THE ECOLOGICAL ORIGINS OF ECONOMIC AND POLITICAL SYSTEMS

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Appendices A through R referenced in this working paper will be made available upon publication

We offer a theory that explains variance in global economic development, accounts for its geographic clustering, and shows why these patterns only emerged after 1800. Its mechanics focus on the challenge of survival that faced all societies prior to the 19th century: insuring against starvation. Local factor endowments conditioned how societies could respond to that challenge, thereby shaping pre-1800 forms of social organization. These, in turn, conditioned how rapidly societies could respond to the next challenge of survival they all faced, absorbing a broad suite of mutually dependent, post-1800 technologies that were crucial to geopolitical competition. We develop novel geo-spatial datasets to put the predictions of the theory to the test. We find that a vector of exogenous factors that were binding constraints on food production, transport, and storage within the densely populated nuclei from which nation states later emerged account for 63 percent of the cross-country variance in per capita GDP today. Importantly, this vector accounts for progressively less of the variance in economic development (as measured by urbanization ratios) going back in time; before 1800 they account for almost none of it. We also find that a specific combination of factors that permitted some societies to insure against starvation through local trade is associated with faster economic growth from 1800 to 2000, faster development of markets from 1500 to 1800, higher investment in trade-related human capital circa 1800, faster absorption of 19th century technologies, and a lower probability of being colonized.

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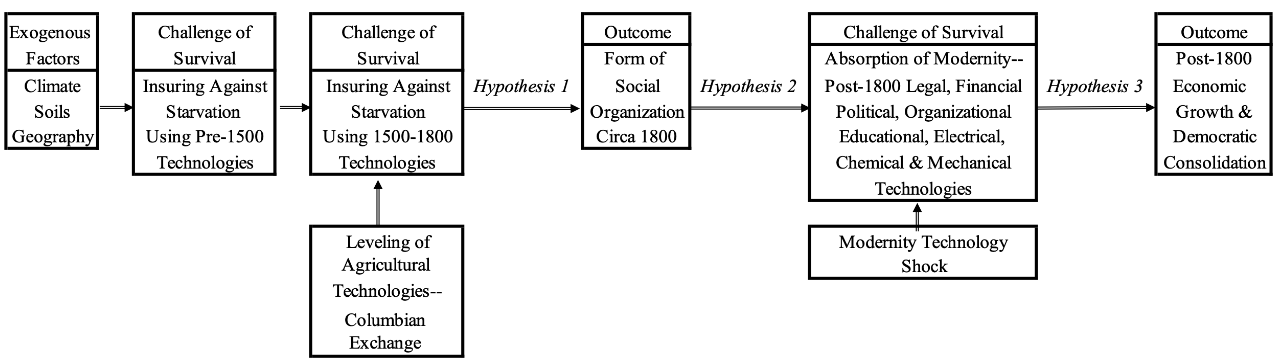
1. Introduction

A vast literature investigates the uneven distribution of economic development across the planet. One influential line of scholarship focuses on the direct effects of the environment (Diamond,1997; Bloom and Sachs,1998; Gallup, Mellinger, and Sachs, 2001; Sachs, 2001; Masters and McMillan, 2001; Hibbs and Olsson, 2004; Olsson and Hibbs, 2005; Putterman 2008; Zuleta, 2012; Nunn and Puga, 2012; Henderson et. al., 2018). Because climate and geography are taken as constants the dimension of time tends not to enter this approach. It therefore does not offer an explanation for why societies wealthy in the past are poor today, and vice versa. Another line of scholarship focuses on the effects of institutions that incentivize private investment (North and Thomas, 1973; North, 1990; Hall and Jones, 1999; Rodrik, Subramanian, and Trebbi, 2004; Ferguson, 2011). Recent empirical advances in this literature have been made by focusing on the impact of choices made by Europeans for their colonies (Engerman and Sokoloff, 1997, 2011; Acemoglu, Johnson, and Robinson 2001, 2002; Easterly and Levine 2003, 2016). The dimension of time enters this approach, but it tends to do so in a static way; it takes as the starting point of history the arrival of Europeans. The institutional choices they made centuries ago are then claimed to cause levels of economic development today. A third line of scholarship focuses on human capital, independent of institutions (Glaeser et. al., 2004; Gennaoili, et. al., 2013). The dimension of time enters this approach, past investments in human capital affect present-day levels of development. It does not, however, offer a theory that explains variance in human capital investments.

