lee, 1994). Recently, scholars have pointed to climate change as a cause of these dynastic cycles (see Zhang et al., 2006; Fan, 2010). Climatic factors have also been adduced as necessary in the rise and fall of the Roman Empire and the social upheavals in late medieval and early modern Europe (Parker, 2013; Campbell, 2016).

We incorporate climatic and other random sociopolitical shocks by distinguishing between general system-wide and regime-specific crises. General shocks such as the collapse of Bronze Age empires c. 1177 BCE or the Little Ice Age of the 17th century are potentially significant as they have the potential to generate synchronized changes across a region—something observed by Lieberman (2003, 2009), who notes the "strange parallels" of synchronized administrative cycles across Eurasia. In contrast, regime-specific crises are modeled as localized shocks, such as the Twenty Years' Anarchy in the Byzantine Empire (695–717), the An Lushan Rebellion of Tang China (755–763), or the War of the Roses of 15th century England. In our extension, these two types of crises occur randomly given exogenous probabilities.

In this version of the model, political cycles are muted in Europe, which never achieves complete unification despite short periods of a hegemonic state. By contrast, China intersects periods of sustained unification interrupted with periods of disunity, resembling the successive dynasties of Chinese history (which motivated the opening quote of this paper). The result echoes Root (2017, 2020), who contrasts patterns of network stability in China and Europe and argues that China's organization as a hub-and-spoke system was less resilient than Europe's polycentricity, and Ko, Koyama, and Sng (2018), who show that the Chinese empire displayed greater volatility of population and economic output than Europe after the collapse of the Roman Empire.

The Mediterranean Sea. In our baseline simulations, we do not see political consolidation in Europe. But then: What about the Roman Empire? We can use our model to shed light on the conditions necessary to generate the Roman Empire and explore why, after its collapse, no subsequent state ever came close to unifying as large a territory again.

In the first exercise, we improve the agricultural productivity of the area around the Mediterranean. We are motivated by historians such as Harper (2017), who have pointed to the confluence of favorable climatic conditions that facilitated the rise of the Roman Empire. This exercise generates slightly larger polities in the Mediterranean but does not come close to causing a polity like the Roman Empire.

In the second exercise, we give Rome a military advantage. Classicists like Harris (1979, 1984) have argued that Republican Roman culture was uniquely bellicose and that this gave Rome an edge in war. This extension also does not generate anything like a Roman Empire.

Finally, we combine both extensions. In this case, we find larger empires emerging, another example of non-linear effects in our model. These Mediterranean-based empires, however, do not regularly extend beyond the Alps and, hence, do not resemble the full extent of the Roman Empire. This suggests that, while exogenous factors such as climate may have played a role in the expansion of the Roman Empire, this was both highly contingent (such as Rome's good fortune in gaining early control of the entire Mediterranean before many competing powers could appear), as many historians have observed, and also a one-off event that was not repeated.

What if Europe had a head start? Historically, the Roman Empire overlapped in time with the Han Empire in China. While the empire of Han was repeatedly reconstructed over time, the Roman Empire was never reinstated (Scheidel, 2009). Was this a fluke?

To investigate, we use the world map of 250 CE as the starting point of a new set of simulations. In 250 CE, the Rome Empire was still the dominant force in Europe, while the Han Empire had fragmented into three kingdoms, an episode that gave rise to the opening quote of our paper. We incorporate exogenous regime-specific shocks, as discussed above, to allow polities to fragment and consolidate. We find that, despite Europe's head start in political consolidation vis-à-vis China, its level of political consolidation tends to fall over time as China's level rises quickly to cause a switch of places. We also observe that if the "Roman Empire" that exists at $t = 0$ collapses under a regime-specific shock, it is never restored. But in China, every political collapse is always followed by a new phase of political consolidation. Appendix E.5 provides more details.

As a further robustness check, we also examine an alternative scenario whereby, at the start of the simulation, China is fragmented into its seven constituent regions as depicted in Figure 14 while a large polity of the size and shape of the Carolingian empire dominates Europe. In this fictional scenario, we still observe that China always ends with a higher Herfindahl index even though it starts from a lower place by artificial construct. In sum, a high degree of political consolidation in Europe is unsustainable, just as political fragmentation in China does not last. More generally, these two exercises show that the initial conditions of our simulation do not change the main result of our paper: unification in China and polycentrism in Europe.

State Formation across Eurasia. Consistent with the historical record, in our simulations, the formation of large states is pronounced in East Asia. As Scheidel (2019) notes, the "easternmost macro-region, East Asia, has been characterized by much stronger dominance of hegemonic empire than any of the others." By contrast, Europe is distinctively polycentric (Figure 16). To what extent can our model also explain broader patterns of state formation across Eurasia beyond East Asia and Europe?

To answer this question, we compute the size of the five largest regimes in Europe, East Asia, South Asia, Southeast Asia, and the Middle East. We observe a hegemonic state regularly emerge in China, northern India, and the Middle East (Figure 19). However, full political consolidation occurs nowhere else except in China. Inspecting the simulations, we can gauge, for example, why a single huge polity does not always conquer the entire Indian subcontinent. First, the Himalayas and the Hindu Kush in the north, the Thar Desert in the west, and the thick jungles of Burma and Gondwana in the east presented significant impediments in terms of either rugged terrain or low agricultural productivity that discouraged state expansion in these directions.[25] Second, the rugged Deccan plateau in southern India was a significant barrier to empire-building.[26] Third, the tropical climate of southern India, which historically posed difficulties in gathering and moving armies (Lieberman, 2003, 2009), further impeded the conquest of the south by the north.

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[25] While the thick jungles of Burma and Gondwana created unbridgeable outer limits to Mughal expansion (Gommans, 2002, p. 198), the mountains were not insurmountable to armies. The Mughals conducted mountainous expeditions into Kashmir (1561, 1585, 1588), Garhwal (1635, 1656), Baltistan (1637), and Ladakh and Tibet (1679–84). However, the lack of forage and food impeded the extension of permanent political authority north of India. As Gommans (2002, p. 23) puts it: "Indian armies were faced by tremendous logistical problems. One mid-18th-century source considered the Kabul area a land of snow: 'Men and cattle from India are not able to withstand the icy cold winds of that area. That is why it is difficult for the people of India to capture and occupy the Muslim countries of that area'." See also Nath (2019) for Mughal warfare and the South Asia environment.

[26] The Deccan plateau rises to over 1000 meters. It was the site of numerous conflicts between states from northern India and those from southern India. Multiple Hindu states in the Deccan could resist the expansion of Muslim empires such as the Mughals.

Likewise, while we also observe large states arising in the Middle East, the process of political consolidation in the region is typically incomplete because of the region's relatively rugged terrain and large tracts of deserts in the region's interior.

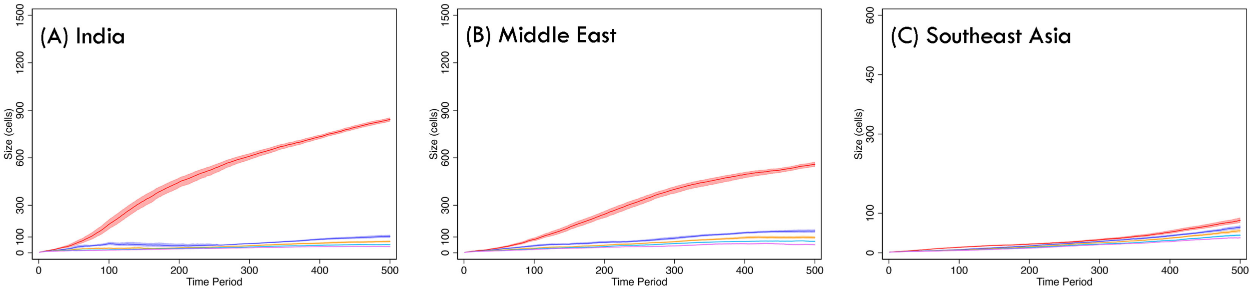

Figure 19: Land Area of Five Largest Regimes in India, Middle East, and Southeast Asia.

In the case of Southeast Asia, the tropical climate and the rugged terrain explain why, in our simulations, polities in the region are usually small, and the political map is highly fragmented even compared with Europe.[27] In sum, comparing Figures 16 and 19, while China is unique in its extremely robust tendency toward political unification, Europe's inclination toward polycentrism is also unparalleled.

9 Conclusion

This paper has developed a dynamic model to adjudicate among competing explanations of Europe's polycentrism and China's political centralization. Our analysis evaluates Jared Diamond's argument that Europe's mountain barriers and the shape of its coastline were responsible for its polycentrism, whereas Chinese geography encouraged political centralization. By developing a model of state formation that quantitatively incorporates the role of topography and agricultural productivity, we provide a rigorous formulation of the fractured-land hypothesis. Our simulations demonstrate that either topography or the location of productive land can generate political unification in China and persistent polycentrism in Europe.

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[27] Southeast Asia was less populous than other major regions of Eurasia until the 19th century, and state formation took place later and under less favorable conditions there than elsewhere (Lieberman, 2003, 2009). Some periods saw the formation of states with a considerable geographical scope, such as the Khmer Empire in the 9th century, the Taoungoo Empire in the 16th century, or the Kingdom of Siam in the 18th and 19th centuries. But these larger states only retained regional hegemony for brief periods, and the more common pattern was political fragmentation.

We have also documented how the simplest fractured-land hypothesis misses the observed slow speed of state formation in Africa and the Americas. We have proposed several additional mechanisms, previously suggested by many historians, that can reconcile our model with the data. In that sense, we have used our model as a measurement device to suggest improvements in the theory.

Finally, our model can be a starting point for additional explorations. For example, we could incorporate military technological change (Hoffman, 2015), investment in state capacity (Gennaioli and Voth, 2015; Johnson and Koyama, 2017; Becker et al., 2020), or epidemic diseases (Voigtländer and Voth, 2013b). We could also add climatic change, migration, time-varying agricultural technology (new crops, irrigation systems), variation in transportation capabilities (Bakker et al., 2018), or cultural aspects that feed back into the creation of states. For instance, after a state has existed for many periods, its inhabitants may have developed an "imagined community," making it harder to conquer and easier to maintain unified (Anderson, 1991). Think about how, in a few generations during the late Republic and the Principate, the conquered peoples of Italy started thinking about themselves as "Romans." Also, some cells may share a religion, which makes unification easier, or be separated by it, which makes conflict more likely.

In summary, evaluating the relative contributions of geographical and human endowment to state formation would be essential. Although such a measurement is beyond the scope of the current (already lengthy) paper, our methodological approach is flexible in allowing for these and many other quantitative exercises and generating probability distributions of historical outcomes. We hope to see many of those extensions soon.

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Online Appendices for "The Fractured-Land Hypothesis"

We now include a series of appendices with extra information regarding our main paper, "The Fractured-Land Hypothesis."

A Additional Information on Data

This appendix provides more details on the datasets listed in Table 2 that we use to construct our baseline specification and robustness checks.

Table 2: Data Sources

	Variable	Data	Source	Specification
1	Productivity (y)	Global Agro-Ecological Zoning (GAEZ) v4	FAO & IIASA (gaez.fao.org)	Baseline
2	Productivity (y)	Cropland Suitability Index	Ramankutty et al. (2002)	Alternative
3	Productivity (y)	History Database of the Global Environment (HYDE 3.1)	Goldewijk et al. (2017)	Alternative
4	Early development (r)	Digital Soil Map of the World (DSMW)	FAO (fao.org)	Baseline
5	Early development (r)	Harmonized World Soil Database (HWSD) v1.2	FAO (fao.org)	Alternative
6	Early development (r)	KK10 scenario of Anthropogenic Land Cover Change	Kaplan and Krumhardt (2011)	Alternative
7	Temperature (x_{hot}, x_{cold})	WorldClim 1.4 Paleoclimate for the Mid-Holocene	WorldClim (worldclim.org)	Baseline
8	Temperature (x_{hot}, x_{cold})	WorldClim 1.4 Climate Data (1960s)	WorldClim (worldclim.org)	Alternative
9	Ruggedness (x_{rugged})	90m SRTM digital elevation data	CGIAR-CSI (srtm.csi.cgiar.org)	All

A.1 Historical Resource Availability, y

Our primary source of historical resource availability is the Food and Agriculture Organization's Global Agro-Ecological Zones database version 4, or GAEZ v4 in short (Table 2, Row 1).[28] In that way, we follow a growing literature that has used the GAEZ dataset (in its different vintages) to investigate the historical origins of development. See, among others, Alesina, Giuliano, and Nunn (2013), Galor and Özak (2016), and Mayshar, Moav, and Pascali (2022). We employ the most recent vintage of GAEZ v4, released in 2021. Compared with previous versions, this vintage is based on higher-resolution data and improved methods (Fischer et al., 2021).

