The Physics of Statecraft:

Technology, Terrain, and the Territorialization of Modern States[1]

T. Camber Warren

Department of Defense Analysis
Naval Postgraduate School

Lars-Erik Cederman

Sebastian Schutte

Center for Comparative and International Studies
ETH Zurich

Abstract

While variation in the power and size of states has long been recognized as one of the central drivers of geopolitical behavior, few studies have directly addressed the question of how and why different states came to be the sizes they did. The most prominent formal contributions to this question, based in a logic of voluntary optimization, fail to account for some of the most fundamental patterns observed in empirical data on state sizes, including the fact that territorial sizes are consistently lognormally distributed. In contrast, we develop an ecological model of coercive competition, which seeks to capture both the positive feedback dynamics inherent in states' pursuit of territorial expansion, and the physical constraints of projecting power over long distances. Moreover, we show that the empirical predictions derived from this model are in strong agreement, both qualitatively and quantitatively, with real distributions of state sizes observed over the period 1500 AD to 1998 AD.

---

[1] Paper prepared for presentation at the Annual Meeting of the American Political Science Association, New Orleans, LA, August 30 - September 2, 2012.

Introduction

Variation in the power and size of states has long been recognized as one of the central drivers of geopolitical behavior (Waltz 1979; Gilpin 1981). However, few studies have directly addressed the question of how and why different states came to be the sizes they did. Historians have generally treated such topics as questions that defy generalization, that can only be explained on the basis of highly contingent, path-dependent outcomes (see e.g. Weber's (1949) classical critique). In contrast, we argue here that such perspectives, in their fascination with minor variations in foliage, have missed the impressive obduracy of the forest form. There are, in fact, hints of order even amidst the apparent chaos of world politics. Drawing on the tools of Geographic Information Systems (GIS) and Extreme Value Theory (EVT), we demonstrate that the basic shape of the distribution of territorial state sizes has remained remarkably constant across five centuries of state evolution. Throughout modern history, the territorial sizes of states have always followed the characteristic right-skewed tail of a *lognormal* distribution, meaning that very large states occur more frequently than would be expected under the standard assumption of normality. Indeed, the lognormality of the distribution of state sizes seems to represent one of the most basic and enduring empirical regularities yet discovered in the study of international politics.

While examinations of temporal changes in average state sizes have provided valuable insights into the factors that favor larger and smaller polities (Lake and O'Mahony 2004), we argue that the remarkable consistency of the lognormal form also demands explanation. The most prominent formal work on this topic assumes that state sizes arise voluntaristically from attempts to maximize the efficiency of public goods provision (Alesina and Spolaore 2003). Unfortunately, this perspective provides no insights into why state sizes would be lognormally distributed, and makes no attempt to account for the *actual* sizes of *any* real states. In contrast, we argue that any successful model of state size must explain both what has remained constant in the state-generating process, and what has changed. That is, such a model must simultaneously provide an account of why state sizes are so consistently lognormally distributed, and why average state sizes vary so greatly over time and space.

To do so, we trace the development of the modern territorial state back to its roots in the 16th century, and introduce a computational approach that allows us to move beyond mere qualitative agreement with stylized facts, to models which generate *quantitative* predictions on the basis of *empirically grounded* mechanisms and parameters. In contrast to the *static* model of *voluntaristic optimization* offered by Alesina and Spolaore, we offer an *ecological* model of *coercive competition*. Deriving insights from students of state formation, such as Tilly (1992), Herbst (2000), and Scott (2009), the model is premised on the notion that territorial states represent a particular kind of "social organism" that evolved in response to changing circumstances on the European subcontinent following the Middle Ages. The model demonstrates that both the lognormal form and the variation in its mean are the product of a particular kind of positive feedback loop which emerged for the first time in the unique geopolitical ecology of early modern Europe. This feedback loop -- in which territorial expansion generates increased rates of resource extraction that in turn yields greater coercive capacities and further expansion -- represents the central engine by which territorial states came to dominate the geopolitical stage (Tilly 1992; Spruyt 1994).

The model also demonstrates that the positive feedback of the conquest process has been counteracted by two fundamental physical constraints: (1) the constraint of *distance*, which causes power to weaken as distances from the center of power grow, and (2) the constraint of *gravity*, which causes effective distances to grow more rapidly in rough and difficult terrain. By formalizing the simple logic underlying these basic physical mechanisms, and seeding the model with real-world data on terrain roughness and city locations from 1500 AD, we seek to recreate the conditions of the birth of the territorial state in early modern Europe. We show that the basic logic of this dynamic produces a recognizable distributional signature, which acts like a "fingerprint" for identifying the underlying data generating process. Moreover, this same logic readily accounts for the observed shift in the average size of states over time, on the basis of technological improvements that altered the severity of the costs imposed by distance and gravity. The model also allows us to demonstrate, counterfactually, that in the absence of either of these basic constraints the constellation of geopolitical actors would have evolved into a very different form, completely lacking the observed lognormal signature. We thus conclude that the fundamental physical relationships of distance and gravity have underlain the process of state formation and state growth since the inception of the modern state system.

The Evolution of States

A long tradition of work in the field of political economy characterizes the size of sociopolitical entities -- whether firms, cities, or nations -- as a function of a fundamental trade-off between the benefits and costs of larger groupings (Bean 1973). On the one hand, increasing size brings a number of benefits, especially in providing goods that benefit from greater economies of scale. On the other hand, larger aggregations bring with them a number of costs, including energy devoted to control and administration, which eventually constrain further expansion. The sizes that actually arise are thus seen as the result of attempts to optimize payoffs in the face of these competing pressures.

In a seminal contribution that applies this logic to the sizes of contemporary states, Alesina and Spolaore (2004) argue that state sizes are the product of attempts to maximize the trade-off between increasing economies of scale in the production of public goods and increasing preference heterogeneity over competing public goods. Stated briefly, Alesina and Spolaore (2004) propose that many public goods -- such as schools, roads, and militaries -- can be provided more efficiently at larger spatial scales and thus incentivize larger political aggregations. At the same time, political aggregation becomes increasingly costly over long distances because people become increasingly diverse in their preferences regarding the nature of the public goods that will be provided by the state. Observed state sizes are thus seen as a solution to this optimization problem, in which rational decision-makers -- either voters or a central planner -- seek to maximize the efficiency of public goods provision.

While this account has provided a number of important insights into the fundamental trade-offs of increased state size and the inherent difficulties of multilevel governance, several important theoretical shortcomings have inhibited its ability to generate useful empirical predictions. First, the model is premised on the existence of single-dimensional "line states" that have length but no width, and thus bear no resemblance to any real-world topologies. While this construction eases the analytic tractability of the model, it renders impossible any attempt to relate the model's predictions to measurable empirical quantities.   Second, it is important to note that distance becomes relevant within this account only because it is assumed to correlate strongly with preference heterogeneity, and thus is expected to produce more intractable disagreements over the proper use of state resources. The model thus characterizes the foundations of state existence in fundamentally voluntaristic terms, divorced from the structural realities of blood and iron through which modern territorial states were actually forged. Finally, the predictions of the model can only take the form of static equilibria, rendering difficult any attempts to capture the historical process of competition and expansion through which territorial states came to exert geopolitical influence.

In stark contrast, scholars such as Tilly (1992), Herbst (2000), and Scott (2009) offer a perspective on state formation that could be labeled "ecological." The roots of this perspective can be traced back to Otto Hintze ([1902] 1975), who more than a century ago criticized the social sciences for their tendency to treat the statehood "as a fixed and immutable quality" (159). Mirroring our critique of Alesina and Spolaore (2003), Hintze ([1902] 1975) argued that such approaches served "to wrench each single state from the context in which it was formed" (160). Turning this reasoning on its head, Hintze boldly claimed that: "external conflicts between states form the shape of the state," including its size, contiguity, and external configuration ([1902] 1975, 160).

This approach treats territorial states as a particular kind of "social organism" that arises in human contexts that are favorable to its growth and maintenance (Scott 2009, 42). As Tilly explains, such organisms cannot arise in isolation:

> "In the nature of the case, national states always appear in competition with each other, and gain their identities by contrast with rival states; they belong to *systems* of states" (1992, 23).