Missing is a unified theory that takes into account climate and geography, and that links them to the process by which societies around the globe, including those that were colonies and those that were not, diverged over time in terms of their investments in human capital, the emergence of institutions that facilitated contracting, and their ability to absorb new technologies that propelled growth. We offer such a theory, as well as a battery of empirical tests of it.

Our theory, which we depict in Figure 1, draws on an approach that is commonly employed in the physical sciences, as well as some fields of empirical macroeconomics, in that it focuses on identifying a vector of exogenous factors that increased the probability that a particular constellation of features would emerge from a complex system. In this approach, the features of a system—its endogenous, observable outcomes—are understood as simultaneously determined emergent properties.[1] It is not therefore meaningful to identify the marginal effect of the features on one another. An example from evolutionary biology illustrates the intuition. For most biologists, it is not meaningful to ask how much of rabbit speed is caused by the fact that coyotes hunt them, and how much is caused by living on a grassland. As Gordon (2014) points out, the task is to identify the vector of exogenous factors that increased the probability of a specific process of co-evolution— an equilibrium path of development—whose emergent properties include fast rabbits, clever coyotes, and tall grass, such that one place has lots of them, while another place has none. It is also meaningful to ask how the two systems would differentially respond to a gross external shock, such as an increase in mean global temperature.

Figure 1: Ecological Origins of Economic and Political Systems



The mechanics of our theory are focused on *the* fundamental problem of survival that faced all human societies prior to the 19th century, when railroads, steamships, and refrigeration made it economically feasible to ship calorie- and nutrient-dense staple foods long distances, insuring against starvation. The vector of exogenous factors was the local climates, soils, and disease environments that conditioned how societies could address that challenge. The adaptations were the human behaviors that

[1] An emergent property is an endogenous outcome of a system that has properties not found in that system's component parts. This occurs because of interactions among the exogenous variables and feedbacks among the endogenous variables.

emerged to meet that challenge under the constraints imposed by those local factor endowments. The systems were the resulting pre-1800 forms of social organization—societies' legal systems, stocks of human capital, lifeways, moral systems, social structures, and distributions of power. The gross external shock was modernity; a broad suite of mutually dependent technologies that emerged through a multi-country recursive process in the 19th and 20th centuries, and that set off a worldwide competition for geopolitical dominance. The emergent properties of the different equilibrium paths of development include levels of economic development, democracy, human capital, and other indicia of prosperity at any point after 1800.

Our claim is that factor endowments conditioned how societies could respond to the challenge of insuring against starvation before 1800, giving rise to different forms of social organization. Those forms of social organization, in turn, conditioned how quickly societies could respond to the next great challenge of survival they all faced; absorbing the technologies of the modern (post-1800) world to avoid being conquered, colonized, or dominated by another society that had moved more quickly.

Our point of departure is a basic historical fact. Until the transportation and refrigeration technologies of the mid-19th century made it economically feasible to move staple foods long distances, societies had to produce sufficient food calories, and make them available year-round, under constraints imposed by local factor endowments. Plainly put, how people could insure against starvation in a desert was very different from how they could do so in a rainforest. Even in England and the Netherlands, which historians point to as importers of grain from the Baltic, imports never accounted for more than 10 percent of consumption before 1800 (Allen 2000:14). Hoskins (1964: 29) lays bare the ramification: "In [England]…in which one-third of the population lived below the poverty line and another third barely on or barely above it; in which the working class spent fully 80 to 90 percent of their incomes upon food and drink; in such a country the harvest was the fundamental fact of economic life."