The database divides the world's land surface into grid-cells of size 5' latitude/longitude (approximately 75 km^2). The dataset reports the potential annual yields (in weight per unit of

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[28] See `https://gaez.fao.org/` for a complete description of the dataset.

area) of 53 crops for each grid-cell. Among these crops, we focus on cereal grains, which are appropriable and, hence, central to the rise of tax-levying states (Mayshar, Moav, and Neeman, 2017; Mayshar, Moav, and Pascali, 2022).

We follow Galor and Özak (2016) and (1) identify the major cereal grains that existed on every continent before the Columbian Exchange, (2) compute the GAEZ v4 yield of each of these crops for every cell of the continent, (3) convert the yields into calories using the National Nutrient Database for Standard Reference published by the U.S. Department of Agriculture, and (4) identify the highest calorie-yielding cereal for every cell to determine the attainable caloric yield of the cell. Figure 5 shows the results of this exercise. Table 3 lists the cereal grains in our dataset, pre-Columbian distribution by continent, and caloric contents.

Table 3: Cereal Grains: Pre-Columbian Availability and Caloric Content

Cereal Grain	Pre-Columbian Availability	Calorie ('000 per gram)
Barley	Asia, Europe, North Africa	3.52
Buckwheat	Asia	3.43
Foxtail Millet	Asia, Europe, North Africa	3.78
Indigo Rice	Asia, Sub-Saharan Africa	3.70
Maize	The Americas	3.65
Oat	Europe, North Africa	2.46
Pearl Millet	Asia, Africa	3.78
Sorghum	Asia, Africa	3.39
Rye	Europe	3.38
Rice (Wetland)	Asia, Sub-Saharan Africa	3.70
Wheat	Asia, Europe, North Africa	3.42

Source: Galor and Özak (2016) and USDA National Nutrient Database for Standard Reference.

GAEZ v4 data provide potential yields of different crops based on (1) two alternative assumptions of water supply (rain-fed and irrigation), (2) three different levels of input/management (low, medium, high), and (3) three 30-year historical reference periods (1961–1990, 1971–2000, and 1981–2010). On top of these, the dataset provides two different measures of crop yield: agro-climatic potential yield and agro-ecological attainable yield. Agro-climatic potential yield considers climatic factors such as temperature, precipitation, sunshine duration, wind speed, and humidity but does not account for soil and terrain conditions. Agro-ecological attainable yield considers all of these conditions.

We employ the hypothetical yield based on rain-fed, low-input agriculture to mitigate concerns about the endogeneity of potential yields. We consider 1961–1990, the earliest period available, to minimize the impact of modern technology on our estimates. Finally, we choose agro-ecological attainable yield over agro-climatic potential yield because the latter's omission of soil and terrain considerations introduces a large systematic bias into its estimates.

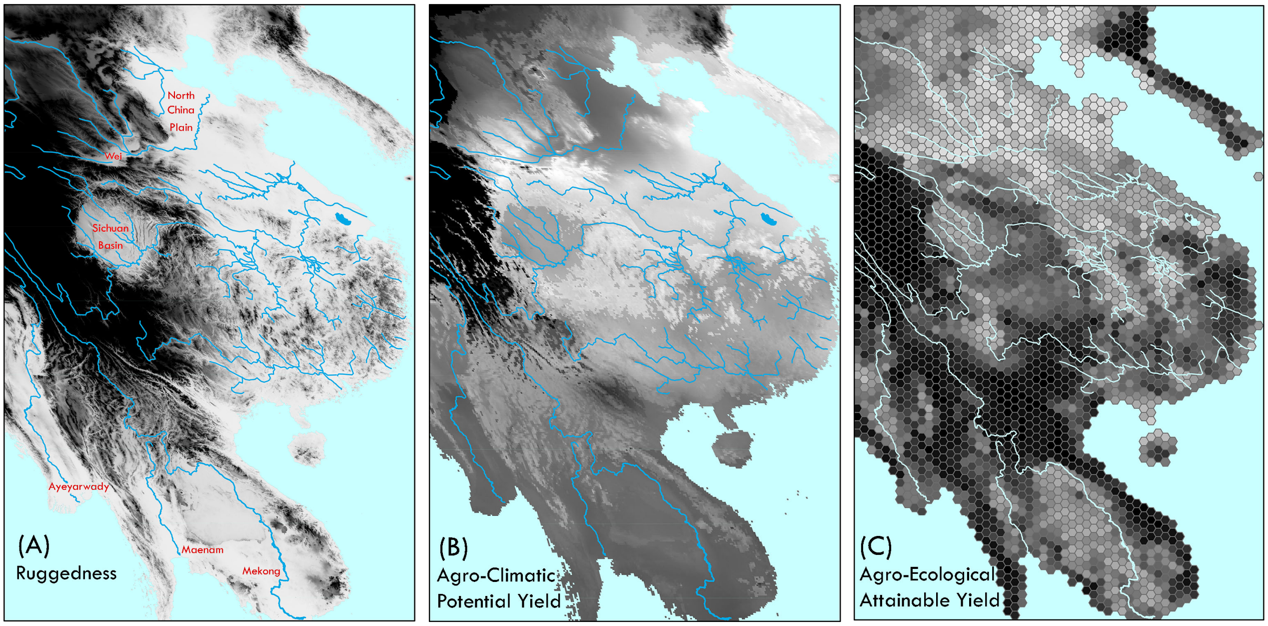

Figure 20: In Panel A, a darker shade implies a higher elevation. Panels B and C display the GAEZ v4 agro-climatic potential yield and agro-ecological attainable yield, respectively (darker implies lower productivity).

Figure 20 illustrates the bias. Panel A plots the terrain of East Asia, with a lighter shade representing lower ruggedness. Panel B depicts the agro-climatic potential yield (in calories), with a lighter shade representing higher productivity. Comparing the two panels shows that low-lying and flat areas in China are often less productive than more rugged areas. For instance, in Panel B, the Sichuan basin, historically referred to as "a land of plenty" (*tianfu zhiguo*) by the Chinese, is relatively barren compared to the mountains that enclose it. Likewise, the Wei River Valley, which formed the power base of the Qin dynasty, and the North China Plain, have lower agro-climatic potential yields than their more rugged surroundings. The problem is not limited to China. In Indochina, the plains of the Ayeyarwady (Myanmar), Maenam (Thailand), and Mekong (Vietnam, Laos, Cambodia) rivers have lower agro-climatic potential yields than their upstream hinterlands. These perverse patterns are likely driven by the monsoon in East Asia and the fact that mountainous areas generally experience higher rainfall during the summer monsoon season. Hence, we discard the agro-climatic potential yield in favor of the agro-ecological attainable yield. Panel C shows that the agro-ecological attainable yield is lower in hilly areas than in the plains they envelop.

Using GAEZ v4 for historical research is not without problems since it estimates productivities based on 1961–1990 climatic, soil, and terrain conditions. Thus, GAEZ v4 may underestimate the productive advantage enjoyed by regions that developed early but subsequently suffered environmental degradation due to the overexploitation of resources. Figure 5 suggests that Mesopotamia and the Nile, Indus, and Wei River Valleys do not enjoy a significant productivity advantage over their neighbors, which contradicts the historical narratives built around other sources of information (archeological, documentary, etc.). For example, deforestation due to human exploitation contracted the network of tributaries of the Wei River (the largest affluent of the Yellow River), which became shallower or even dried up entirely over time (Mostern, 2016).

We do not correct GAEZ v4 estimates because the possible underestimation of historical resource availability in China and other non-European regions that witnessed an early development of states biases our results against faster political consolidation in China than in Europe. Correcting the potential bias would only strengthen the result.

Nonetheless, to ensure that our results are not overly dependent on GAEZ v4 data, we use two alternative measures of historical resource availability (Rows 2–3 of Table 2). First, we use the Cropland Suitability Index by Ramankutty et al. (2002), which measures the fraction of land suitable for agriculture. Like GAEZ v4, the Cropland Suitability Index gauges present-day agricultural conditions. We prefer GAEZ v4 over the Cropland Suitability Index because, among other things, the latter is coarser with a resolution of 5-minute by 5-minute latitude-longitude (as opposed to GAEZ v4's 30 arc-seconds by 30 arc-seconds resolution).

Second, in Appendix D.2, we construct an alternative y variable using the estimated population density in 0 CE in the History Database of the Global Environment (HYDE) version 3.1 (Goldewijk et al., 2017).[29] This measure is motivated by a simple Malthusian logic: before the Industrial Revolution, population density was directly linked to land productivity and its ability to support dense populations (Ashraf and Galor, 2011). Unlike GAEZ v4 and the Cropland Suitability Index, HYDE is constructed as a historical dataset. However, its methodology, including the data employed to conduct hindcasting, has received substantial criticism from Guinnane (2021) and others, and, therefore, we do not use it as our baseline.

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[29] See `https://www.pbl.nl/en/image/links/hyde`.

As described in the main text (Panel A of Figure 11) and Appendix D (Panel C of Figure 25), our results are highly robust to switching from GAEZ v4 to the two alternative datasets. Besides these two exercises, we have replicated all our simulations (baseline, preferred, and checks) using these two alternative measures of y, and still find high consistency with our findings based on GAEZ v4. These additional results are available upon request.

A.2 Initial Level of Development, r

In our baseline specification, we use the percentage of land covered by alluvium as a proxy for early development advantage in 1000 BCE, r (Row 4 of Table 2). This choice is based on archaeological observations that wetlands played a central role in early sedentism (Pournelle, 2003; Hritz and Pournelle, 2015). The sedentary communities of Lower Mesopotamia, Jericho on the West Bank, Harrapan and Haripunjaya of India, Hemudu and Erlitou of China, Teotihuacan of Mexico, and Lake Titicaca of Peru were all wetland-based (Scott, 2017). It was also in alluvium-rich regions, including Mesopotamia (Tigris River), Egypt (Nile), the Indus Valley (Indus), and North China (Yellow River), that the world's first statelets emerged. As Scott (2017, p. 50) describes, the ecology of wetlands gave alluvium-rich areas an early advantage in agriculture and hence in the growth of complex societies.

In our baseline model, the productivity of cell i at $t = 0$ is $y_0 = r \cdot y_{GAEZ}$, where y_{GAEZ} is the highest attainable caloric yield from the pre-Columbian cereals derived from GAEZ v4. It then grows linearly at an increment of $\frac{y_{GAEZ} - r \cdot y_{GAEZ}}{500}$ per period between $t = 0$ and $t = 500$, so that $y_{500} = y_{GAEZ}$. Our baseline alluvial soil cover estimates are derived from the FAO Digital Soil Map of the World (DSMW). Following the approach adopted in GAEZ v4, we use Fluvisols and Gleysols soil types to represent alluvium.[30]

As a robustness check on the DSMW dataset, we use the FAO's Harmonized World Soil Database (HWSD) version 1.2 to compute the percentage of land covered by alluvial soils (Row 5 in Table 2). The HWSD has the advantage of being relatively new and more detailed than the DSMW. However, the HWSD is a harmonized dataset based on several data sources compiled by various agencies (FAO, the European Soil Bureau Network, the Chinese Academy of Sciences, etc.). We keep the DSMW as our baseline dataset to mitigate the potential heterogeneity left

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[30] As Fischer et al. (2021) spell out, "Fluvisols are by definition flooded by rivers," while "the soil profiles [of Gleysols] indicate regular occurrence of high groundwater tables through reduction (gley) features" (p. 116).

in the HWSD even after harmonization. However, we use the HWSD as a robustness check in Appendix D.2 (Figure 25). A comprehensive set of results using the HWSD in place of the DSMW to generate the baseline and preferred specifications as well as robustness checks in Figures 8–13 is available upon request.

Furthermore, to ensure that our results are not overly dependent on the use of alluvium share as a proxy for early development, we use the KK10 scenario of Anthropogenic Land Cover Change estimates from Kaplan and Krumhardt (2011) to generate another two alternative r variables as robustness checks (Row 6 of Table 2). The KK10 dataset has a spatial resolution of 5 arc-minutes or about 9 km. at the equator. It reconstructs estimates for anthropogenic land use from 8000 BP to 1850. The dataset has the advantage of not relying on one single factor (e.g., alluvium) to measure early development. In addition, when reconstructing the estimates, it assumes a negative relationship between land use per capita and population density, which is arguably an improvement over the assumption of constant land use per capita (as used in HYDE 3.1) in light of Boserup (1965).