Polities are, in Scott's apt phrase, "constituted in each other's shadow" (2009, 28).[2] They do not arise independently out of isolated attempts at optimization, but rather "co-evolve" alongside

---

[2] For a trenchant analysis of the role of "mutually constitutive" relations between states, and the resulting ambiguity inherent in the classical division between "agency "and "structure", see Wendt (1999).

each other, locked into a perpetual race for growth and survival (Scott 2009, 17-18). There is thus no act of voluntary choice by which the fixed geographic boundaries of territorial states are produced. Such boundaries emerge, rather, from competitive -- and frequently violent -- interactions between states (Cederman 1997). The specific boundaries that come to achieve dominance as "social facts" (Searle 1995) at a given historical moment should therefore be viewed as emergent properties of a particular system of coercive interaction.[3] As Hechter argues,

> "boundaries between groups initially flow from institutions of control rather than from already pre-established social identities. Hence, identities are derived from boundaries rather than vice versa." (Hechter, 2000 23)

Moreover, the political forms that arise and achieve dominance in a particular place and time are not optimal equilibria, but rather adaptive responses to the pressures of different social and political contexts. That is, different state forms are simply "logical responses to their physical environments" (Herbst 2000, 51). As Tilly explains, alternative forms of political organization,

> "do not represent alternative 'strategies' so much as contrasting conditions of life. Rulers pursuing similar ends -- especially successful preparation for war -- in very different environments responded to those environments by fashioning distinctive relations to the major social classes within them. The reshaping of

---

[3] On the critical importance of "social facts", even in the life-or-death struggles that characterize the politics of international security, see Adler (1997), Checkel (1998), and Ruggie (1998).

> relations between ruler and ruled produced new, contrasting forms of government, each more or less adapted to its social setting" (Tilly, 1992 30)

Thus, if we wish to understand the fundamental forces underlying the generation of state power, we should treat variable political forms as products of a competitive ecology of state-making projects. Much like the economic approach described above, this ecological perspective implies that in order to understand the behavior of the system as a whole, we should focus on the conflicting pressures generated by the benefits of size and the constraints of distance (Scott 2009, 37). However, whereas the economic approach focuses on the constraints generated by demographic heterogeneity and the diversity of preferences, we propose that the more fundamental constraints on state size have, for the past 500 years, been rooted instead in the physics of coercion. In summary, whereas the dominant approach to the puzzle of state sizes offers a *static* model of *voluntaristic optimization*, we develop in its place an *ecological* model of *coercive competition*.

Territory, Coercion, and Positive Feedback

Scholars have long recognized the capacity to project coercive force over distance as the defining quality of effective states (Mann 1986). In fact, prior to the 19th century state revenues were devoted almost exclusively to military security, accounting for 70 - 90 percent of national budgets (Gaubatz, 2009, 12). For most of the past thousand years, the basic problem faced by all states and would-be states has remained essentially the same: the projection of coercive force over long distances is incredibly costly. Prior to the 15th century in Europe, these costs changed very little: "Long-distance control and communications were of the same general order as they had been in Roman times" (Mann 1986, 444). Indeed, movement across even open terrain was so slow and laborious, that direct projection of coercive force was generality limited to the scale of individual cities and their immediate hinterlands (Spruyt 1994). As Tilly (1992) explains, rulers during Europe's Middle Ages:

> "prevailed as conquerors, tribute-takers, and rentiers, not as heads of state that durably and densely regulated life within their realms. Inside their jurisdictions, furthermore, rivals and ostensible subordinates commonly used armed force on behalf of their own interests while paying little attention to the interests of their nominal sovereigns. Private armies proliferated through much of the continent. Nothing like a centralized national state existed anywhere in Europe." (39-40)

However, by the end of the 15th century, momentous changes were afoot. Important improvements in the technologies of communication, fortification, and bombardment, combined with rising densities of population and capital across the continent, fundamentally altered the benefits of scale in early modern Europe (Tilly 1992). For instance, travel times from London to York shifted from 6 days in the late 15th century, to 55 hours in 1570 (Hechter 2000, 47). Thus, for the first time it became possible to exert direct coercive control over multiple cities at a cost that rendered feasible their incorporation into a single political unit (Spruyt 1994). Once this critical technological threshold was crossed, Europe entered a new phase in its history, characterized by emergence of warfare on a massively increased scale:

> "War wove the European network of national states, and preparation for war created the internal structures of the states within it. The years around 1500 were crucial. Europeans had started using gunpowder seriously in warfare toward the middle of the fourteenth century. Over the following 150 years, the invention and diffusion of firearms had tipped the military advantage toward monarchs who could afford to cast cannon and build the new kinds of fortress that cannon could not easily shatter. ... On a European scale, then, the late fifteenth century marked an important transition: as the large military states began to feel the stimulus of capitalist expansion, the advantages of the small mercantile states began to disappear." (Tilly 1992, 76)

This same period witnessed exponential increases in the scales of state armies and the demands of taxation used to support them. For instance, Spain's forces expanded from 20,000 soldiers in 1492 to 100,000 in 1532, while tax revenues rose from 900,000 reales in 1474 to 26,000,000 in 1504 (Tilly 1992, 78-79).

This rapid expansion in the scale of governance and military activity profoundly altered the incentives facing state-making projects in early modern Europe, generating a novel competitive ecology, and along with it a novel species of political organization: the territorial state. Such states, for the first time in world history, articulated and defended claims of territorial sovereignty on the basis of sharp borders and uniform authority within those borders (Spruyt 1994). Put another way, fixed territorial borders between states were an emergent property of a new system of coercive interaction made possible by improved technologies of communication and control. Herbst (2000) explains the importance of this life or death struggle to the development of the territorial state form:

> "Wars of territorial conquest ... have been central to the formation of particular types of states because they create, quite literally, a life and death imperative to raise taxes, enlist men as soldiers, and develop the necessary infrastructure to fight and win battles against rapacious neighbors.
>
> Because European states were forged with iron and blood, it was critical for the capital to physically control the hinterland. ... In particular, the constant threat of war and the need to protect valued territory meant that the physiology of the state forced leaders to place particular emphasis on control of remote areas that could be lost in battle." (13-14)

As technological improvements rendered the construction of territorial states increasingly feasible across the European continent, claims rooted in fixed boundaries and territorial sovereignty laid the foundation for the emergence of a powerful positive feedback loop, in which increasing state size generated increasing capacity for further expansion. Tilly (1992) captures the logic succinctly: "everyone who controlled substantial coercive means tried to maintain a secure area within which he could enjoy the returns from coercion" (70). In principle, the larger the area that could be secured, the greater the returns that could be enjoyed. Hence it became possible for a nascent power center to devote resources to the military domination of a neighboring polity and thereby increase total revenue extraction. Those revenues could then be used to increase the reach and leverage of center's coercive forces, which could in turn be used to propel further territorial expansion. The result was a new dynamic of territorial competition driven by ever greater scales of conquest and political aggregation (see Cederman 1997, Chap. 4).

As we argued above, the primary restrictions on this dynamic arose from basic physical constraints on the projection of coercive power over long distances. Because coercive leverage requires physical access to its target, state power inevitably attenuates as distance from the center increases (Boulding 1962). More specifically, we can identify two separate mechanisms of power decay, which we file under the stylized headings of *distance* and *gravity*. By "distance," we mean simply that it takes more time and energy to travel a longer distance than a shorter distance. As a result, messages are delivered with less reliability, armies reach their destinations with less strength, and surveillance occurs with less accuracy (Herbst 2000, 49). By "gravity," we mean simply that it is harder to move uphill than it is to move downhill, and harder to move downhill than it is to move across flat terrain. This implies that the difficulties imposed by distance will be more severe -- that is, the total time and energy expended will increase more rapidly as a function of distance -- when travelling over rough and mountainous terrain. The "friction" of difficult terrain thus causes the projected power of the state to decay more rapidly across steep mountain ranges than across broad plains (Scott 2009, 43).