Importantly, for a period that extended from the Columbian exchange (the movement around the world of plants, animals, tools, people, and diseases that was set in motion by the arrival of Columbus in the Americas in 1492 and the establishment of a sea route from Europe to India in 1498) to the early 19th century, societies addressed the challenge of insuring against starvation with a common stock of knowledge about the technologies to produce, store, and transport calorie- and nutrient-dense foods (Crosby 1986; Nunn and Qian 2010). Prior to the Columbian Exchange there were no potatoes in Ireland, no tomatoes in Italy, no cassava in Africa, and no maize in China. The Americas not only lacked wheat, oats, rice, and barley, they also had no horses or oxen pull ploughs, wagons, or barges. After the Columbian Exchange, knowledge of these (and numerous other) food-related technologies disseminated rapidly. What varied across societies—for a period of roughly three centuries—were the climatologic and geographic factors that determined what could be grown, how much of it could be grown, how far it could be moved, how long it could be stored, and how much of it had to be stored.

Our first hypothesis is that agents met the fundamental challenge of insuring against starvation by adapting in an incremental, uncoordinated, and protracted manner.[2] Some of the adaptations that they hit upon were social, such as ways of behaving and planning, and expecting others to behave and plan. Some of those adaptations became institutionalized as systems of property rights, taxation, and governance. Because complex combinations of factor endowments varied, social and institutional adaptations varied. This process did not require anyone to make conscious choices: as Alchian (1950) famously pointed out, behaviors that favor survival can be understood as the environment adopting agents with specific behaviors, rather than as agents adapting to the environment.

What emerged from this process of adaptation were different ways of organizing societies. We posit a taxonomy of four basic forms of pre-modern social organization: Transactional, Risk-Pooling,

[2] Adaptation means the good fit of organisms to their environment, but its meanings and underlying mechanisms vary across academic specializations. There is what physiologists call adaptation: the non-heritable "phenotypic plasticity that permits organisms to mould their form to prevailing circumstances" during their own lifetimes, such as the ability of human beings to adapt to high altitude. There is what evolutionary biologists call adaptation: the Darwinian mechanism of selection upon genetic variation. Finally, there is what social scientists call adaptation: the ability of societies to create standard ways of doing things that are conducive to group survival. This "cultural adaptation" is heritable through learning, but is non-Darwinian (Gould and Lewontin 1979: 592-93). We use the term in this last meaning.

Self-Sufficient, and Pastoral ecologies, in which an ecology is understood to mean the physical environment, the living organisms, and the social adaptations made by human beings to survive. Transactional ecologies emerged where a complex combination of factor endowments favored insuring against starvation through the trade of easy-to-store—and hence easy-to-trade—low moisture annual crops. Their core characteristic was decentralized decision-making coordinated through markets. Risk-Pooling ecologies emerged where it was easy to grow and store low moisture annual crops, but where spatially and temporally correlated droughts ruled out local trade as an insurance mechanism. Instead, a complex combination of factor endowments favored insuring against starvation through forced sharing. Their core characteristic was centralized decision-making. Self-Sufficient ecologies emerged where a complex combination of factor endowments favored insuring against starvation through the production and consumption of difficult-to-store—and hence difficult-to-trade—high moisture perennial crops. Their core characteristic was decentralized, but uncoordinated, decision-making by households. Pastoral ecologies emerged where a complex combination of factor endowments precluded crop production of any type, and instead favored insuring against starvation through the herding of large herbivores that could convert the cellulose in wild grass into meat and milk. Their core characteristic was decentralized, but uncoordinated, decision-making by mobile bands.[3]

These ecologies should not be thought of as hierarchically ordered; each was an effective solution to the problem of insuring against starvation under constraints imposed by nature. They should also not be understood as reified entities with sharp boundaries, but as continua; adjacent cases might be only marginally different from one another, but the extremes are quite distinct.