However, like HYDE 3.1, the estimates in KK10 are reconstructed based on the hindcasting method, with its associated problems. Furthermore, using KK10 as our r measure is likely to underestimate the early development advantage of China vs. Europe for two reasons. First, its anthropogenic land-use estimates do not distinguish between pasture and intensive agriculture. Hence, some areas outside the "cradles of civilization" (for example, parts of northwestern Europe) show an above-average fraction of land use, possibly due to the presence of pastoral activities. Since, unlike cropping, pastoral activities are not known to induce state formation, this bias would favor a false early emergence of large states in western Europe (although we do not see this phenomenon in our simulations). Second, as explained in Kaplan et al. (2011, pp. 777–8), to avoid overestimating human-induced land use in tropical regions in prehistoric times, the KK10 dataset rescaled human-induced land-use estimates outside Europe downward. Despite these concerns, we continue to observe faster political consolidation in China than in Europe when using the KK10 human-induced land-use estimates as a proxy for early development in Section 5.3 (Figure 11) and Appendix D.2 (Figure 25).

A.3 Temperature

Our baseline temperature variables are based on WorldClim 1.4 downscaled paleoclimate data for the Mid-Holocene, about 6000 years ago (Row 7 Table 2).[31] The dataset has a spatial resolution of 30 arc-seconds (about 900 m. at the equator). Like other climatic datasets investigating the past, the WorldClim Mid-Holocene is generated via simulations with a Global Climate Model (GCM). Given that the GCM processes are complex and every simulation is different (since weather is partially stochastic), we use the WorldClim 1.4 climate data for the 1960s to construct an alternative set of temperature variables for robustness checks (Row 8 of Table 2).

A.4 Ruggedness

Our ruggedness variable draws from the CGIAR-CSI GeoPortal's SRTM (Shuttle Radar Topography Mission) 90m Digital Elevation Dataset, which is based on data produced by NASA (Row 9 of Table 2). The NASA dataset covered slightly more than 80% of the globe. The CGIAR-CSI GeoPortal dataset, widely used in the GIS community, applies interpolation methods to fill the data voids. Reuter, Nelson, and Jarvis (2007) detail the interpolation methods employed. The CGIAR-CSI dataset is organized into grid-cells of 5' x 5' and has a spatial resolution of about 90 m. at the equator. The ruggedness of each hexagon in our model is the standard deviation of elevation of the 5' x 5' grid-cells enclosed by the hexagon.

B War and Wealth

In our baseline and preferred specifications, the probability of a border conflict depends on the productivity of the cell (Section 3.4.1). This formulation is built on the Hobbesian thesis, the circumscription theory, the Malthusian argument, and theories in political economy highlighting commitment problems in an anarchic political environment. Here, we present two empirical checks to show that our assumption of a positive correlation between war and wealth is also consistent with historical data.

Unfortunately, testing the correlation between war and wealth is more complicated than it seems: if affluent areas were more likely to witness outbreaks of war, they would be the first to

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[31] See `https://www.worldclim.org/data/v1.4/worldclim14.html` and Hijmans et al. (2005) for details.

experience war and undergo political consolidation. Counterintuitively, wars would increasingly occur in less affluent areas as time passed because the more affluent areas would have already gone through political consolidation and become the core or interior of a large state. This poses a challenge; without an accurate dataset of the earliest wars (with precise locational information on where these wars took place), we cannot test the assumption directly.

Figure 21: Europe in 1500 (Nussli, 2011)

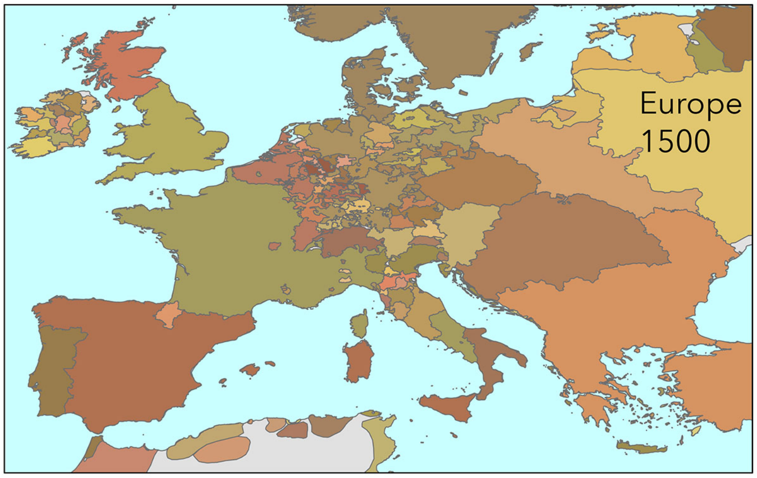

Table 4: Were Border Cells More Productive?

	Productivity
Border cell	-1466.4*** (62.2)
N	6188

Note: Constant term not reported. *** significant at 1%; Based on European borders in 1500. Results based on European borders at other century marks (1000–1400) are available upon request.

We circumvent the problem in two ways. First, if war and political consolidation indeed began in more affluent areas, cells along the borders of victorious states that have expanded for some time should have lower productivity than cells in their interior. We check this for Europe in 1500, for which reasonably good quality data on political boundaries are available (Figure 21) and where political consolidation has occurred for the whole 2,500 years of our study period. Table 4 documents that the average attainable caloric yield of cells along the borders is roughly 1470 calories or 58% of the standard deviation lower than that of interior cells, a prediction solidly in line with our assumption.

Our second test investigates the location of wars in the late Middle Ages, between 1300 and 1500 (Figure 22). If we focus our attention on cells where the likelihood of *interstate* war is non-zero (i.e., border cells where political consolidation is still ongoing), we should observe that wars were more frequent among cells with higher productivities. Table 5 corroborates that this is indeed the case using European borders in 1500.

Figure 22: Border Wars (1300–1500)

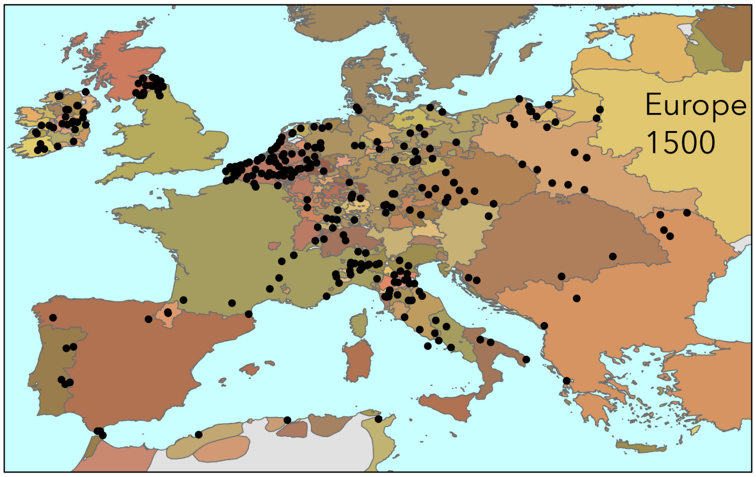

Table 5: Productivity & War Among Border Cells

	Productivity
War (1300–1500)	858.6*** (281.3)
N	2619

Note: Constant term not reported. *** significant at 1%; Based on European borders in 1500. Results based on European borders in 1300 and 1400 available upon request.

C Summary of Specifications: Baseline and Alternatives

Table 6 summarizes all the specifications reported by Figures 8–12 in Section 5. The table shows that China and Europe are comparable in resource availability and fracturedness in our baseline and the various alternative specifications. If anything, China is slightly disadvantaged in both dimensions in most of the specifications. This observation highlights that it is not aggregate resource availability and fracturedness, but their geographical distributions, that drive China to unify relatively quickly while Europe develops into a polycentric system.

To be sure, these tests are correlational (as finding a good causal research design seems hard). But their results coincide with the historical narratives. Territorial rulers in Europe repeatedly fought over the Low Countries and Lombardy during the late Middle Ages and early Modern Age (notice the accumulation of black dots in these two regions in Figure 22) because they were high-productivity regions that brought large tax revenues.[32]

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[32] We are thinking, for instance, about the Wars in Lombardy, from 1423 to 1454, for the control of Lombardy, which had a lasting impact on Italian politics for centuries, or the wars around the Burgundian domains that ended with the death of Charles the Bold in 1477 and the subsequent dynastic realignments all across Europe with consequences lasting to today.

Panel A	Baseline Fig. 8, 9 (1)	No Climatic Obstacles Fig. 10A (2)	No Obstacles Fig. 10B (3)	Uniform Resource Fig. 10C (4)
y_0	(Soil)×(GAEZ)	(Soil)×(GAEZ)	(Soil)×(GAEZ)	0.5
y_{500}	(GAEZ)	(GAEZ)	(GAEZ)	0.5
α_{sea}	0.1	0.1	1	0.1
σ	0.333	0.333	1	0.333
$\theta_{rugged} \cdot x_{rugged}$ (90th pctl)	2	2	0	2
θ_{cold}	2	0	0	2
θ_{hot}	2	0	0	2
Resource (median y)				
–China$_{t=0}$	0.01	0.01	0.01	0.50
–China$_{t=500}$	0.53	0.53	0.53	0.50
–Europe$_{t=0}$	0.00	0.00	0.00	0.50
–Europe$_{t=500}$	0.60	0.60	0.60	0.50
Fracturedness (median $\Theta\mathbf{x}$)				
–China	1.41	0.95	0.00	1.41
–Europe	1.37	0.56	0.00	1.37

Panel B	No Obstacles + Uniform Resource Fig. 10D (5)	Alt. Y (CSI) Fig. 11A (6)	Alt. Initial Conditions Fig. 11B (7)	Alt. Conflict Mechanisms Fig. 12A, 12B (8)
y_0	0.5	(Soil)×(CSI)	(KK10)×(GAEZ)	(Soil)×(GAEZ)
y_{500}	0.5	(CSI)	(GAEZ)	(GAEZ)
α_{sea}	1	0.1	0.1	0.1
σ	1	0.333	0.333	0.333
$\theta_{rugged} \cdot x_{rugged}$ (90th pctl)	0	2	2	2
θ_{cold}	0	2	2	2
θ_{hot}	0	2	2	2
Resource (median y)				
–China$_{t=0}$	0.50	0.02	0.11	0.01
–China$_{t=500}$	0.50	0.72	0.53	0.53
–Europe$_{t=0}$	0.50	0.00	0.15	0.00
–Europe$_{t=500}$	0.50	0.66	0.60	0.60
Fracturedness (median $\Theta\mathbf{x}$)				
–China	0.00	1.41	1.41	1.41
–Europe	0.00	1.37	1.37	1.37

Table 6: Summary of specifications in Figures 8–12.

D Additional Robustness Tests

This appendix includes additional robustness tests on several parameter values and checks the effects of using alternative datasets and modifying the random contest function.

D.1 Parameters Θ and β

First, we vary the values of the parameter vector Θ, which measures the influence of the geographical and climatic characteristics on war outcomes. In the baseline, we set $\theta_{rugged} \cdot x^*_{rugged} = \theta_{hot} \cdot x^*_{hot} = \theta_{cold} \cdot x^*_{cold} = \theta = 2$, where x^*_{rugged}, x^*_{hot}, and x^*_{cold} represent the 90th-percentile values of x_{rugged}, x_{hot}, and x_{cold} respectively. To explore a wide range of alternatives, we set θ to each integer between 0 and 8. We repeat the simulation 30 times for each integer value, creating 10,000 bootstrap samples.

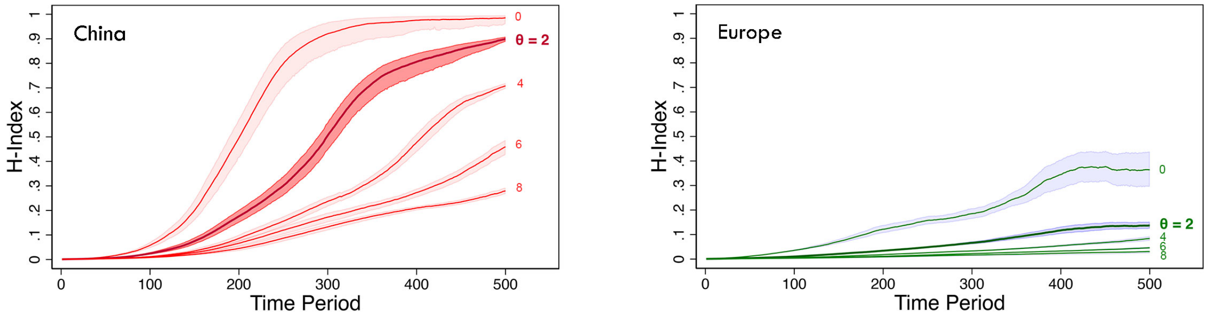

Figure 23: Varying θ between 0 and 8. For each value, we conduct the simulation exercise 30 times and display the average Herfindahl (unification) indices for China (left panel) and Europe (right panel). The shaded intervals depict the 0.95 bootstrap confidence interval.