We view these mechanisms of distance and gravity as uncontroversial statements of two (though certainly not the *only* two) basic and necessary physical constraints underlying the projection of coercion across territory. In the sections that follow, we demonstrate that by formalizing these simple maxims in the context of an empirically grounded computational simulation of state growth in early modern Europe, it becomes possible to produce quantitative agreement with a number of empirical regularities that have yet to be effectively captured through the analytic lens of static, voluntaristic equilibria.

Advantages of the Computational Approach

The theoretical and empirical difficulties encountered in the model of state sizes promoted by Alesina and Spolaore (2003), which we outlined above, are generally symptoms of a methodological perspective which privileges analytic tractability over empirical grounding. Line states, voluntaristic choices, optimization, and static equilibria are all modeling choices that, while clearly divorced from the realities of real-world state formation, are needed in order produce closed-form solutions that can be proven to hold under general conditions. While the rigor and consistency of such approaches should be lauded, it should be noted that these modeling choices also carry substantial methodological costs. Most importantly, it becomes impossible to subject the predictions of the model to rigorous empirical scrutiny. Note that the Alesina and Spolaore model not only fails to provide an explanation of the lognormality of the distribution of state sizes, it also fails to make predictions concerning *actual* sizes of *any* real states. Instead, the empirical implications derived from the model take the form of qualitative agreement with certain stylized facts (e.g. school policies should be subject to more local control because they are characterized by greater preference heterogeneity) that can never be falsified and can only be indirectly connected to the model's central mechanism.

In contrast, the great advantage of the computational approach developed here lies in the flexibility with which model mechanisms and parameters can be specified. By eliminating the need for closed-form solutions, computational simulations allow researchers to specify model forms that more closely approximate the mechanisms we believe to be operating in the real world, dramatically increasing the opportunities for empirical validation and falsification. Moreover, by seeding the model with real-world measurements of relevant parameters, we show that it is possible for computational approaches to move beyond mere qualitative agreement with stylized facts, to instead pursue *quantitative* agreement with entire distributions of observed outcomes. This, in turn, allows us to greatly increase our confidence that we have captured an important element of the real-world data generating process.

In a sense, this amounts to trading the benefits of analytic *rigor* for the benefits of empirical *relevance*. However, at the root of this trade lies the fundamental difficulty in computational approaches to formal modeling: in achieving this much-vaunted flexibility, the researcher risks generating an explosion of free-floating parameters that undermine the inferential validity of the model because they can all too easily be used to "tune" the model's output into any desired pattern. This difficulty certainly does not mean computational methods should be abandoned, but it does mean that researchers should be sensitive to the problems caused by massive parameter spaces and the "curse of dimensionality" (deMarchi 2005), and should consider ways to mitigate such inferential barriers.

The solution we adopt here is threefold: First, we seek extreme parsimony when specifying the "free" parameters that will be allowed to vary in our computational experiments, restricting the model to only two main moving parts. Second, whenever possible we seek to ground the model's underlying parameters in real-world measurements, to avoid leaving excessive freedom for "curve-fitting" adjustments. Third, for those arbitrary parameters that cannot be empirically grounded, we conduct robustness checks in which the parameter is systematically varied or randomized to ensure that the model's results are not dependent on the selection of a particular value for that parameter. In this way, we hope to demonstrate that the flexibility of computational approaches to formal modeling need not undermine their empirical validity.

Simulating Conquest and Decay

Our ecological model of coercive competition seeks to represent the positive feedback loop between resource extraction and territorial expansion that emerged in Europe around 1500 A.D.[4] In the model states grow stronger by achieving increased territorial size which in turn increases the ease with which they can pursue additional territorial expansion. This positive feedback dynamic is constrained by the tendency of state power to decay in strength as it is projected through longer and more difficult geographic paths. By simulating the competitive process of growth and conquest through which territorial states were constituted, the model generates quantitative predictions concerning the global distribution of state sizes that are likely to arise in different geopolitical contexts.

The model begins with a two-dimensional grid of 129,500 (370 x 350) square tiles. Onto this grid we project a map of the European subcontinent, derived from the GTOPO30 elevation database supplied by the U.S. Geological Survey. The original data, measured at a resolution of 1 kilometer square cells, is mean-sampled to match the resolution of the simulation grid, where each tile is approximately 7 kilometers wide. In this way, each non-ocean simulation tile is assigned an elevation value which matches the mean elevation of the corresponding patch of earth in the real world. On top of this, we project a second layer of data which records GIS coordinates for the locations of major cities in 1500 AD, derived from the EurAtlas GIS Vector dataset. Because state-making projects can only arise in the presence of cities (Tilly 1992; Scott

---

[4] See Cederman (2003) for an earlier attempt to model state sizes using the GeoSim framework from Cederman (1997) and Cederman and Giardin (2010).

2009), these city locations allow us to empirically ground the pool of potential starting locations for the development of territorial states.[5] Each simulation tile which includes at least one city begins the simulation as a "capital" tile, which means that it can conduct the basic operations of state formation and growth: resource extraction, power projection, and territorial expansion. Based on this empirical seeding, the simulation begins with 812 proto-states (see Figure 1).

In each time step of the simulation, each state capital (selected in randomized order) first calculates the total quantity of resources that are extracted from the tiles it dominates. In the first time step, this dominion consists solely of the capital tile, but as the simulation proceeds states have the opportunity to expand the territory over which they exert coercive leverage. Without loss of generality, we normalize the maximum resources possibly extracted from a tile to 1. The actual resources extracted from a given tile are a fraction of this maximum, determined by the effective distance between the capital and the tile it is dominating. Following Boulding (1962), we assume that this loss-of-strength gradient takes the form of an exponential decay, which arises naturally from the assumption that a fixed percentage of the efficiency of the state's coercive leverage is lost for every unit of time $\boldsymbol{t}$ that must be expended to reach the target.[6] Hence, the resources that a state receives from tile i are given by:

$$\boldsymbol{r}_i = \boldsymbol{\delta}^t \qquad (1)$$

where $\boldsymbol{\delta} \in [0, 1]$ is a parameter which captures the degree to which power decays with increasing travel time, with higher levels of δ representing weaker rates of decay and $\boldsymbol{\delta} = 1$ representing a complete absence of decay. The total resources $\boldsymbol{R}$ available to a given state is then simply the sum of the resources extracted from each of the $\boldsymbol{k}$ tiles over which it rules:

---

[5] Robustness checks with randomized capital locations indicate that the models results are not dependent on these specific locations. But by grounding the locations in empirical data, we ensure that they were not "tuned" to produce desired results.

[6] Equivalently, we could characterize this as the "energy" that must be expended to reach a target.

$$\boldsymbol{R} = \sum_{i=1}^{k} \boldsymbol{r}_i \qquad (2)$$

Recall from above our argument that the amount of time *t* needed to reach a target is a function of the physical constraints of both *distance* and *gravity*. That is, *t* should increase, not only as a function of the straight-line map distance that must be travelled, but also as a function of the terrain barriers that must be overcome. To operationalize this argument, we draw insights from the U.S. Army Field Manual (1998) which includes guidance to field commanders for calculating the relationship between distance, terrain ruggedness, and expected marching time for infantry formations. Total time is given by the straight-line distance ***d*** (in meters) between points A and B, multiplied by the effective travel rate (in seconds per meter). The effective travel rate is given by the sum of a baseline walking rate ***c***, representing the rate of travel on perfectly flat terrain, and a penalty term for terrain ruggedness. The manual indicates that the penalty term is a simple linear function of the steepness of the slope ***s*** (in decimal degrees) between points A and B, with ascents (i.e. ***s*** > 0) adding twice as large a penalty as descents (i.e. ***s*** < 0) of equivalent steepness. Thus, the total travel time ***t*** between two adjacent tiles is given by:

$$\boldsymbol{t} = d(c + \beta s) \qquad for\ s \geq 0$$

$$\boldsymbol{t} = d\left(c + \frac{\beta}{2} s\right) \qquad for\ s < 0 \qquad (3)$$

where $\boldsymbol{\beta} \in [0, \infty]$ is a parameter capturing the degree to which steeper slopes increase the costs of movement over terrain, with high values representing higher costs, and $\boldsymbol{\beta} = 0$ representing the complete absence of penalties for difficult terrain. The manual also indicates that the standard baseline walking rate for infantry on flat terrain is 4 kilometers per hour, which allows us to empirically ground the constant ***c*** with a value of 1.111 seconds per meter.