Our second hypothesis is that the form of social organization that emerged after the Columbian Exchange, but before it became feasible to transport staple foods long distances in the 19th century, conditioned how societies could respond to a new great challenge of survival—the technology shock of

[3] One might also posit a fisheries ecology. Data constraints do not permit us to operationalize it.

modernity. Modernity was a broad suite of mutually dependent technologies that began to emerge in the 18th century but reached fruition in the 19th and 20th centuries. The new technologies were legal, financial, educational, organizational, and political, as well as mechanical, chemical, and electrical.[4] Each individual technology was the product of a multi-country recursive process,[5] and each depended upon the others to achieve its full utility.[6]

From the point of view of any individual society, modernity was an exogenous shock: no one society generated it; no one society could stop it; and no one society could chose to ignore it. As Kotkin (2014: 4-5) puts it: "…the package of attributes that we call modernity was not the result of some inherent sociological process, a move out of tradition, but of a vicious geopolitical competition in which

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[4] Examples of these new technologies include mass suffrage (which emerged in the 17th Century United States out of the practice of colonists giving one another proxies to represent them at assembly meetings), judicial independence (which emerged out of England's 1701 Act of Settlement), patents of invention as tradeable property rights (which emerged out of British jurisprudence in the 1750s), separation of powers and federalism (discussed by Montesquieu in 1748 in *The Spirit of the Laws*), the mass conscript army (Russia, 1705), the factory system (Britain, 1760s), modern chemistry (France, 1790s), the application of steam power to manufacturing and transport (Britain and the United States, early 1800s), military planning by a permanent General Staff (Prussia, 1810s), the research university (Prussia, 1810s), general incorporation laws (United States, 1810s), interchangeable parts (United States, 1810s), the railroad (Britain, 1820s), electrical telegraphy (multiple countries, 1830s), electrical machinery (multiple countries, 1830s), oil refining (Poland 1850s), the secret ballot (Australia, 1850s), refrigeration (Australia, 1850s), Bessemer steel (Britain, 1850s), dynamite (Sweden, 1860s), and the internal combustion engine (multiple countries, 1800s to 1880s).

[5] Patents of invention as tradable property rights provides an example of this recursive process. The concept emerged out of British jurisprudence in the 1750s (Bottomley 2014). The United States Patent Act of 1793 improved on the British system by simplifying the process of securing a patent and lowering the cost by 95 percent. Britain, seeing the superiority of the U.S. system, adopted many of the features of U.S. law in 1852. The U.S. system also became the basis for the patent laws of Germany (1877) and Japan (1888). The German system, in turn, influenced the patent systems of Argentina, Austria, Brazil, Denmark, Finland, Holland, Norway, Poland, Russia and Sweden (Kahn 2008).

[6] No single agent could, for example, declare into existence the technology of interchangeable parts; there had to be other agents who had invested in the human capital to design and fabricate jigs and cutting tools. No agent could then unilaterally declare that those jigs and tools, the parts they manufactured, or the machines composed of them, were covered by a patent; tradeable intellectual property rights required a government to write a patent law, a bureaucracy to maintain a registry, and courts to adjudicate disputes. No agent could then declare that his interchangeable parts company could sell shares that enjoyed limited liability; the technology of general incorporation required a government to write a commercial code and a bureaucracy to register corporations. For that code to be effective in mobilizing capital, however, the government had to be constrained from amending corporate charters arbitrarily (Malmendier 2009), which implied the need for governance technologies that limited the discretion of public officials, such as an independent judiciary, separation of powers, and electoral suffrage. The same held for patent laws: they were effective when governments were constrained from arbitrarily amending patents (Kahn 2008).

a state had to match the other great powers in modern steel production, modern militaries, and a modern mass-based political system, or be crushed and potentially colonized." Nevertheless, as Gershenkron (1961), Parente and Prescott (1994), Comin and Hobijn (2010), and Comin and Mestieri (2018) show, societies absorbed the technologies of the modern era at dramatically different rates.

We argue that rates of absorption of the technologies of modernity varied because societies could not jettison their pre-existing forms of social organization overnight without cost. They inherited stocks of human capital, systems of law, forms of contract and property rights, moral codes, lifeways, and distributions of power that had coevolved over the course of centuries.