Figure 23 reports the mean and the 95% confidence interval of Herfindahl (unification) indices for China (left panel) and Europe (right panel). When $\theta = 0$, geographical and climatic obstacles do not influence war outcomes. As θ increases, the likelihood of war ending with no victor or conquest increases as the influence of geoclimatic factors strengthens. While the Herfindahl indices of China and Europe decrease with θ, for all values of θ, China displays a stronger tendency toward political unification.

Second, we vary the value of the secession parameter β. In our baseline calibration, we set $\beta = 1 \times 10^{-5}$, a low value, to avoid biasing our results against Europe, which is more likely to produce states that are non-compact in shape due to its long coastline, or against the northern European Plain, which has a funnel shape with a western portion that is long and relatively narrow. Figure 24 reports the results when we multiply β by 10, 5 , $\frac{1}{5}$, and $\frac{1}{10}$, respectively. For each value of β, we repeat the simulation 30 times, create 10,000 bootstrap samples, and compute the mean and the 95% confidence interval of Herfindahl indices for China and Europe.

When β is ten times its baseline value, European political consolidation is extremely sluggish. In this case, a polity that comprises the cells of Europe would have to annex territories at a rate of 900 cells (approximately 1 Iran or 20 Austrias) every 50 periods to prevent itself from shrinking. While China experiences slower political consolidation too, it continues to consolidate steadily and can achieve a high degree of unification at period 500. At lower values of β, unification continues to occur faster in China than in Europe.

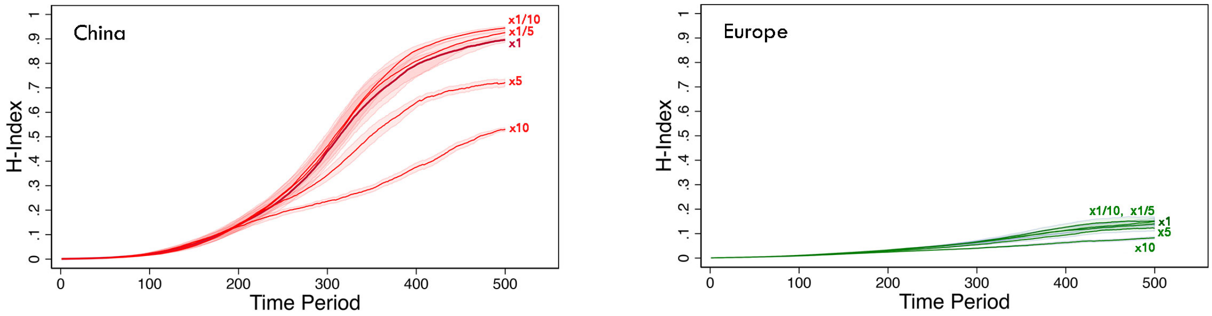

Figure 24: Varying β between 0.1 and 10 times its calibrated value. For each value, we conduct the simulation exercise 30 times and display the average Herfindahl (unification) indices for China (left panel) and Europe (right panel). The shaded intervals depict the 0.95 bootstrap confidence interval.

We conducted further robustness analyses that we do not include in the interest of space. For example, we allowed α_{sea} to be 0.01, 0.1, 0.5, and 1. The results, available upon request, were very robust to the choice of α_{sea}.

D.2 Alternative Datasets

Section 5.3 conducts two robustness tests using alternative datasets. First, we replace GAEZ v4 with Ramankutty et al. (2002)'s Cropland Suitability as our measure of historical resource availability. Second, we use Kaplan and Krumhardt (2011)'s KK10 Anthropogenic Land Cover Change data on 1000 BCE in lieu of alluvial soil cover as a proxy for early developmental advantage.

Figure 25 reports the results from conducting four more robustness checks with our datasets. In Panel A, we still rely on Kaplan and Krumhardt (2011)'s KK10 Anthropogenic Land Cover Change data to measure early developmental advantage (r). But now, we use the 0 CE instead of the 1000 BCE estimates. The purpose of doing so is two-fold: first, it is plausible that the 1000 BCE estimates may be noisier due to a relative dearth of evidence. Second, we would like to check if giving Europe a larger early developmental advantage (considering that the Mediterranean region was relatively developed in 0 CE) affects our findings. While we see a slight increase in the pace of political unification in Europe, the same is also observed in China, which could be explained by a relatively developed North China in 0 CE. Thus, our findings remain intact.

Panel B uses the alluvial soil cover data of FAO Harmonized World Soil Database (HWSD) version 1.2 to measure early developmental advantage. Compared to the DSMW database used

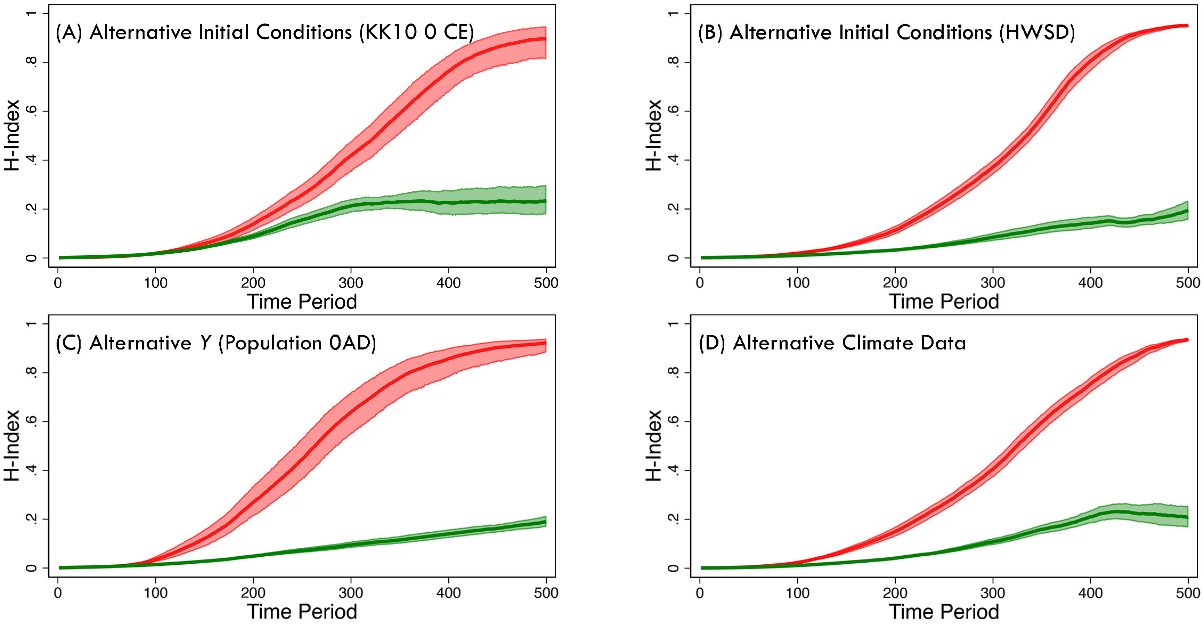

Figure 25: Data robustness checks. Panels A and B employ alternative datasets to capture initial conditions (r); Panel C uses an alternative measure for historical resource availability (y); Panel D uses an alternative data source to compute the temperature variables (x_{hot}, x_{cold}). For each specification, we conduct the simulation exercise 30 times and display the average Herfindahl (unification) indices for China (red) and Europe (green). The shaded intervals depict the 0.95 bootstrap confidence interval.

for our baseline, the HWSD is a harmonized dataset based on several data sources compiled by various agencies (FAO, the European Soil Bureau Network, the Chinese Academy of Sciences, etc.). Panel B shows that using the HWSD dataset has little noticeable effect on our results. We keep the DSMW as our baseline dataset to mitigate the potential heterogeneity left in the HWSD even after harmonization.

Panel C replaces GAEZ v4 with the population estimates in 0 CE of the History Database of the Global Environment (HYDE) version 3.1 as our measure of historical resource availability (y). We continue to observe faster political consolidation in China. For completeness, we also conduct robustness checks using the 1000 BCE, 500, and 1000 estimates from HYDE and obtain qualitatively similar results (available upon request).

Panel D uses the WorldClim 1.4 climate data for the 1960s to construct an alternative set of temperature variables instead of the WorldClim 1.4 downscaled paleoclimate data. Again, the results are similar to those in the baseline specification.

D.3 Alternative Conflict Mechanisms

In Section 5.3 of the main paper, we check whether modifying how wars take place in our model could affect our findings. In this subsection, we implement two more robustness checks on the conflict mechanisms. Both checks investigate the effects of explicitly incorporating transport costs into our model.

In our baseline simulation, when a large polity that controls many cells engages a small polity in war, the former has a higher probability of winning according to the contest function given by equation (1). However, if the cells controlled by the large polity are extremely rugged, this might constrain the polity's ability to mobilize resources and lower its chances of winning. This concern is mitigated by the fact that productivity and ruggedness are highly correlated in the dataset. Hence, to keep the model conceptually and computationally simple, we do not factor in transport costs explicitly.

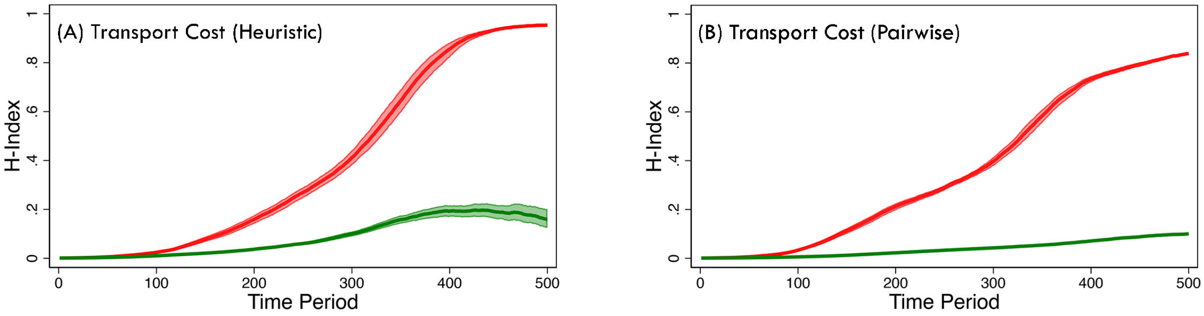

Figure 26: Varying the contest function. For each specification, we conduct the simulation exercise 30 times and display the average Herfindahl (unification) indices for China (red) and Europe (green). The shaded intervals depict the 0.95 bootstrap confidence interval.

However, as a heuristic check, in Panel A of Figure 26, we discount the productivity of every cell by its ruggedness when computing the aggregate productivity (Y) of a polity that enters into equation (1). The exercise in Panel B goes a step further. For any two cells in the world represented in Figure 2, we compute the least-cost route (or route of lowest ruggedness) between them. Now, if polity i fights a war in cell k, the aggregate resources that it devotes to the war (Y_i) are the sum of the productivity of every cell that polity i controls discounted by the ruggedness of the least-cost route between the cell and k. For both extensions, we continue to observe a faster pace of political consolidation in China than in Europe. The second extension, in particular, adds realism to the model at the cost of making it computationally cumbersome. This said, the results are reassuring.

E Enriching the Model

We now include additional details about the several extensions of our baseline model that we described in Sections 5 and 8 of the main text.

E.1 Major Rivers and Loess Soil

A river fosters the interdependence of its upstream and downstream areas. In particular, China was a riverine civilization that depended upon its rivers to serve as its primary means of transportation until the early 20th century (Skinner, 1977). This natural water system was complemented by the Great Canal, built in the Sui dynasty (581–618), which connected the Yangtze and Yellow Rivers. However, a wide river also impedes movement between its two banks, especially during times of war. In some episodes of Chinese history, regimes in southern China successfully built defense lines along the Huai and Yangtze rivers to deter invasions from the north for prolonged periods (Sng et al., 2018).

To capture the dual roles of rivers, we identify the world's groundwater resources using the BGR-UNESCO "Major River and Lake Basins of the World" dataset. We set the obstacle value $\Theta \cdot x$ to zero when cells along the same river come into contact and increase the obstacle value $\Theta \cdot x$ by two when a riverine cell comes into conflict with a non-riverine cell. We simulate this extension 30 times to create 10,000 bootstrap samples. Panel A of Figure 13 shows the new results, which are roughly the same as in the baseline specification, with only a slightly slower unification of China.

Historians have also observed that regular flooding along the Yellow River gave North China a head start in state development because flood management problems increased tensions between upstream and downstream states along the Yellow River and accelerated the emergence of a unified regime through intense warfare (Huang, 1988). Our model does not consider this factor, but doing so would likely increase the pace of unification in China further.