Thus, to calculate the degree of power loss experienced in travelling between a capital tile A and an immediately adjacent tile B, the model sets $\boldsymbol{d}$ equal to the straight-line map distance between the centroids of the two tiles, calculates the slope $\boldsymbol{s}$ on the basis of the empirically-derived altitude difference between the two tiles, and then applies equations (1), and (3) on the basis of the two free parameters that are left subject to experimental variation: $\boldsymbol{\delta}$, which captures degree to which power projection decays with effective distance (i.e. travel time) and $\boldsymbol{\beta}$, which captures the degree to which effective distance increases with slope. For longer distances, say between capital tile A and the non-adjacent tile D, the total travel time $\boldsymbol{t}$ is simply is simply the sum of the travel times experienced between each of the adjacent cells on the shortest path from A to D (i.e. A to B to C to D)

In each time step, each state is also given the opportunity to expand its territorial reach by one tile. Once the state has calculated its total resources using equations (1), (2) and (3), it considers expansion by searching for the tile on the border of its dominion that would yield the greatest rate of resource extraction if it were captured. If this tile is currently unoccupied, it is seized by the conquering state, and immediately begins contributing the resources given by equation (1) to the total resources of the conquering state. If the tile is occupied by a competing power center, each rival state $\boldsymbol{j}$ calculates the strength of the power $\boldsymbol{P_j}$ it can project onto the contested tile by multiplying its total resources $\boldsymbol{R_j}$ by the degree of loss $\boldsymbol{\delta^t}$ experienced in travelling to tile $\boldsymbol{i}$ from the capital of state $\boldsymbol{j}$: $\boldsymbol{P_j = R_j\left(\delta^{\,t(i)}\right)}$, and whichever state projects greater local power becomes the ruler of the tile.

As the simulation progresses, some states amass increasing amounts of territory and resources, and thereby gain the capacity to dominate their neighbors (see Figure 2). This in turn yields greater resources, and thus and even greater ability to seize additional territory. This positive feedback dynamic is constrained, however, by physical limits on the capacity to project power over distance. In this way, we seek to capture the ecological logic of coercive competition through which the territorial state achieved dominance on the European subcontinent, and thereby shed light on the fundamental ways in which physical constraints have conditioned the possibilities for state-making in the modern world. Because both the inputs and the outputs of the model are grounded in real measurements of real landmasses, it can be readily subjected to rigorous empirical validation. Moreover, by experimentally manipulating the values of $\boldsymbol{\beta}$ and $\boldsymbol{\delta}$, across multiple runs of the simulation, it becomes possible to systematically investigate the impacts of changing technological conditions over time, as well as counterfactual worlds in which distance and terrain have no bearing on state activities. We turn to such experiments in the following sections.

Empirical Data and Methods

Reliable data on the territorial sizes of states has been made available by the efforts of Lake and O'Mahony (2004) for the period 1815-1998. However, estimating the sizes of states in 1500 AD is somewhat more difficult. To overcome this hurdle, we relied EurAtlas GIS Vector dataset, which includes geo-coded polygons measuring the territorial boundaries of all the sovereign and dependent political entities that can be identified in historical atlases for the year 1500 AD. In the case of overlapping jurisdictions, every attempt was made to code the boundaries on the basis of actual coercive control, regardless of the rhetorical claims sometimes made by distant monarchs. Operationally, we define territorial states as political entities characterized by (1) an identifiable leadership structure claiming internal sovereignty over its subjects, and (2) sharply defined external territorial boundaries on all sides, recognized (at least nominally) by neighboring states. Note that this definition excludes both dependent political entities that rule in name only but lack real coercive leverage, and imperial political forms that extract resources from their subjects but lack sharply delineated territorial boundaries. In all, we identify 92 political entities that qualify as territorial states in 1500 AD (see Figure 3).

To assess the distribution of state sizes in each of these periods, it is helpful to introduce the use of log-log plots, as shown in Figure 4. Each dot on the figure represents a separate territorial state, with states from 1500 AD marked in red, and states from 1998 AD marked in purple. For each of these two samples, we plot what are known as complementary cumulative density functions (CCDF), which show the probability of observing outcomes larger than some threshold, *x*. Because the values are plotted in log-log space, each step along the x- and y-axes represents an increase by an order of magnitude rather than an increase by a single unit.

The two CCDF plots provide effective snapshots of the entire system of territorial states, as it existed in 1500 and in 1998. As can be immediately discerned from the figure, the global distribution of state sizes has undergone substantial change over the past 500 years. Over that period, the average state size has increased from 74,572 square kilometers to 854,887 square kilometers. The CCDF plots also reveal key facts about the form of the state size distribution in each of these periods. The fact that both series continue to extend rightward without ever reaching a vertical asymptote, even at their most extreme values, is indicative of a "heavy tailed" distributions in which extreme values are more likely than would be implied by standard Gaussian distributional forms (Clauset, Shalizi, and Newman 2009; Sornette 2006). However, as opposed to the well-known "powerlaw" distributional form that remains linear throughout the log-log space (Clauset , Young, and Gleditsch 2007; Clauset and Wiegel 2010; Smith 1987), the slight downward curvature of our two CCDFs indicates that the variables are likely to be *lognormally* distributed.

Lognormal distributions can be defined quite simply: if $\boldsymbol{Y}$ is a normally distributed random variable, $\boldsymbol{X} = \exp(\boldsymbol{Y})$ has a lognormal distribution; similarly, if $\boldsymbol{X}$ is lognormally distributed, then $\boldsymbol{Y} = \log(\boldsymbol{X})$ is normally distributed. The right-skewed "heavy tail" of the lognormal distribution declines more slowly with size than do normally distributed values, meaning that large outcomes occur with greater frequency than would be expected under assumptions of Gaussian behavior. Whereas normally distributed random variables are characteristic of linear, additive processes in which small deviations tend to cancel each other out, lognormal distributions are frequently characteristic of multiplicative feedback processes in which growth feeds further growth (see Limpert, Stahel and Abbt 2001, for a helpful review). To confirm our suspicion that the two samples are lognormally distributed, we log-transform the variables and then apply the Shapiro-Wilk normality test (Shapiro and Wilk 1965). For both samples, the test statistic is well above the critical value ($p = 0.2684$ and $p = 0.7606$, respectively) meaning that we cannot reject the null hypothesis that the original data are drawn from a lognormal distribution. We thus conclude that the lognormality of state size distributions has been a consistent property of the territorial state system since its inception around 1500 AD.

Computational Results

In the theoretical discussion above, we argued that both the consistency of the lognormal form, and its shifting mean over time, demand a unified explanation capable of reproducing the most basic patterns observed in the data. We argued further that the interaction of a positive feedback dynamic of territorial conquest, with the physical constraints of distance and gravity, provided a plausible account of the basic forces driving the evolution of state sizes. To demonstrate the empirical validity of our theoretical account, we conduct computational experiments in which we "grow" the territorial state system in Europe from the ground up, while systematically varying underlying parameters of interest, $\boldsymbol{\beta}$ and $\boldsymbol{\delta}$.

Each run of the simulation is allowed to continue for 1,000 time steps, though convergence to a stable state generally occurs before 500 time steps. At the end of each run, the set of tiles dominated by each capital is recorded, and converted into an estimate of the number of square kilometers those tiles represent on the real-world map. This list of state sizes constitutes the main "prediction" of the model. By systematically varying the parameters, $\boldsymbol{\beta}$ and $\boldsymbol{\delta}$, it becomes possible to "predict" the distribution of state sizes that will arise under a variety of counterfactual circumstances. First, consider a simulated world in which $\boldsymbol{\delta} = 1$, meaning that projected power experiences no decay with greater distances. We find that such models, regardless of the values of the other parameters, consistently fail to produce lognormal state size distributions (Shapiro-Wilk test rejects the null hypothesis, with $p < 0.001$). Next, consider a simulated world in which $\boldsymbol{\beta} = 0$, meaning that terrain difficulty exercises no influence on the strength of the decay. Again we find that such models, regardless of the values of the other parameters, consistently fail to produce lognormal state size distributions. As summarized in Figure 5, our experiments reveal that lognormal size distributions only arise in the region of the parameter space where $\boldsymbol{\delta} < 1$ and $\boldsymbol{\beta} > 0$. That is, lognormal size distributions arise only when the positive feedback of conquest is constrained by the interaction of *both* distance and gravity. In the absence of either of these forces, simulated state sizes fail to match the fundamental patterns evidenced in the empirical data. We thus conclude that the ecological dynamics of coercive competition, combined with the physical constraints of distance and gravity, provide a compelling account of the remarkable consistency of the lognormal form in the observed distributions of state sizes.