Societies therefore responded differentially to the shock of modernity. Transactional Ecologies were better suited than the others to absorb the new technologies as a broad suite because they could do so organically, from below; a dense network of markets that had already emerged endogenously could coordinate the activities of agents that had already been incentivized to invest in transaction-specific human capital, such as literacy, numeracy, and fluency with complex contracts. Risk-Pooling ecologies could not absorb the new technologies in this organic, bottom-up manner, but had to do so by engineering their absorption from the top down—in ones and twos, in fits and starts—because a centralizing authority, populated by agents that had been incentivized to invest in human capital related to administration and coercion, had already emerged endogenously to manage a system of enforced sharing. Self-Sufficient and Pastoral ecologies had neither a dense network of markets that could coordinate, nor a centralizing authority that could engineer, the absorption of the new technologies.

Our third hypothesis is a corollary of hypotheses one and two. Because local factor endowments (conditional on post-Columbian Exchange technologies) conditioned pre-19th century forms of social organization, and because those forms of social organization conditioned rates of technological absorption during the 19th and 20th centuries, the distributions of economic development, human capital, democratic consolidation, and other indicia of prosperity that we observe across countries today are jointly-determined outcomes of different equilibrium paths of development that were set in motion by those local factor endowments.

Our theory generates sharp predictions about the timing of divergence across countries in levels of economic development, democratic consolidation, technological absorption, investments in trade-related human capital, and the growth of markets. It also makes predictions about which countries were colonizers and which were colonized during the 19th and 20th centuries. Finally, it generates predictions about the geographic clustering of economic development around the planet.

We develop novel datasets to put these predictions to tests against evidence. We use geo-spatial tools to recreate as closely as we can the ecological characteristics that bounded the production, transport, and storage of calorie- and nutrient-dense foods circa 1800 in the densely populated nuclei from which nation states later emerged. We construct a dataset on urbanization ratios to measure levels of economic development, covering the densely populated nuclei and in the nation states that emerged from them. More in Appendix A, but briefly, we build a panel of 20,297 geo-coded cities and towns with at least 20,000 people in any of the years 1500, 1600, 1700, 1800, 1850, 1900, 1950, and 2000.

We analyze the data using both quantitative and historical approaches. We apply Naïve Bayes and Random Forest techniques. We complement these machine learning methods by examining the histories of four cases that are outliers in the distribution of factor endowments such that they should be canonical cases of each ecology type.

Our major discovery is that a vector of exogenous factors that were binding constraints on food production, post-harvest storage, and transport within the densely populated nuclei from which nation states later emerged account for roughly 60 percent of the cross-country variance in per capita GDP today. Importantly, we also find that this vector of exogenous factors accounts for progressively less of the variance in levels of economic development, as measured by urbanization ratios, as we go back in time from 2000 to 1950, 1900, 1850, and 1800, such that circa 1700, 1600, and 1500 they account for almost none of it. We obtain a materially similar result when we substitute the level of democratic consolidation as the dependent variable. The results indicate, in short, that climate and geography played an important role in economic development, but did not do so directly. Rather, they conditioned long run paths of development.

We also discover that societies that emerged from Transactional ecologies experienced faster rates of post-1800 economic growth; greater levels of post-1800 democratic consolidation; faster growth of markets from 1500 to 1800; greater levels of investment in forms of human capital associated with trade and contracting; and faster rates of absorption of a canonical modern technology. They were also the most likely to be colonizers during the New Imperialism. We find that societies that emerged from Risk-Pooling ecologies are associated with rates of post-1800 economic growth, democratization, and technological absorption slower than those that emerged from Transactional ecologies. They did, however, experience faster growth than societies that emerged from Self-Sufficient or Pastoral ecologies and were also less likely to be colonized.

A powerful test of a theory is whether it can account for the fact patterns that support theories advanced by other researchers. We therefore introduce the exogenous variables of interest from Engerman and Sokoloff (1997), Hall and Jones (1999), Acemoglu, Johnson, and Robinson (2001, 2002), and Easterly and Levine (2016) into our models. We find that our vector of factor endowments accounts for more of the variance in levels of economic development today than the variables of interest from other theories, and that the addition of those variables has only a minor impact on our results. This does not imply that those other theories are wrong. Rather, it suggests that factors that other scholars have hypothesized as causal either proxy for our vector of factor endowments or were endogenous outcomes of the paths of development posited by our framework.