However, the flood-prone Yellow River might have contributed to early state formation in China in another way: its floods replenished the soil and allowed agriculture to develop early and remain sustainable even with limited farming knowledge (Ho, 1975). Notably, the Chinese loess plateau, one of the world's largest loess regions with a land area larger than Germany, was looped by the Yellow River along the river's middle reaches. Loess, a fine-grained, windblown sediment, is stoneless and, hence, easy to work on even with primitive tools. Its well-aerated nature further makes it excellent for cereal cultivation (Catt, 2001). In the Guanzhong basin, adjacent to and overlapping with the loess plateau, the combination of an abundance of loess and alluvial soils and easy access to water from the Yellow River and its tributaries made it an extremely productive agricultural zone in ancient China. It was from Guanzhong, centered in the city of Xi'an, where the Qin dynasty extended its power to complete the first unification of China in the 3rd century BCE.

Panel B of Figure 13 incorporates the hypothesis postulated in Scott (2017) that loess and alluvium were the only soils capable of sustaining a dense concentration of grain cultivation in early history by computing, for every hexagon in the world, the fraction of area covered by deep loess deposits (greater than 100 meters) and adding it to r, the parameter that measures early development (recall that in the baseline, r measures the fraction of area covered by alluvial soil). The exercise generates faster unification in China, but our main findings remain unchanged.

E.2 The Eurasian Steppe

We incorporate the Eurasian steppe into our model in two separate exercises, reported by Panels C and D of Figure 13.

The first exercise deals with the historical roles of the Eurasian steppe as (i) a conduit between Asia and Europe; and (ii) a source of military threats to sedentary societies in Eurasia. Scholars have observed that the steppe exerted a profound influence on Eurasian history (Lattimore, 1940, 1947; Barfield, 1989; Di Cosmo, 1994). With a string of oasis towns connecting the belt of grassland stretching from Hungary through Central Asia to Manchuria, the steppe served as a "highway of grass" that facilitated the movement of people, goods, technology, and disease across Eurasia (Frachetti, 2008, p. 7).

Also key was the influence of the steppe in intensifying Eurasian (and North African) warfare. For instance, Turchin et al. (2013) argue that the steppe shapes agrarian societies in two ways: (i) through the destruction of less powerful polities; and (2) through the diffusion of military technologies (such as chariots, horse archers, and stirrups) that make conflict more destructive. These technologies hinged on the availability and quality of horses. In premodern times, horses were an invaluable military asset, a powerful war machine likened to modern tanks (Ropa and Dawson, 2020). Control of horses allowed some states to develop highly mobile cavalry forces that could easily outflank infantry units and charge down routed opponents.

Importantly, horses were a location-specific resource. Equine domestication began in the Eurasian steppe and steppe horses were especially stocky and vigorous (Zheng, 1984). Moreover, only an extensive expanse of grassland could support a high density of horses and correspondingly a high concentration of skills in breeding and riding them. Thus, states near the Eurasian steppe fielded larger and better cavalry forces, giving them an advantage in war (Barfield, 1989; Gat, 2006; Turchin et al., 2013).

Scholars have also shown that climate played a crucial role in the conflicts between the steppe nomads and their agricultural neighbors (Bai and Kung, 2011). A cold and arid climate often triggered steppe invasions and drove waves of steppe peoples west into Eastern Europe and south into the Middle East, India, or China. The ecological conditions in the steppe east of the Altai Mountains, where temperature swings were greater than anywhere else, were especially fragile and prone to fluctuations (McNeill, 2021).

Thus, traditional scholarship links the Huns, whose migration into Eastern Europe precipitated the movement of barbarian peoples that eventually destroyed the Western Roman Empire, to the Xiongnu, a nomadic confederation that dominated the eastern steppe during the Han dynasty of China (Gibbon, 2003; Neparáczki, Maróti, and Kalmár, 2019). Other scholars find a continuity between the Avars and the Rourans in the eastern steppe (Róna-Tas and Berta, 2011). Indeed, recent research on the genetic origins of the Avars suggests they were of East Asian origins (Csáky et al., 2020). The movement of the Avars westward might have resulted from the formation of Turkic tribal confederacies in the eastern steppe. These Turkic peoples also pushed west over time (notably the Göktürks and the Bulgars), invading central Asia, Anatolia, and the Iranian plateau in the 10th–11th centuries. It is notable too that the Mongols, whom we discuss below and who briefly created the largest land empire ever witnessed in history, came from the eastern steppe.

Motivated by the previous discussion, Panel C of Figure 13 extends the baseline model to account for the role of the steppe as a "highway of grass" by reducing the obstacle value $\Theta \cdot x_k$ by one if cell k is a part of the Eurasian steppe, effectively halving the overall $\Theta \cdot x_k$ in the steppe.

In addition, we introduce a parameter ψ into the contest function (1) and rewrite it as:

$$\pi_{i,win} = \frac{\psi_i \cdot Y_{i,t}}{(\psi_i \cdot Y_{i,t} + \psi_j \cdot Y_{j,t}) \times (1 + max\{\Theta \cdot \mathbf{x}_k, \Theta \cdot \mathbf{x}_{\bar{k}}\}} \tag{5}$$

where $\psi_i = 3$ if regime i originates as a cell in the eastern steppe and $\psi_i = 1$ otherwise. The extension assumes that a regime that originates from the eastern steppe is more proficient in war because it had better access to horses and was socially conditioned and militarized by the ecology of the eastern steppe to seek survival through conquest (Di Cosmo, Frank, and Golden, 2009). A $\psi_i = 3$ is the largest plausible difference, as steppe armies were on occasion defeated by sedentary populations.

As before, we simulate this extension 30 times to create 10,000 bootstrap samples. Panel C of Figure 13 shows that even by reducing the geographical barriers in the steppe cells and making the eastern steppe cells three times better at conflict, the paper's main results remain unchanged.

Recall that our baseline model assumes that state formation rests on the economic foundation of cereal production as estimated by GAEZ v4. But, although some agrarian production was present, the steppe was dominated by pastoral nomadism (Barfield, 1989). Thus, we further refine our baseline model by setting the productivities of all steppe cells uniformly to one-third of the median productivity level of the cells in China. In that way, we consider the steppe as a homogeneous grassland biome dominated by pastoralism.

Considering (i) the population density disparity between China and Inner Asia historically,[33] and (ii) the land-intensive nature of pastoral nomadism,[34] our assumption likely overestimates energy production in the steppe. We allow for this overestimation to compensate for the fact that pastoral nomadism likely enhanced the military potential of steppe regimes through channels not fully captured by caloric production.

Panel D of Figure 13 shows the result of this exercise. Again, we continue to see that China unifies quickly while Europe remains fragmented after 500 periods.

Several features of these two exercises deserve emphasis. First, we aim to better capture the

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[33] Jia Yi, a 2nd century BCE scholar, estimated that the Xiongnu confederation of the steppe comprised approximately 300,000 households during his time. By contrast, the contemporary Han dynasty controlled 10 million households or 50 million heads at the peak of its power (Twitchett and Fairbank, 1986, Table 15).

[34] On average, raising livestock requires approximately 100 times as much land as crop cultivation to produce the same amount of calories (Poore and Nemecek, 2018).

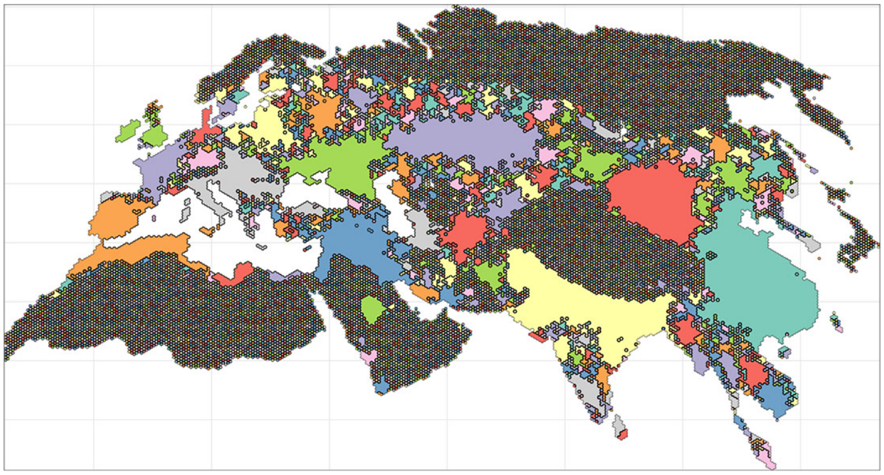

Figure 27: Preferred specification: Representative simulation at t=500.

dynamics of the steppe from circa 1,000 BCE to circa 1500. The purpose of our model is to generate pattern predictions and not to forecast specific or one-off events. In general, steppe confederacies could create sizable but short-lived polities that occupied territory on the edge of the Eurasian steppe. This was true of the Huns, Avars, and Magyars in central Europe; the Khazars in Ukraine; the Turkic polities of Anatolia; the various Uyghur kingdoms; and later, the Golden and Great Hordes and their successor states such as the Crimean, Qasim, and Kazakh Khanates. In the above exercises, we observe patterns comparable to those that we see historically. Large steppe-based confederations do emerge. Figure 27 illustrates a representative map of the preferred specification simulation after 500 periods. In this simulation, large polities are very much like the eastern (Blue Horde) and western (White Horde) wings of the Golden Horde and the Oirats spanning a large part of the eastern and western steppe.

Second, neither of these exercises generates an empire comparable to the Mongol Empire at its largest extent. This is unsurprising. The rise of the Mongol Empire has been attributed to several contingent and one-off factors. Traditional scholarship places great weight on the personality and achievements of Temüjin or Genghis Khan. More recent work emphasizes a unique set of climatic factors (Hvistendahl, 2012; Pederson et al., 2014). Hvistendahl (2012, p. 1598) summarizes this as follows:

> [A]s Genghis Khan began consolidating power, weather conditions appear to have substantially improved—and to nomads who rely on access to lakes for watering animals, that would have made all the difference. In times of abundant rain,

> pastoralists thrive, Hessl says: Very little human effort is needed to "create large amounts of meat that is mobile, that can be used for war, and that can be used to transport things." Whole herds can be tended by children—leaving the men free to fight.
>
> If more rainfall boosted grassland productivity and overall energy output, that could help explain why the Mongols were able to transition from a "chieftain society, where positions are hereditary" to managing a complex state covering a vast empire, Di Cosmo says: "A centralized state requires more resources." The horses and food accumulated on the steppe would have enabled the Mongols to set out for China in pursuit of gold and silk—and from there on to more distant lands.

Thus, we add another variant to our preferred specification, which includes the two steppe modifications discussed above. We assume that the boost in grassland productivity in the 13th century can be represented by an increase in the caloric yield of cells in the eastern steppe by a factor of three, i.e., we set the productivity of every cell in the eastern steppe to the median productivity of China. That is, the steppe is as productive as China, three times better militarily, and distances are effectively halved.

This exercise generates large steppe polities but with a low probability. For instance, out of 30 simulations of this specification, we observe a single empire spanning the steppe only once (Figure 28). In comparison, Figure 29 illustrates a more representative map at $t = 500$ of this specification. Instead of a single empire spanning the steppe, we see polities that arguably resemble the four khanates of the Mongol Empire (Figure 30).

We interpret these results as a relatively good performance of the model. First, the Mongol Empire was both unique and short-lived. The Mongols began to invade other polities after 1206. It was only in 1221 that they succeeded in conquering the Khwarazmian empire in central Asia. After that point, Mongol expansion was very rapid. But the empire was permanently divided in 1259 as Kublai Khan expanded into the rest of Song China, founding the Yuan dynasty, while the Golden Horde, Chagatai Khanate, and Ilkhanate became independent. All in all, a single Mongol Empire spanning the entire Eurasian steppe lasted for around *25 years* out of the 2,500 years of our time period or around 1% of the time. It would be a problem for our model if it systematically generated steppe polities as large as the Mongol Empire, as it would

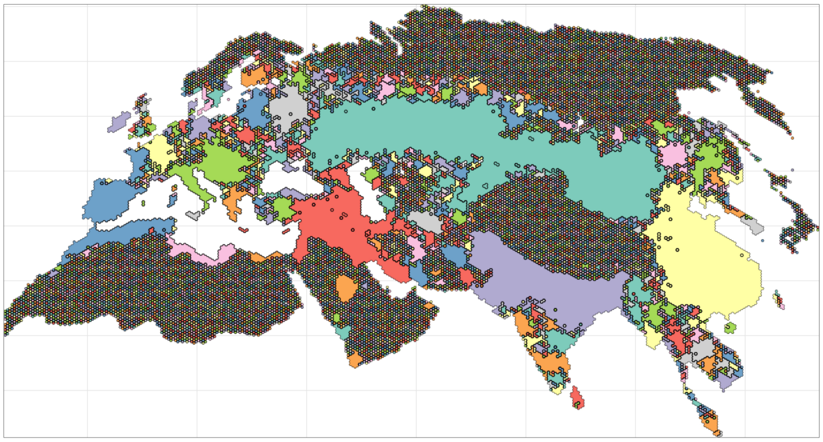

Figure 28: Improved steppe climate: One simulation at t=500.