This conclusion is reinforced if we examine separately the contemporary distribution of state sizes that arose in the Middle East and Africa. As opposed to many other areas of the world in which states faced strong competition for territorial holdings, in the Middle East and Africa state borders were determined almost exclusively by the mandates of European colonial powers, whether acting alone or through multinational bodies such as the League of Nations. The consequences of this non-competitive history are apparent if one examines the CCDF of state sizes in Africa and the Middle East alongside the CCDF of state sizes in the rest of the world, as shown in Figure 6. The African and Middle Eastern regions have none of the heavy-tailed characteristics of state sizes in other regions, and the Shapiro-Wilk test for this subsample leads to a strong rejection of the null hypothesis that the data were drawn from a lognormal distribution ($p < 0.001$). Evidently, in the absence of the dynamics of ecological competition for territory, Africa and the Middle East have never generated the kinds of territorial hegemons that have characterized the geopolitics of other world regions.

In addition to capturing the *qualitative* dynamics underlying the generation of lognormal state size distributions, our model also allows us to generate *quantitative* agreement with the distributions of state sizes observed in different historical periods. Here the empirical sample is limited to the European subcontinent so as to match the conditions of the simulation. As shown in Figures 7 and 8, our model achieves remarkably good fit with the empirical distributions from both the inception of the territorial state system (1500 AD), and the peak of Europe's process of territorial consolidation (1875 AD). Moreover, these fits are achieved by varying only a single parameter, $\boldsymbol{\beta}$, while holding all other factors constant. The simulated fit for 1500 AD (Figure 7) is generated using parameter values of $\boldsymbol{\delta} = 0.999$ and $\boldsymbol{\beta} = 7000$, while the simulated fit for 1875 AD (Figure 8) is generated using parameter values of $\boldsymbol{\delta} = 0.999$ and $\boldsymbol{\beta} = 2000$.

The central implication of these results is that the underlying process by which state sizes were generated in 1875 was far less constrained by the difficulties of rugged terrain than it was in 1500. We thus conclude that technological shifts, which allowed states to more efficiently overcome the costs of projecting power over rugged terrain, represent a plausible explanation for the observed increase in the average size of states over the past five centuries. Moreover, the remarkable persistence of the lognormal distributional form of state sizes, even in the contemporary period, combined with the inability of counterfactually "frictionless" worlds to generate such distributional signatures, provides strong evidence that the physical constraints of distance and gravity continue to exercise powerful influence over the constitution of the interstate system.

Conclusion

The analysis presented above has sought to demonstrate the utility of an empirically grounded approach to computational social science. By grounding the inputs to our simulation with empirical data, and systematically comparing the model's outputs to real-world patterns in the size distributions of states, we hope to have shown that the verisimilitude of computational simulations need not come at the expense of inferential rigor. Indeed, it is the flexibility of the computational approach we have pursued here which made possible the specification of a model which could be both parsimonious, yet still tied to realistic mechanisms of resource extraction, power projection, and conquest. In contrast to the static model of voluntaristic optimization offered by Alesina and Spolaore (2003), this ecological model of coercive competition captures the inherently conflictual nature of the dynamic process through which territorial states were initially constituted, and through which they achieved dominance on the world stage.

Moreover, the results derived from the model shed new light on the fundamental mechanisms through which state power is achieved, demonstrating the degree to which the physical forces generated by natural terrain have conditioned the possibilities for state-making in the modern world. The basic impedances of distance and gravity, which underlay emergence of the territorial state form in early modern Europe, remain powerful to this day in their ability to constrain the reach and capacity of contemporary states. As academics and policymakers alike consider the prospects of building new state structures in difficult geographic contexts from Afghanistan to Yemen, we would therefore do well to remember the lessons of history and the inherent limits to our powers of creation.

References

Adler, Emanuel. 1997. Seizing the Middle Ground: Constructivism in World Politics. *European Journal of International Relations* 3 (3): 319-363.

Alesina, Alberto and Enrico Spolaore. 2003. *The Size of Nations*. Cambridge: MIT Press.

Bean, Richard. 1973. War and the Birth of the Nation State. *Journal of Economic History* 33: 203 - 221.

Boulding, Kenneth. 1962. *Conflict and Defense*. New York: Harper and Row.

Cederman, Lars-Erik. 1997. *Emergent Actors in World Politics: How States and Nations Develop and Dissolve.* Princeton: Princeton University Press.

Cederman, Lars-Erik. 2003. Generating State-Size Distributions: A Geopolitical Model. Paper prepared for presentation at the Agent 2003 conference on "Challenges in Social Simulation", University of Chicago, October 2-4, 2003.

Cederman, Lars-Erik and Luc Girardin. 2010. Growing Sovereignty: Modeling the Shift from Indirect to Direct Rule. *International Studies Quarterly* 54: 27–48.

Checkel, Jeffrey. 1998. The Constructivist Turn in International Relations Theory. *World Politics* 50: 324 - 348.

Clauset, Aaron , Cosma Rohilla Shalizi and M. E. J. Newman. 2009. Power-law Distributions in Empirical Data. *SIAM Review* 51 (4): 661-703.

Clauset, Aaron and Fredrik W. Wiegel. 2010. A Generalized Aggregation-Disintegration Model for the Frequency of Severe Terrorist Attacks. *Journal of Conflict Resolution* 54 (1): 179-197.

Clauset, Aaron, Maxwell Young and Kristian S. Gledistch. 2007. On the Frequency of Severe Terrorist Attacks. *Journal of Conflict Resolution* 51 (1): 58 - 88.

de Marchi, Scott. 2005. *Computational and Mathematical Modeling in the Social Sciences*. Cambridge: Cambridge University Press.

Downing, Brian M. 1992. *The Military Revolution and Political Change: Origins of Democracy and Autocracy in Early Modern Europe*. Princeton: Princeton University Press.

Gaubatz, Kurt Taylor. 2009. City-State Redux: Rethinking Optimal State Size in an Age of Globalization. *New Global Studies* 3 (1): 1 - 22.

Gilpin, Robert. 1981. *War and Change in International Politics*. Cambridge: Cambridge University Press.

Hechter, Michael. 2000. *Containing Nationalism*. New York: Oxford University Press.

Herbst, Jeffrey. 2000. *States and Power in Africa: Comparative Lessons in Authority and Control*. Princeton: Princeton University Press.

Lake, David A. and Angela O'Mahony. 2004. The Incredible Shrinking State: Explaining Change in the Territorial Size of Countries. *Journal of Conflict Resolution* 48: 699-722.

Limpert, E., W. Stahel and M. Abbt. 2001. Log-normal Distributions across the Sciences: Keys and Clues. *BioScience* 51 (5): 341–352.

Mann, Michael. 1986. *The Sources of Social Power Volume I*. Cambridge: Cambridge University Press.

Ruggie, John Gerard. 1998. What Makes the World Hang Together? Neo-Utilitarianism and the Social Constructivist Challenge. *International Organization* 52 (4): 855-885.

Scott, James C. 2009. *The Art of Not Being Governed*. New Haven: Yale University Press.

Searle, John R. 1995. *The Construction of Social Reality*. New York: The Free Press.

Shapiro, S. S. and M. B. Wilk. 1965. An Analysis of Variance Test for Normality (Complete Samples). *Biometrika* 52 (3-4): 591–611

Smith, L.R. 1987. Estimating Tails of Probability Distributions. *The Annals of Statistics* 15 (3): 1174–1207.