The idea that economic outcomes have ecological origins, extends at least as far back as Ibn Khaldun (1377), who pointed to the differences between "desert civilizations" and "sedentary societies." The idea informs recent scholarship on relative levels of pre-modern state centralization and economic development, such as Wittfogel (1957), Carneiro (1970), Putterman and Weil (2010), Morris (2010), Ashraf and Galor (2011), Motamed, Florax, and Masters (2014), Alsan (2015), Scott (2017), Mayshar et. al, (2019), and Dal Bó, Hernández-Laos, and Mazzuca (2019). Spolaore and Wacziarg (2013) provides a review of the literature, as well as empirical tests whose core finding is consistent with an ecological approach: first-nature characteristics worked on economic development indirectly "through broader features of a population, rather than institutions only…"

To the best of our knowledge, the closest antecedent to this paper is Engerman and Sokoloff (1997), which advances the hypothesis that there were three different paths of long-run development in the Americas that were set in motion by variance in factor endowments related to soils, climates, mineral deposits, and Native American population densities at the time of colonization. While the evidence in Engerman and Sokoloff (1997) is restricted to the Americas, Easterly and Levine (2003) obtain results that are broadly consistent with their hypothesis by employing instrumental variable techniques on a cross-sectional dataset of 72 former colonies; tropics, germs, and crops affected economic development through institutions, rather than directly.

Our paper differs in two important respects: evidence and mechanisms. The evidence we present is geo-spatial, systematic, and covers both colonial and non-colonial societies over the past five centuries. The mechanics in Engerman and Sokoloff (1997) focuses on how variance in factor endowments gave rise to variance in levels of inequality during the colonial period, which then shaped choices regarding policies and institutions after independence. Our mechanics emphasizes how the biophysical properties of crops interacted with transport costs, temperature and humidity, malaria endemicity, trypanosomiasis endemicity, and the scale and frequency of weather shocks to generate different forms of social organization, which, in turn, conditioned the ability of societies to absorb the technologies of the modern era as a broad suite.

This paper continues as follows. Section 2 provides background about the factor endowments that constrained strategies to insure against starvation during 1500-1800. It also explains how we built geo-spatial datasets that approximate those factor endowments. Section 3 uses the geo-spatial data to explore how complex combinations of those factor endowments pushed societies toward different social and institutional ecologies. Section 4 tests the predictions of our framework by examining the histories of four outliers in the distribution of factor endowments: the regions surrounding New York City (present-day United States), Beijing (China), N'shenge (Democratic Republic of the Congo), and Ulaanbaatar (Mongolia). Section 5 provides a battery of statistical tests of the predictions of our framework. Section 6 presents robustness tests. Section 7 shows how our framework can accommodate alternative theories. Section 8 concludes.

2 Approximating Factor Endowments

2.1 Defining the Relevant Local Economy and Society: Largest City Hinterlands

As a first step we must specify the relevant local area from which a country's form of social organization emerged. The nation states that we observe today did not exist during 1500-1800. They emerged through a process in which a densely populated, economically powerful region absorbed its neighbors through conquest, colonization, diplomacy, and cultural assimilation. Germany provides an example. Until 1871 it was a congeries of more than 300 independent principalities, duchies, free republican cities, and kingdoms. Those entities were politically and culturally subordinated to the region around Berlin, the Margraviate of Brandenburg, over the course of the 17th, 18th, and 19th centuries. Germany is not sui generis. The nation state of China emerged through a process in which the North China Plain, the densely populated coastal plain that ends in Beijing, subordinated the regions and peoples to its south and west. The nation state of Mexico emerged through a process in which the Valley of Mexico, the fertile intermontane basin around Mexico City, subordinated the regions and peoples to its north, south, and west. The nation state of Angola emerged from the Kwanza River Valley, the coastal plain that extends inland from the port of Luanda, which provided a path for the Portuguese to colonize the interior highlands during the 18th century; at independence in 1975 that colony became the People's Republic of Angola. What all these densely populated nuclei had in common was a city that, circa 1800, was already the largest in the territory that later came to be a sovereign nation state.