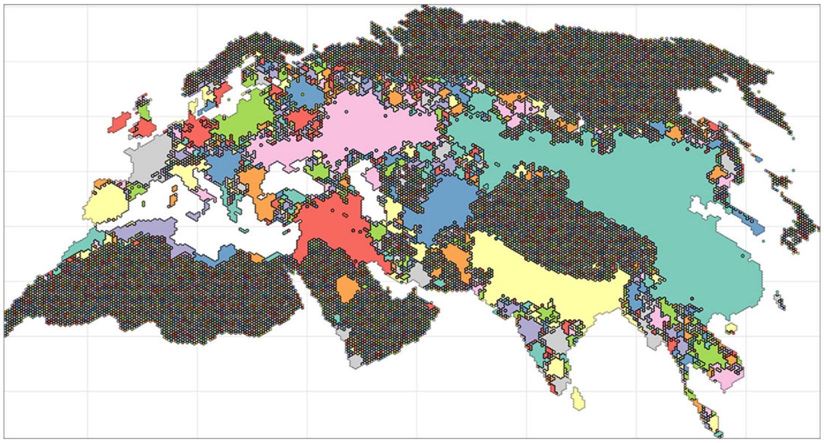

Figure 29: Improved steppe climate: Another simulation at t=500.

Figure 30: The Four Khanates of the Mongol Empire.

be counterfactual.

Second, our exercise teaches that beyond favorable climatic conditions, additional factors (for instance, the organizational genius of Genghis Khan or other factors that have been overlooked in the literature thus far) also played a critical role in the rise of the Mongol Empire. More generally, it shows that a confluence of exceptional and accidental circumstances would be required for a pan-Eurasian steppe empire to emerge in history, which explains why it was such a rare and short-lived event.

E.3 Climatic Shocks and Dynastic Cycles

To further account for contingency in history and to study the role of large exogenous events, such as natural disasters or incompetent leaders on the rise and fall of polities, we modify the model by extending our simulation range to 4000 periods and allowing random shocks to occur each period. Specifically, we consider two kinds of negative shocks: a general shock that affects all polities (e.g., the Little Ice Age), and a regime-specific shock (e.g., the ascension of a weak ruler such as Charles II of Spain, r. 1665–1700, or the Chongzhen Emperor, r. 1627–1644, or the predisposition of the Carolingians to divide their lands among different heirs). Thus, we call these events “climatic shocks” and “dynastic cycles.”

We set the probability of a general shock occurring at $\frac{1}{1000}$ and the probability of a regime-specific shock occurring at $\frac{1}{200}$. Thus, on average, a general shock occurs once every 1000 periods, and each polity independently experiences a specific shock once every 200 periods. When a shock occurs, the regime disintegrates into its constituent cells. These two frequencies are mostly irrelevant since nearly all of our parameter values are time-invariant, and they just determine how often we will observe a collapse of existing state systems.

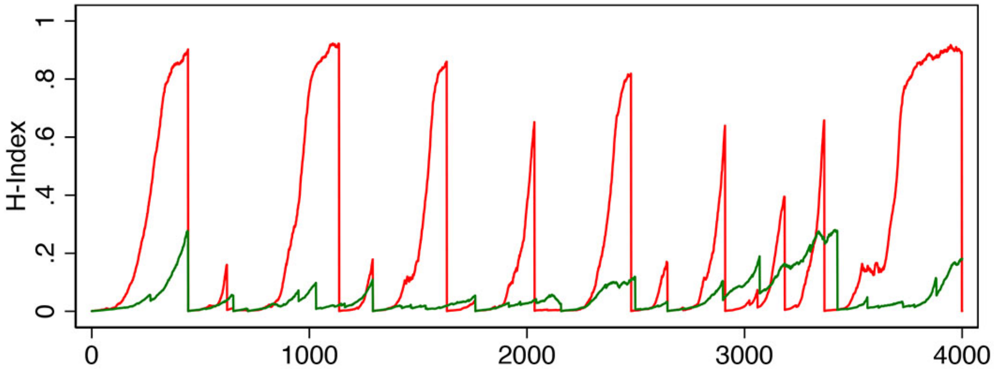

Figure 31: This figure depicts one realization of a 4,000-period simulation where we allow for both general shocks (prob. 0.001) and regime-specific shocks (prob. 0.02) occurring.

Figure 31 depicts the Herfindahl indices for China and Europe from a representative simulation.

China experiences periods of sustained unification interrupted by periods of disunity, resembling the patterns of dynastic rise and fall so often depicted in Chinese historiography. Some periods of unified rule are short-lived; others persist for many periods. By contrast, political cycles are relatively muted in Europe. Europe never achieves full unification in this realization of the model. There are periods of heightened military conquests that rest on one state becoming hegemonic in Europe, but these are always transitory; polycentrism remains persistent.

E.4 The Mediterranean Sea

Historically, the Roman Empire controlled the Mediterranean region for centuries. But in our baseline calibration, we observe little political consolidation in the Mediterranean (Panel A of Figure 32 and Panel A of Figure 33). Here, we expand on our discussion in the main text of how our model can account for the emergence of the Roman Empire.

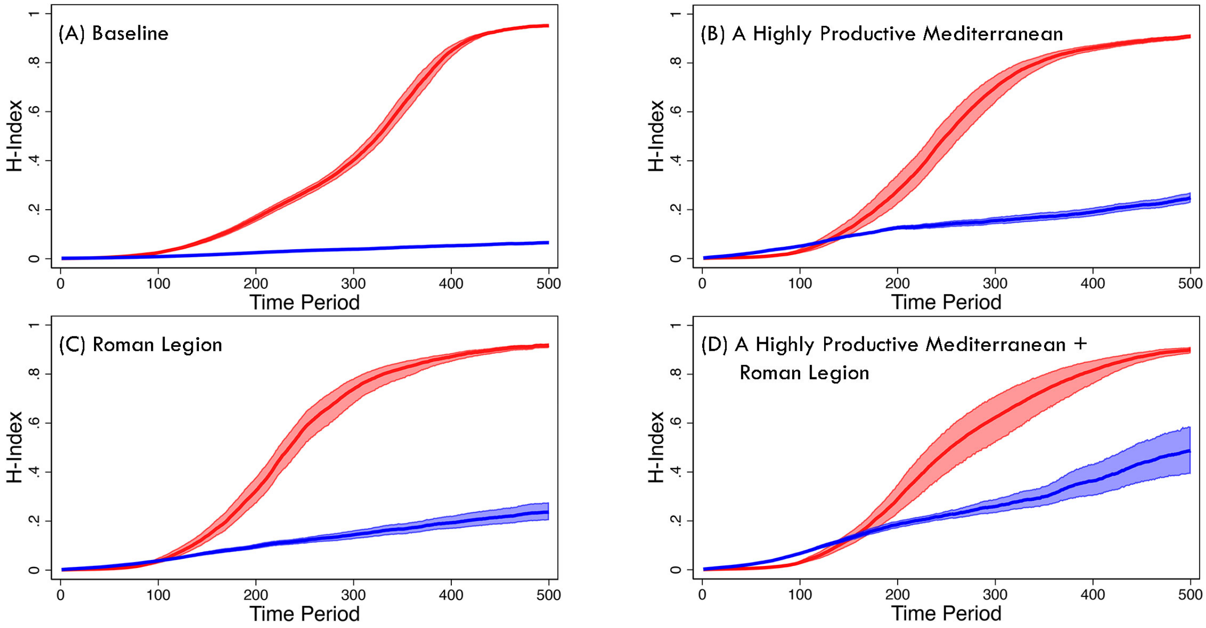

Figure 32: Political consolidation in China (red) and the Mediterranean (blue) under various scenarios.

Historians see the Roman Empire as a unique event (see, for instance, Scheidel, 2019, 35–48). Indeed they have suggested several idiosyncratic factors that may have been responsible for its emergence. First, the Roman economy was built on its access to the extremely productive North African agriculture during the Classical period, when the region was wetter than today (Murphey, 1951; Reale and Dirmeyer, 2000). Consequently, the provinces of Egypt and Africa (modern-day Algeria, Morocco, and Tunisia) were the “bread baskets” of the empire.[35]

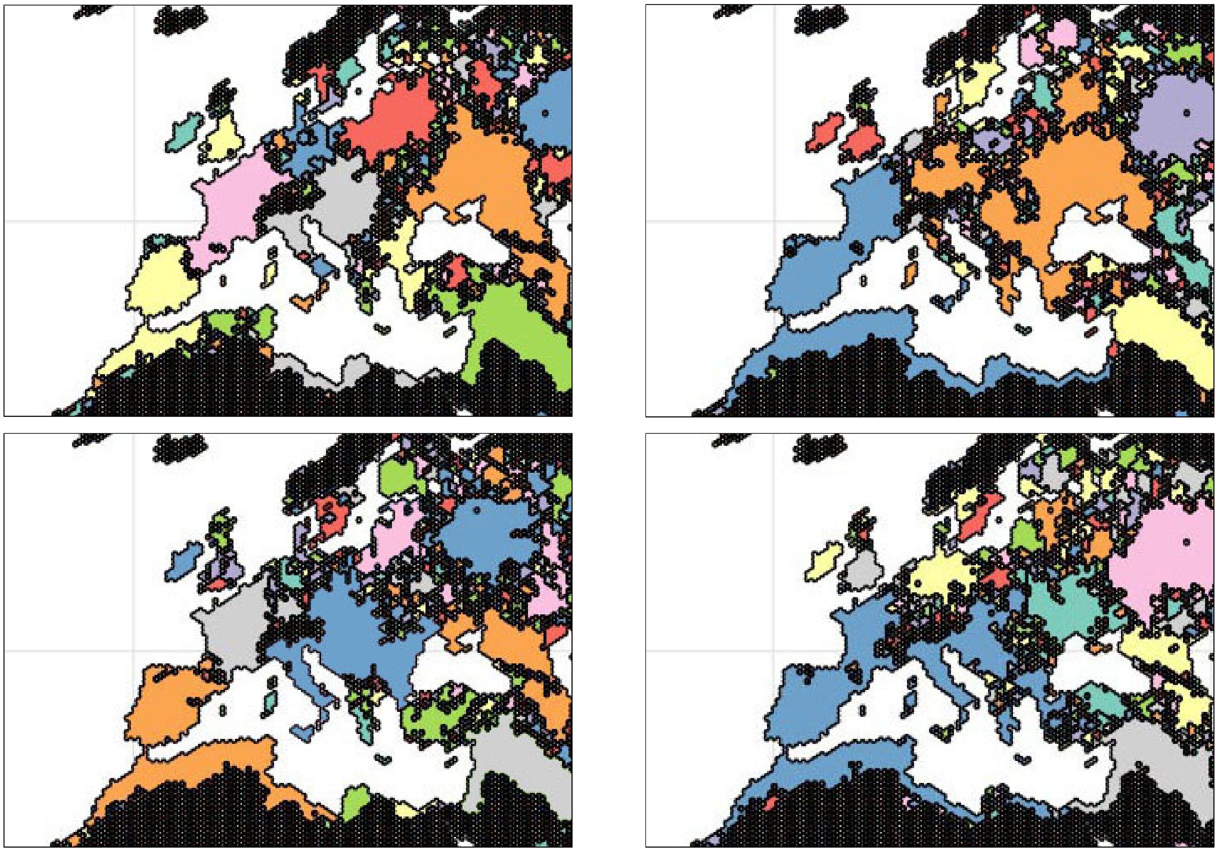

Figure 33: Representative simulations at period 500 for (A) the baseline calibration; (B) a high productivity Mediterranean; (C) military superiority of Latium; and (D) high productivity Mediterranean and military superiority of Latium.

Conditions across the western Mediterranean were so favorable to cereal agriculture between 200 BCE and 150 that this period has been referred to as the Roman Climate Optimum. Wheat agriculture responds favorably to higher temperatures, particularly in the growing season. And the climate in the Mediterranean was warmer, wetter, and more stable than it has been in preceding or succeeding periods and “a potent incubator of growth” that “fueled the agricultural engine of the economy” (Harper, 2017, p. 52).