Sornette, Didier. 2006. *Critical Phenomena in Natural Sciences*. 2nd ed., 2nd print. Berlin: Springer.

Spruyt, Hendrik. 1994. *The Sovereign State and Its Competitors*. Princeton: Princeton University Press.

Strayer, Joseph R. 1970. *On the Medieval Origins of the Modern State.* Princeton: Princeton University Press.

Tilly, Charles. 1975. *The Formation of National States in Western Europe*. Princeton: Princeton University Press.

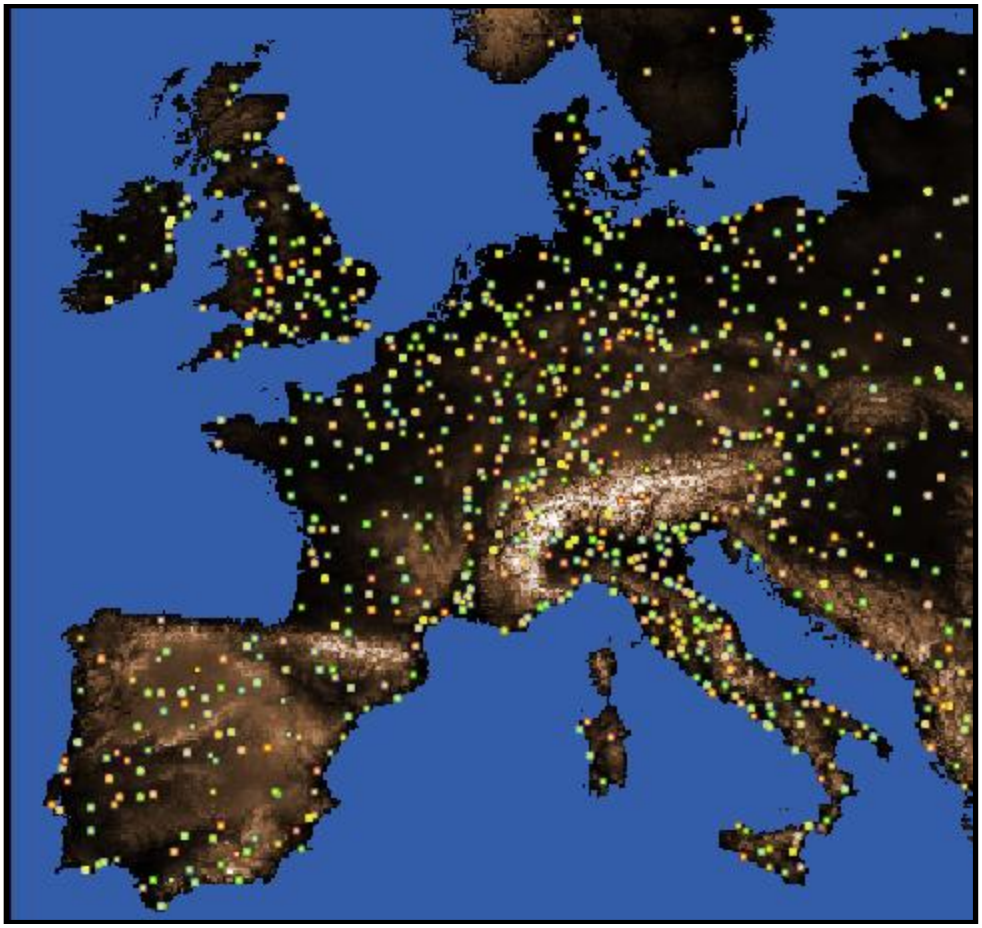
Tilly, Charles. 1992. *Coercion, Capital and European States: AD 990 – 1992*. 2nd ed. Cambridge: Blackwell.

Waltz, Kenneth N. 1979. *Theory of International Politics*. New York: McGraw-Hill.

Weber, Max. 1949. Objective Possibility and Adequate Causation in Historical Explanation. *The Methodology of the Social Sciences*, edited by E. A. Shils and H. A. Finch. New York: The Free Press.

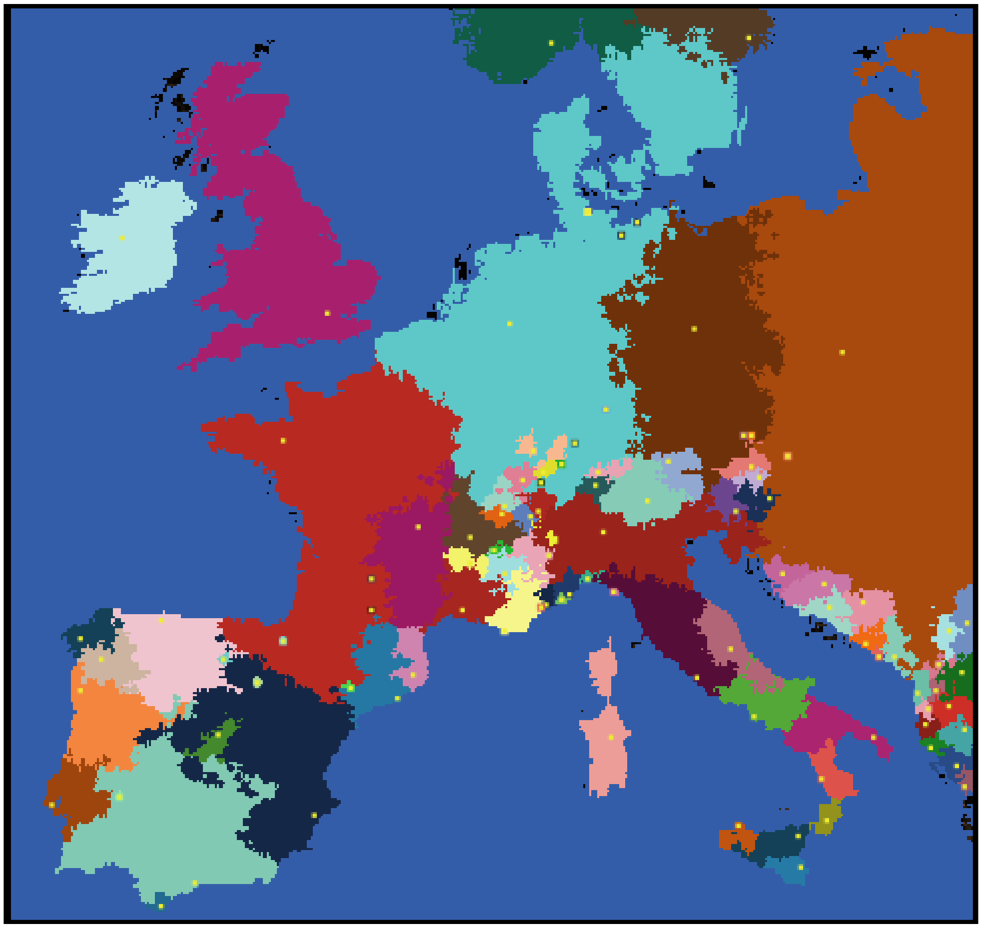
Wendt, Alexander. 1999. *Social Theory of International Politics*. Cambridge: Cambridge University Press.

Figure 1 - Representative Simulation Run : Time Step 1



Note: Elevation values are painted using a scale that ranges from dark brown at the lowest altitudes to white at the highest altitudes. Each colored pixel represents the location of a city in 1500 AD, which are used to empirically seed the potential starting locations for state-making projects.