We therefore operationalize the relevant local area from which a country's form of social organization emerged as the economic hinterland of the largest city in every modern-day country in 1800. We address the issues related to measuring largest-city hinterlands here briefly, and discuss them at length in Appendix B. We measure the size and shape of largest-city hinterlands as a function of the distance one metric ton could be moved with a given energy budget,[7] using three 18th century technologies; the boats used by Lewis and Clark to row and pole up the Missouri River for riverine, lake, and ocean transport;[8] a horse-drawn Conestoga Wagon for overland transport; and human porters for areas of Africa where tsetse fly-transmitted trypanosomiasis killed horses, mules, and oxen. The uneven spatial distribution of navigable water, flat terrain, and tsetse fly endemicity therefore drive variation in hinterland size. We set costs and budget constraints in terms of physical parameters (friction, energy, work) rather than economic costs (dollars per ton-mile).

We assume that all oceans, seas, and lakes were navigable using pre-steam technology. River navigability is, however, more complicated because societies have been altering rivers to improve navigability for almost as long as people have been traveling on them. Their ability to do so increased dramatically after the invention of dynamite in 1867 and modern earth moving equipment in the 1920s. One cannot, therefore, rely on present-day maps of navigable rivers, because improvements to them likely correlate with societies' levels of economic development. More in Appendix Q that provides coding decisions on every major river in the world, but we rely on country- and region-specific historical sources that describe navigation and attempted navigation with pre-steamship technology, setting a threshold as any stretch of river that could be traveled upstream and downstream at least six

[7] We estimate the energy budget based on Fogel (1964: 75-79) about the distance of typical wagon hauls for agricultural goods in the 19th Century United States.

[8] These boats were smaller that ocean-going vessels, thereby overestimating the energy costs of ocean transport and biasing against our hypotheses because countries in North America and Western Europe, which tend to be dominated by Transactional ecologies and high levels of economic development, have long coastlines relative to their size.

months per year using boats of a similar size to those used by Lewis and Clark to travel up the Missouri River in 1804. Briefly, we put back into modern maps all rapids and sandbars, and we remove all canals, except for China's Grand Canal, because it was constructed during the Sui dynasty (581-618 CE).

Figure 2 displays maps of four hinterlands—those of N'shenge, Ulaanbattar, Beijing, and New York—so that readers can see the considerable variance in hinterland sizes and shapes.

Figure 2: Four Examples of Hinterland Shapes and Sizes

Nshenge, Congo DR | Ulaanbaatar, Mongolia | Beijing, China | New York, USA

Side by side hinterland comparison drawn at 1cm:75km. Hinterland size is a function of terrain slope, the presence of navigable water, and the presence of endemic tsetse flies that made the use of draught animals impossible.

2.2 Crop Types, Calorie Production, and Risk-Return Tradeoffs

The distance a society could move calorie- and nutrient-dense foods was not relevant unless it could produce them. We therefore estimate what, and how much of it, could be grown.

There are hundreds of different food crops, but those that are sufficiently calorie and nutrient-dense to serve as a staple fall into five broad categories: cereal grains (simple dry fruits that do not open at maturity, such as rice or wheat); pulses (simple dry fruits that open along a seam at maturity, such as beans and lentils); starchy fruits (fleshy fruits with high starch contents, such as bananas and breadfruit); tubers (enlarged underground starch and nutrient storage organs used by some plants to survive periods of drought or cold, such as yams and potatoes); and corms (similar to tubers, but distinct in that they do not sprout buds that can be used to propagate the plant, such as taro and cocoyam). Importantly, the Columbian Exchange spread the different cultivars within these five groups, as well as knowledge about how to grow them, around the planet.