A second relevant factor is the political and military culture of Rome. Scholars have highlighted cultural features that may have been specific to Rome and may help explain its success. Among those, we can highlight the martial ethos of Roman society and Roman politics

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[35] See Rickman (1980). According to Linn (2012, pp. 305–306), “[S]ince the first century BCE, whenever Rome was shut off from North African grain, a shortage typically had ensued . . . All these instances demonstrate two facts about the relationship between North Africa and the city of Rome: (1) North Africa was the lifeline for the city of Rome; (2) warfare commonly led to a food crisis in Rome because of transport blockages.”

that encouraged politicians to seek electoral successes through external wars (Harris, 1979, 1984; Rosenstein, 2007). Scheidel (2019, pp. 72–74) summarizes some of this in his depiction of Republican Rome as a machine for perpetual war. Another unique feature of Rome was its ability to integrate new citizens. Rome was generous in extending citizenship, and this ensured that it had a steady supply of young men to fight in its armies (see Scheidel, 2019, pp. 65–68).

Motivated by this scholarship, we consider several extensions to the model. In Panel B of Figure 32, we increase the productivity of every cell surrounding the Mediterranean Sea by a factor of 1.25, or to the median productivity of Europe, whichever is higher. We observe an increase in political consolidation. Nonetheless, the mean Herfindahl index remains low and reaches only around 0.2 at its peak. Moreover, this extension does not generate an empire that resembles the Roman Empire. Indeed, in some simulations, Italy remains highly fragmented (see, for a specific example, Panel B of Figure 33).

Next, in Panel C of Figure 32, we give regimes originating from Latium, which formed the core of the Roman city-state, an advantage in war. As in the steppe extension, we use Equation 5 as the contest function of regime i if the regime originates as a cell in Latium and set $\psi_i = 3$. As before, we repeat the simulations 30 times in each case and create 10,000 bootstrap samples. In this extension, we do see greater political centralization around Italy. It is not uncommon to see polities emerge that control large parts of Italy and the Balkans over time. However, the mean Herfindahl index remains relatively low, and we do not observe anything like the Roman Empire (see, for example, Panel C of Figure 33).

Finally, we combine both extensions in Panel D of Figure 32. In this instance, we observe a non-linear increase in the mean Herfindahl index, which reaches 0.5 at period 500. Even so, the degree of political consolidation remains low compared with China. Indeed, while we now obtain relatively large states emerging around the Mediterranean (see, for example, Panel D in Figure 33), they rarely correspond to the Roman Empire's boundaries.

Overall, this exercise suggests that the political unification of the Mediterranean in Roman times depended on highly contingent historical factors. This is why no subsequent regime could unify a large proportion of Europe.

E.5 What If Europe Had a Head Start?

In all the previous simulations, we have assumed that at $t = 0$, each cell begins as an independent polity. But our model has the versatility to examine scenarios whereby specific large polities preexist and ask: Can such a political configuration be sustainable as an equilibrium? Is there path dependence in our model?

To answer these questions, we conduct two exercises. The first exercise adopts the political map of the world circa 250 CE as the starting point of the simulation exercise. We assume that a large polity in the mold of the Roman Empire dominates the Mediterranean Sea. At the same time, China is divided into three kingdoms corresponding to the frontiers of Wei, Wu, and Shu (Panel A of Figure 34). We pick 250 CE, a (brief) point in history when Europe's political consolidation exceeded China's, as the start of our simulation to investigate if a head start in political unification would have been sustainable for Europe. We incorporate the exogenous regime-specific shocks detailed in Appendix E.3 to allow polities to fragment and avoid foregone conclusions of unification.

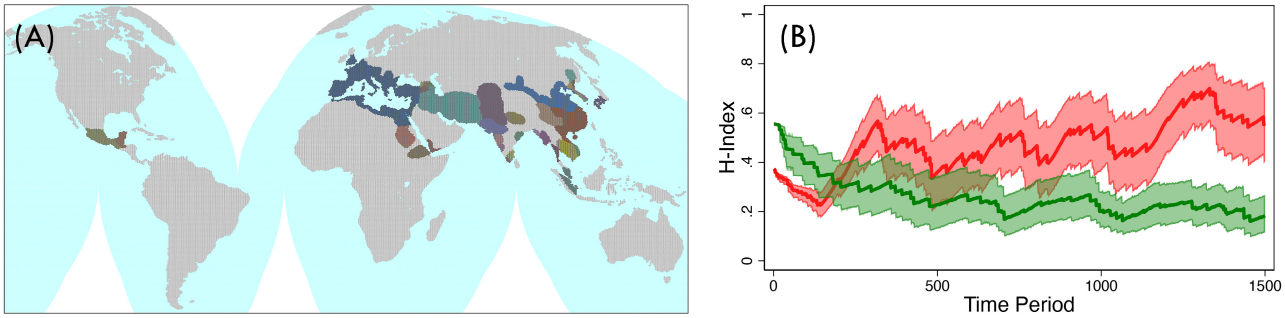

Figure 34: Using the world in 250 CE as the starting point ($t = 0$) of our simulation exercise.

Panel B of Figure 34 depicts the evolution of political consolidation at the two ends of Eurasia over 1500 periods, based on 10,000 bootstrap samples generated from 30 simulations under the preferred calibration. We observe contrasting trends. Europe begins with a higher (average) Herfindahl index than China, but it is soon overtaken by the latter. In fact, Europe ends up with a lower degree of unification than at the start of the simulation.[36]

Our second exercise examines a fictional scenario. At $t = 0$, Europe in the exercise resembles

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[36] The Herfindahl indices rarely rise above 0.8 throughout the 1500 periods considered, even in the case of China. This is because each index score is the mean value of 10,000 samples, and the inclusion of regime-specific shocks implies that at any point in time, there will always be some samples (out of the 10,000) in which China and Europe are politically fragmented.

Europe in 800 CE (Panel A of Figure 35), with a "Carolingian empire" in its center. At the same time, China is counterfactually fragmented into its seven constituent regions, as depicted in Figure 14 (China was mostly unified in 800 CE, under the Tang dynasty). This research design is chosen again to let Europe start with a higher political unification than China. Yet, despite starting with a vastly different map, we get the same result as in the previous exercise.

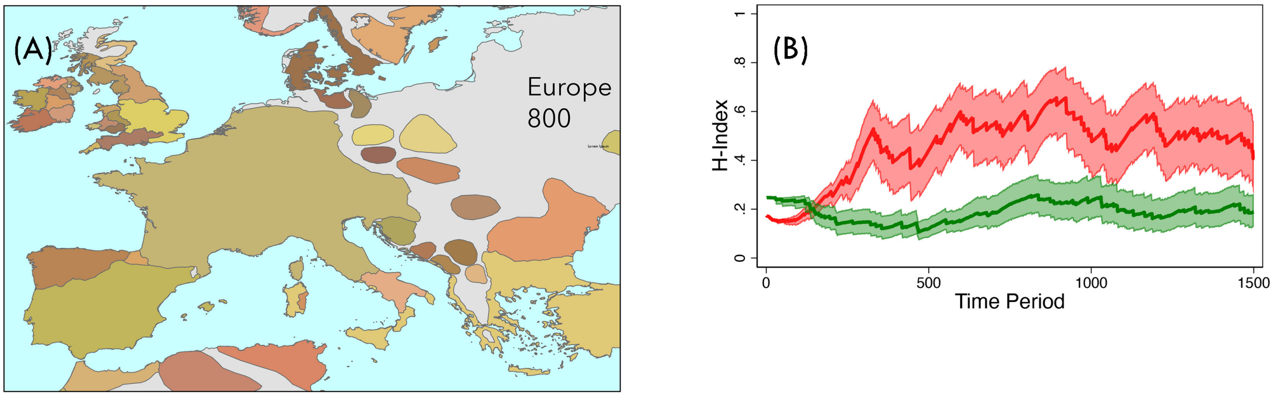

Figure 35: Using Europe in 800 CE (Nussli, 2011) and China as depicted in Figure 14 as the starting point ($t = 0$) of our simulation exercise.

These results suggest that a recurringly unified China and a politically polycentric Europe are not historical flukes. No matter the initial conditions, China unifies but Europe does not. We can, therefore, conclude that initial conditions are not key for our model and that path dependence tends to be washed out.

E.6 State Formation Across Eurasia

Beyond China and Europe, to what extent can our model explain broader patterns of political fragmentation across Eurasia? Figures 16 and 19 use our preferred model to compute the five largest polities originating in China, Europe (in two definitions: west of the Hajnal line and west of the Urals), South Asia, Middle East, and Southeast Asia. As before, we run 30 simulations and compute the bootstrap mean and confidence intervals with 10,000 samples with replacement. In our simulations, the formation of large states is most pronounced in East Asia. Notably, Europe is also distinctive. No other part of the world develops a robust system of medium-sized polities. It is this particular form of polycentricity that Mokyr (2016), Scheidel (2019), and others posit was critical to Europe's economic rise.

To illustrate further, we compute the Herfindahl indices of the five largest polities in these regions. Figure 36 confirms that the formation of large polities is most pronounced in China. After about 250 periods, the rise of one large state dwarfing all other Chinese states becomes apparent and unstoppable. To a lesser extent, we also see large hegemonic states emerging regularly in India and the Middle East. In the case of India, the trend emerges even earlier than in China, but it generally loses momentum over time, and full unification is never achieved. Closer scrutiny reveals that large states always originate from the north (for example, the Maurya, Harsha, and Gupta Empires). This is consistent with what we observe historically. Large polities or empires often emerged in North India. But until the Mughal Empire and the British Raj, they did not come close to unifying the Indian subcontinent.

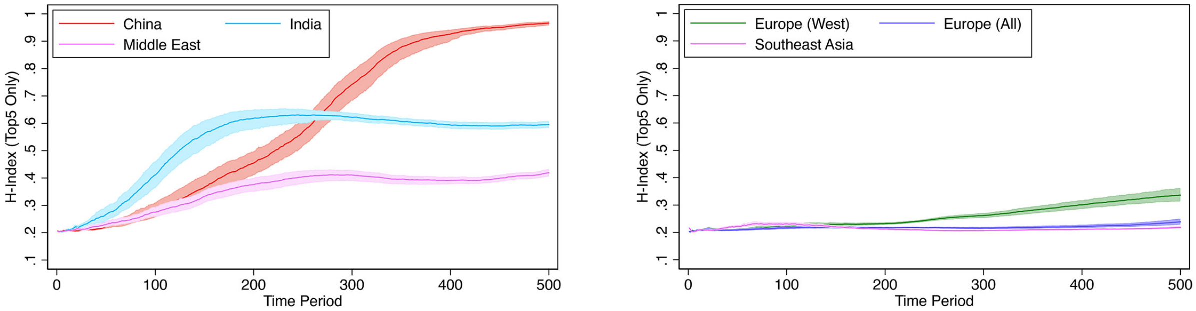

Figure 36: Herfindahl indices of the five largest polities in different Eurasian regions.

In the case of the Middle East, we also observe considerable political consolidation, but nowhere close to the full political unification seen in China. One episode that our model does not easily generate is the rapid Arab conquests of the 7th century. This is not surprising, as the episode has long been regarded as a unique event by historians.[37] The success of the Arab conquest of the entire Sasanian Empire and much of the Byzantine Empire in the mid-7th century has been attributed to three factors: (i) the weaknesses of the Sasanian and Byzantine Empires due to war and plague-induced population losses; (ii) religious divisions within the Byzantine Empire between the dominant Chalcedonian Church and Monophysitism; (iii) the religious cohesion, or *asabiyyah*, of the first Muslims. These factors, particularly the role of religion, are not in our model but could be added in future research.

At the same time, the Abbasid Caliphate was brittle. By 900, it had partitioned into nine components (Scheidel, 2019, p. 140). Our simulations typically produce several mid-size states in the Middle East that can be interpreted as the different successor states of the Caliphate.

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[37] For example, Kennedy (2001, p. 2) observes that "Despite the mass of words, the full explanation for Muslim victory still eludes us."

Consistent with historical observations, in our simulations, we generally do not observe the rise of hegemonic states in Europe and Southeast Asia. In all three cases, the Herfindahl indices are remarkably stable through the 500 periods, hovering at around 0.2, which implies that the largest polities in these regions are consistently evenly matched (the Herfindahl index value of five equal-sized polities is precisely 0.2). However, the similarity between Europe and Southeast Asia is somewhat superficial. As Panel C of Figure 19 illustrates, the largest states in Southeast Asia are tiny. Even at $t = 500$, we generally do not observe any polity amassing more than 100 hexagons (an area slightly smaller than modern-day Laos). In Europe, the largest polities grow and become sizable over time (Panels B and C in Figure 16), but because they grow in tandem, no single power becomes dominant over time. No power acquires the capability to overwhelm all its neighbors singlehandedly. For this reason, the trend is almost flat when we compute the Herfindahl indices for the five largest European states in Figure 36.