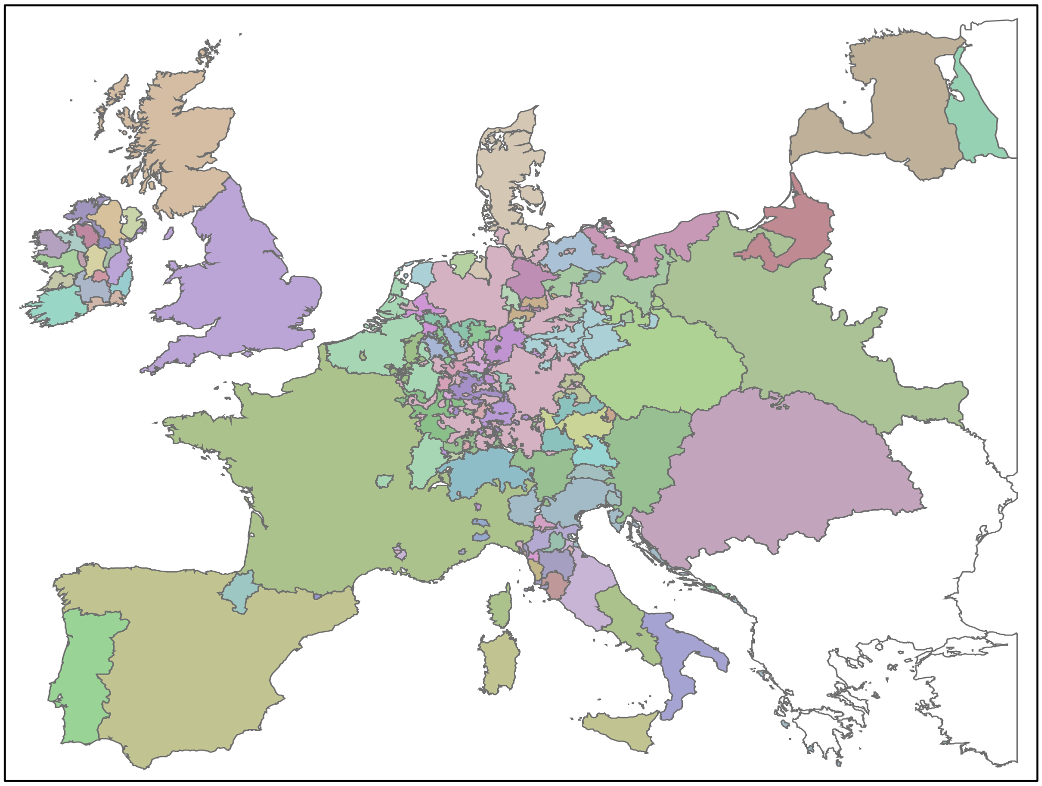
Figure 2 - Representative Simulation Run: Time Step 1,000



Note: State of single representative simulation run after 1,000 time steps. Colored patches represent the territorial holdings of surviving power centers, which are marked as yellow dots.

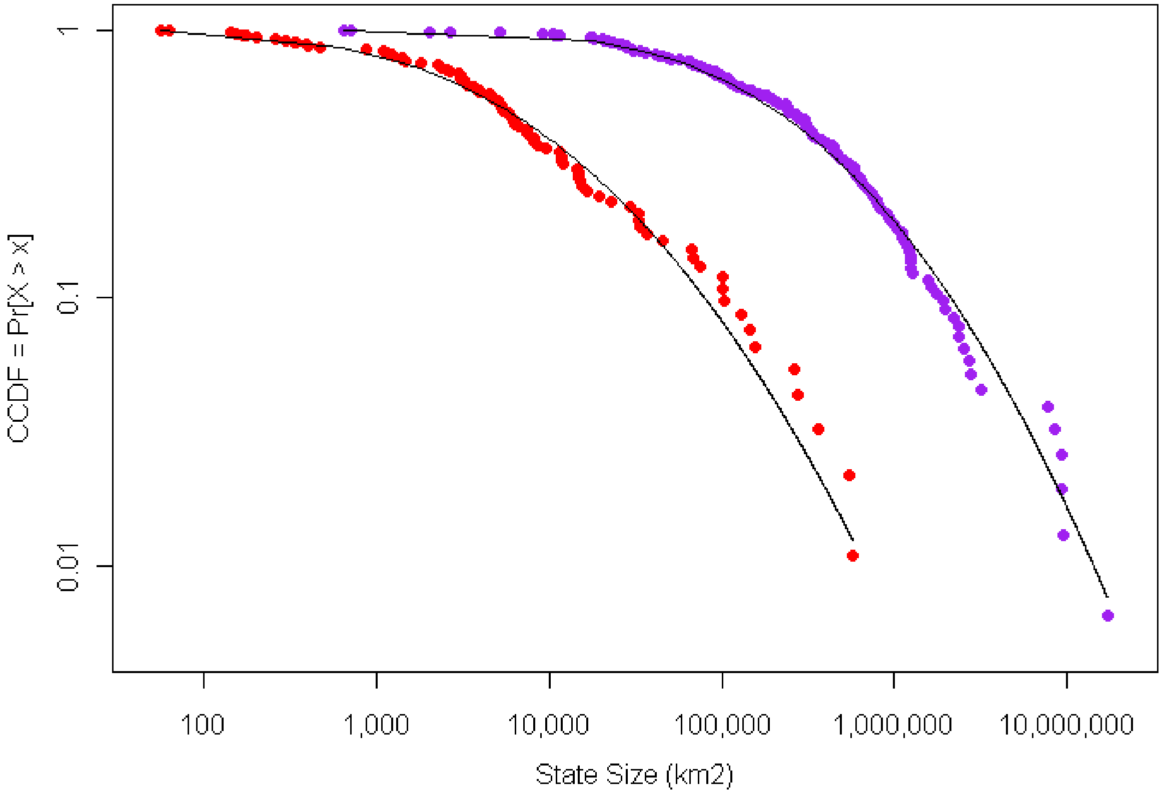
Parameter values: δ = 0.999, β = 7000.

Figure 3 - The Territorial State System: 1500 AD



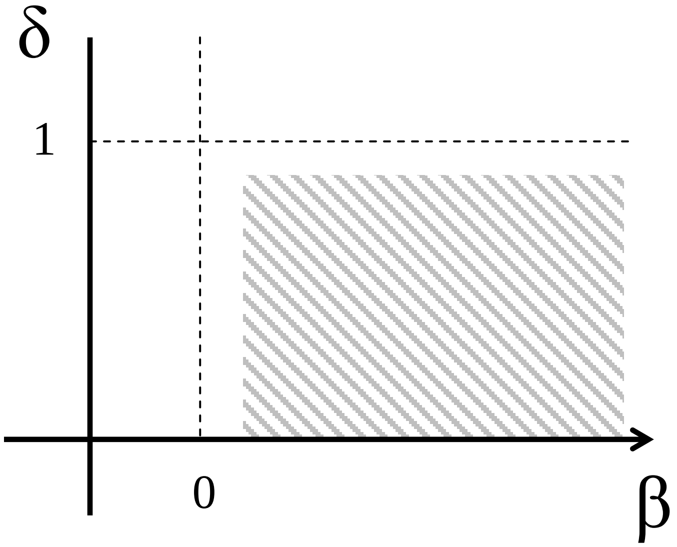
Note: Derived from EurAtlas GIS Vector dataset.

Figure 4 - Global State Size Distributions: 1500 AD vs. 1998 AD



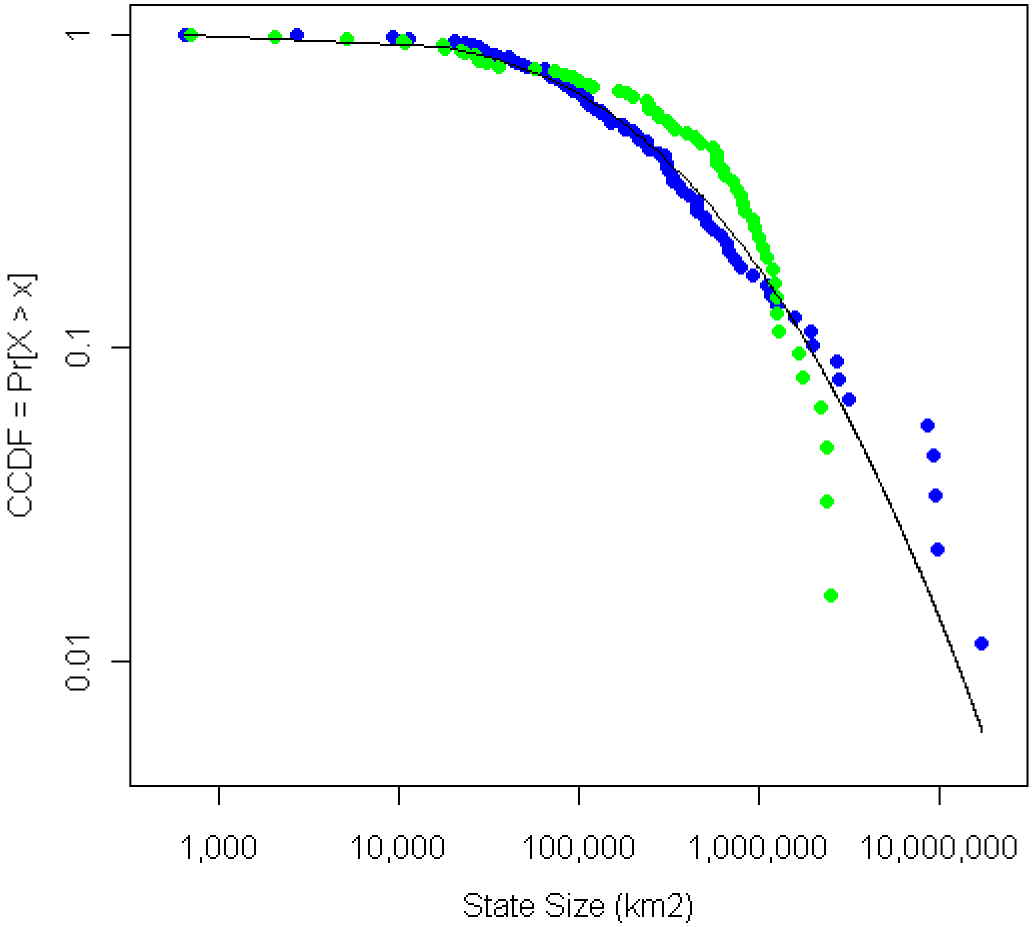
Note: Red dots = 1500 AD. Purple dots = 1998 AD. Black lines represent lognormal MLE fits.

Figure 5 - Distance (δ) vs. Gravity (β)



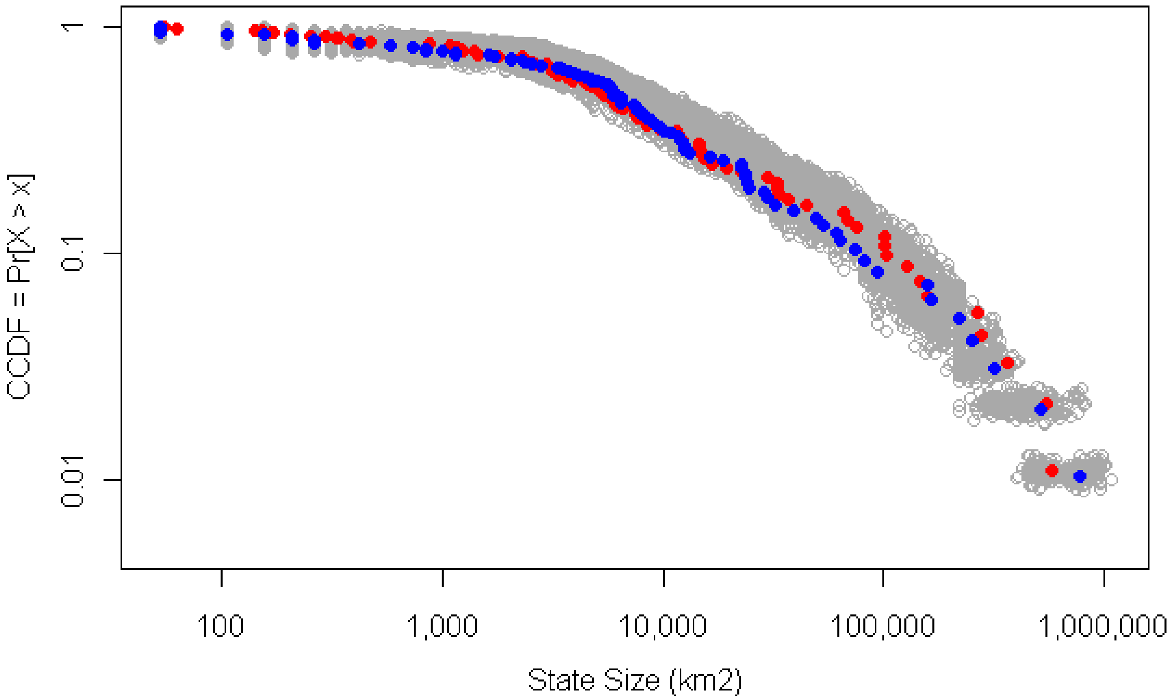
Note: Shaded region represents the region of the (δ, β) parameter space capable of producing lognormal state size distributions.

Figure 6 - State Size Distributions: Colonial Mandates



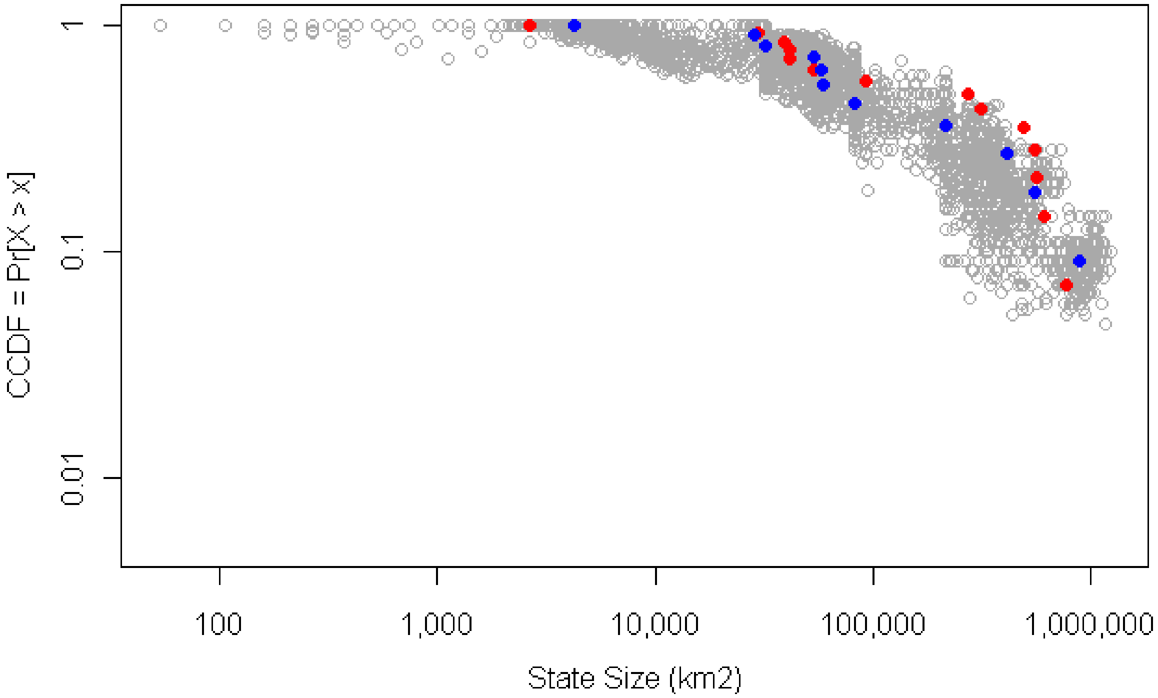
Note: Green dots show Middle East and Africa in 1998. Blue dots show all others in 1998. Black line shows lognormal MLE fit for the "all others" category.

Figure 7 - European State Size Distributions: Simulated vs. Real (1500 AD)



Note: Red dots represent empirical values for European state sizes in 1500 AD. Blue dots represent simulated values for European state sizes, in the best fitting simulation run, generated with parameter values $\delta = 0.999$ and $\beta = 7000$. Hollow gray circles show 95% confidence intervals, generated by plotting the spread of the 95% of runs with the best fit statistics at these parameter values.

Figure 8 - European State Size Distributions: Simulated vs. Real (1875 AD)



Note: Red dots represent empirical values for European state sizes in 1875 AD. Blue dots represent simulated values for European state sizes, in the best fitting simulation run, generated with parameter values δ = 0.999 and β = 2000. Hollow gray circles show 95% confidence intervals, generated by plotting the spread of the 95% of runs with the best fit statistics at these parameter values.