F The Expansion of China in History

Historically, China as a political entity emerged in the middle and lower reaches of the Yellow River. In the 2nd century BCE, the Han dynasty's territorial reach did not encompass China's southeastern coast, the Lingnan region, or the Yungui plateau (Figure 37). Successive regimes gradually absorbed these regions into the Chinese empire, but the process took centuries and, for a long time, Chinese rulers maintained only nominal suzerainty in much of these regions.

Table 3 summarizes the unified regimes in China and their origins. Qin, the first dynasty, originated from the Wei River, a tributary of the Yellow River. The founding emperor of the Former Han dynasty and his closest aides, including the founding prime minister Xiao He, rebelled against the Qin empire near their home county of Pei north of the Huai River. The Later Han dynasty was founded by Liu Xiu, who received support from local magnates from his native region of Nanyang in the Middle Yangtze River Basin. The founder of the Western Jin was a usurper of the Cao Wei regime, which unified northern China from Xuchang in the lower reaches of the Yellow River. Sui and Tang were offshoots of Toba Wei, a proto-Turkic regime originally based in Pingcheng, about 250 km west of present-day Beijing. Northern Song was a usurper state of Later Zhou, which originated from Ye in the Lower Yellow River. The Yuan and Qing rulers were nomadic or semi-nomadic people from the Eurasian steppe. The Ming dynasty, the only unified regime that had ruled China from a capital city south of the Yangtze River, could be traced to the Red Turban rebels who were active in the Huai and Lower Yangtze regions toward the end of the Yuan dynasty.

Figure 37: Early Han Dynasty

Table 3: Major Unifications of China

Dynasty	Period	Origins
Qin	221–206 BCE	Middle Yellow River
Former Han	202 BCE–8	Lower Yellow River
Later Han	25–220	Middle Yangtze
Western Jin	280–316	Lower Yellow River
Sui	581–618	Middle Yellow River
Tang	618–907	Middle Yellow River
Northern Song	960–1127	Lower Yellow River
Yuan	1206–1368	Eastern Mongolia
Ming	1368–1644	Huai River/Lower Yangtze
Qing	1644–1912	Manchuria

In summary, eight unified Chinese regimes started in northern China: either in the Yellow River Basin or in the steppe north of it. Two regimes originated from the Yangtze River Basin. None came from the regions further south (Yungui, Lingnan, and the Southeast Coast). This observation is consistent with our simulation results in Figure 15.

G Africa and the Americas

In this section, we provide further details of the predictions of our model regarding Africa and the Americas.

G.1 Africa

In the main text, we highlighted that scholars have advanced numerous accounts to explain why large agrarian states did not emerge in sub-Saharan Africa before 1500.

One group of explanations focuses on the slow diffusion of technology due to Africa's geography. First, the rarity of copper in many parts of Africa constrained the development of metallurgy and the use of metal tools on the continent (Childe, 1957). The oldest securely dated smelting furnaces in sub-Saharan Africa can be dated to 400–200 BCE, almost a millennium after the end of the Bronze Age and the beginning of the Iron Age in Eurasia (Killick, 2015). Diamond (1997) argues that the verticality of the African continent plus the barrier posed by the Sahara desert, which dried up about 5,400 years ago, prevented many technologies from spreading into sub-Saharan Africa. Consequently, land was less productive in sub-Saharan Africa than in Eurasia (Goody, 1971; Webb, 2006). This was partly due to the absence of tools such as the plow and wheeled transport (Goody, 1971). Furthermore, without artificial fertilizers, land fertility often dropped dramatically, encouraging slash-and-burn agricultural and pastoralism rather than intensive cultivation, which hindered the formation of centralized states.

A complementary group of explanations emphasizes Africa's climate and disease environment. High temperatures in many parts of sub-Saharan Africa mean that insect vectors are very active (Bellone, 2020). Two important examples of parasite-caused diseases are malaria, spread by mosquitoes, and sleeping sickness and nagana, spread by the tsetse fly. Malaria has played an important role in limiting population growth in sub-Saharan Africa. The tsetse fly is responsible for the parasite that causes nagana in domesticated animals. This meant that historically there was a dearth of large livestock in areas affected by the tsetse fly. Alsan (2015) documents how this factor impeded the development of intensive agriculture and state formation. Weil (2014), too, suggests that Africa's disease environment can explain why it had fallen behind Eurasia in terms of population, urbanization, and state development by 1500.[38]

To capture the effect of the slow diffusion of intensive agricultural technologies on state formation in sub-Saharan Africa, we modify our preferred specification and allow cells in this region to annex each other only from $t = 150$ (which would correspond to c. 250 BCE) onward. In addition, recall that our preferred specification is formulated to address GAEZ v4's overestimation of historical productivities in hot and cold regions and should capture, albeit imperfectly, some effects of climate on Africa's historical resource availability.

Unlike the baseline specification, where we see large empires emerging in almost every part of Africa over time (left panel of Figure 34 and Panel B of Figure 17), in the modified preferred specification (right panel of Figure 34), the largest states in Africa are relatively small. Only

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[38] Slavery provides another important explanatory for why states were late forming in sub-Saharan Africa. While the transatlantic slave trade emerged after 1500, the trans-Saharan and Red Sea slave trades date to the early Middle Ages (c. 600 CE in the case of the former (Wright, 2007)). These slave trades could have had a similar (if smaller in magnitude) impact on population densities and social solidarity as established by Nunn (2008) Nunn and Qian (2011) for the post-1500 trades. At the same time, both the trans-Saharan slave trade and the prevalence of indigenous slavery likely also reflect the relative absence of centralized states.

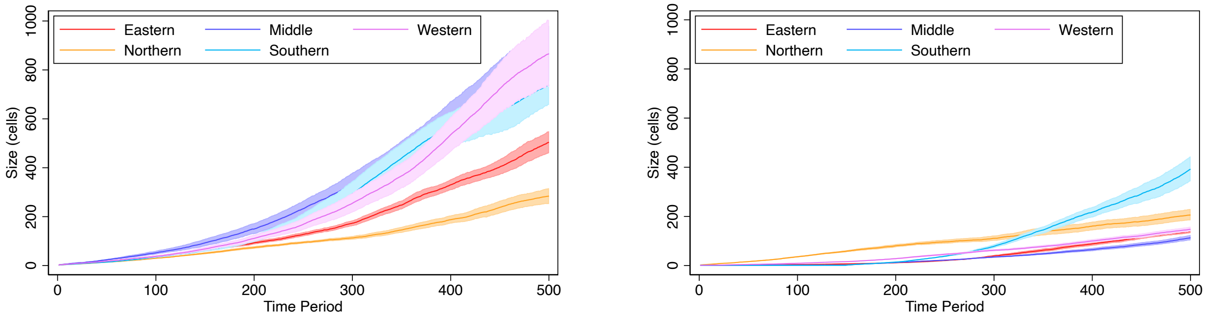

Figure 34: Left panel: baseline simulations. Right panel: preferred specification.

southern Africa—home to the historical kingdom centered on the Great Zimbabwe (c. 11th–15th century) and the 19th-century Zulu kingdom—occasionally produces states larger than 300 hexagons (approximately the size of France).

G.2 The Americas

The isolation of the Americas from Eurasia and Africa determined that, until the Columbian Exchange, its development depended solely on its local agricultural and technological innovations. Only one of the major cereals cultivated today, maize, is indigenous to the Americas. The other six (barley, oats, rice, rye, sorghum, and wheat) belonged exclusively to the "Old World" throughout our study period. The absence of iron tools in the Americas before 1500 meant that the major maize-producing areas today, including Iowa, Illinois, and northern Argentina, were marginal in maize cultivation due to the difficulties in clearing the tough-rooted sod covering the prairies and savannas (Hudson, 2004).[39] Maize cultivation in these otherwise highly fertile plains depended on slash-and-burn techniques, which could only support low population densities.

Furthermore, as in Africa, Diamond (1997) argues that the North-South orientation of the Americas slowed the diffusion of crops as climatic conditions varied across latitude (see also Turchin, Adams, and Hall, 2006). The first Europeans who traveled to the Americas observed that maize grown in different places varied widely in appearance, reflecting their distinct isozymes (Goodman and Galinat, 1988). While this reflects the fantastic ability of maize to adapt to a wide range of environments and climatic conditions, the adaptation process was time-consuming. On the eve of the Columbian Exchange, several millennia after maize was domesticated, Mexico

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[39] In the absence of iron tools, the Indigenous peoples used bison scapulae and bone tools, which wore out quickly, to work their gardens (Bamforth, 2021).

and neighboring Guatemala remained the main maize areas of the Americas, alongside Peru, where maize might have been independently domesticated (Kistler et al., 2018).

Peru deserves a separate mention. As Figure 5 illustrates, attainable yields based on rainfed, low-input cultivation in Peru are quite low, both in highland Peru and its coastal deserts. Without modern agricultural techniques, these lands appear incapable of supporting a large premodern state like the Inca Empire. However, the local peoples had access to guano, the desiccated manure of seabirds rich in nitrates and phosphates. Known as "white gold" (Plazas-Jiménez and Cianciaruso, 2020), guano had been used as a natural fertilizer for several millennia (Poulson et al., 2013).

The Incas highly valued guano. To safeguard its supply, the Inca kings undertook harsh measures, including imposing death penalties for those who killed a bird or disturbed a bird's nest (de la Vega, 1609, (1961); Rodrigues and Micael, 2021). Alexander von Humboldt, a Prussian scientist who visited Peru in 1802 and whose writings helped make guano known to the world, remarked upon realizing guano's properties that he now knew the secret to the glory of the Inca Empire and its predecessors: their possession of large amounts of guano that allowed their deserts to blossom (Cushman, 2014). Importantly, guano was a location-specific asset. Not only was Peru blessed with an abundance of guano-producing birds, but the relative lack of precipitation along the Peruvian coast allowed guano to accumulate and bake instead of being washed away by rain (Szpak et al., 2012). By contrast, although Europe has many seabird colonies, too, high rainfall means that European guano is of inferior quality due to the severe leaching of valuable nitrates.

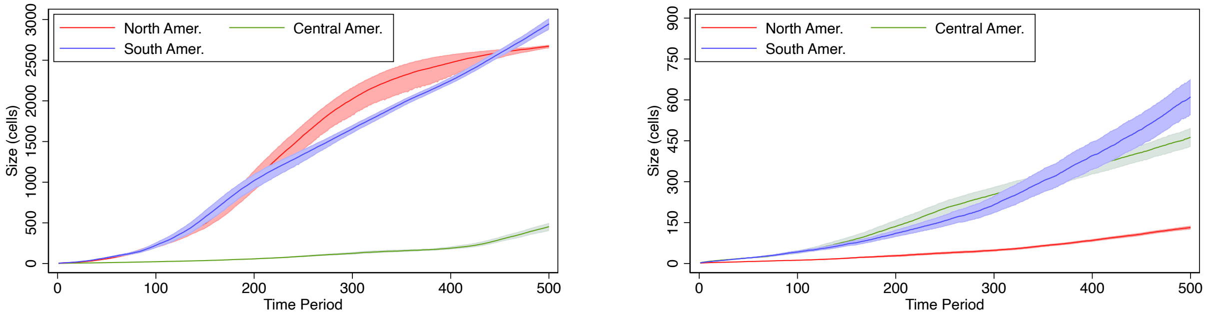

Figure 35: State formation in the Americas. Baseline simulations (left panel) vs. simulation adjusted by the spread of corn (right panel) eastern United States (North America) and Argentina (South America).

We incorporate these insights by extending our model in two ways. First, we account for the timing and spread of sedentary agriculture in the Americas based on Weatherwax (1954, Figure

18) and Blake (2015, Figure 6.1) and allow cells in the Americas to annex each other only after the adoption of maize cultivation. Next, we identify the guano-bearing regions of South America based on Cushman (2014, Map 1). Next, as in the steppe and the Mediterranean extensions, we increase the attainable yield of cells in these regions by a factor of 1.25, or to the median productivity of South America, whichever is higher. Panel C of Figure 18 illustrates how, once we consider these factors, the Americas cease to produce super-sized polities. Conforming to historical observations, the larger states in the Americas typically emerge in the Pacific coast and Andean highlands, Guatemala and the Yucatán Peninsula, and the Mexican plateau, home to the Inca, Maya, and Aztec societies, respectively (Panel C of Figure 18; Figure 35). Figure 35 presents the same information, but now in terms of Herfindahl indices of political unification.

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