These five categories of food crops can be aggregated into two basic groups based on their biophysical properties: low moisture annuals (cereal grains and pulses); and high moisture perennials (starchy fruits, tubers, and corms). One major difference across the two groups is calorie yields per hectare, which are higher for low moisture annuals than for high moisture perennials. Another major difference is post-harvest storage lives; low moisture annuals can be stored far longer than high moisture perennials because of basic differences in reproductive mechanics.[9] A third major difference is that low moisture annuals have defined planting and harvest seasons, while high moisture perennials tend to be self-propagating, and either produce year-round, or can be left in the ground until they are needed.[10]

These biophysical properties implied a risk-return tradeoff. All things being equal, a farmer specializing in low moisture annuals could obtain more calories per hectare than one specializing in high moisture perennials, but the properties of low moisture annuals exposed him to greater risk. First there was weather risk: a crop with a defined growing season could be lost to an April frost, a rainless June, or an August hailstorm. Then there was health risk; the yield of a crop with a defined growing season could be reduced by an illness that precluded the farmer from working on the prescribed days for sowing and harvesting. Third, there was spoilage risk; an annual crop had to be stored until the next harvest, during which time mold and bacteria could render it inedible. Finally, there was expropriation risk: precisely

[9] In an annual plant all roots, stems and leaves die at the end of growing season, but a dormant seed (the dry fruit humans consume) falls to the ground and will not germinate until soil moisture and temperature are once again adequate—which may take years. Cereals and pulses can therefore be stored almost indefinitely if they are stored at a low moisture content and then kept at low relative humidity. Because of their higher moisture contents, lack of dormancy after harvest, and higher respiratory rates tubers, corms, and starchy fruits are much more subject to microbial attack. The post-harvest storage life of starchy fruits is measured in days. Cassava can be stored for only five to seven days; taro for two to six weeks; sweet potatoes a few weeks to four months, and yams 12 to 18 weeks. See Ravi, Aked, and Balagopalan 1996 for a review of a voluminous literature. Cassava could be processed into a storable commodity, by turning it into flour, but the labor costs to do so were prohibitive (Lancaster and Coursey 1984, chap. 5; Vansina 1990).

[10] This feature of corms and tubers is a property of their interannual survival mechanism; their underground starch and nutrient storage organ (the part humans eat) allows them to survive periods of drought or cold. Cassava, for example, can keep unspoiled in the ground for up to two years (Vansina 1978: 176).

because low moisture annuals could be stored, they could serve as a unit of account, a store of value, and a medium of exchange—and anything that has those characteristics could be easily appropriated.

All things were not, however, equal. Many high moisture perennials (e.g., yams, taro, bananas, breadfruit) could be grown in wet soils that would rot the root systems of low moisture annuals. Other high moisture perennials (e.g., potatoes) could be grown in soils too sandy or dry for low moisture annuals. More in Section 3, but differences in climates and soils therefore affected decisions about crop choices, which in turn conditioned forms of social organization.

More in Appendix C, but for each hinterland we calculate the maximum potential kilocalorie yield of 17 low moisture annual and five high moisture perennial crops using data from the Global Agro-Ecological Assessment for Agriculture (GAEZ 3.0), which is a joint project of the FAO and the International Institute for Applied Systems Analysis.[11] GAEZ 3.0 provides a collection of raster datasets covering the globe that estimate the potential yield per hectare of a variety of crops under a variety of conditions, based on crop characteristics, soil characteristics, and climate.[12] To approximate the potential yields of these crops using the technology of the 18th century,[13] we set the GAEZ 3.0 conditions to rain-fed, low inputs.[14] To approximate the highest potential yields available to farmers

[11] For low moisture annuals our analysis includes wheat, sorghum, rye, wetland rice, dryland rice, pearl millet, foxtail millet, oats, maize, barley, buckwheat, peas, green gram, chickpeas, cowpeas, soybeans, and groundnuts. For high moisture perennials, it includes bananas/plantains, sweet potatoes, white potatoes, cassava, and yams.

[12] GAEZ 3.0 has been superseded by GAEZ 4.0. We therefore make the .tiff files that we employ from GAEZ 3.0 available in our replication dataset.

[13] Our analysis assumes that cross-sectional differences in production capacity for the period on which GAEZ makes its estimates (1960-1990) have not changed appreciably since 1500-1800. Turchin et. al. (2019) estimates pre-modern yields for three major crops across eight world areas. It shows that average yields today are 3.5 times higher than in 1500, but that the cross-sectional variation in 1500 is highly correlated with the cross-sectional variation today (R^2=.7). Historical crop yields and current crop yields are both affected by climate, directly through precipitation and temperature, and indirectly through the effect of precipitation and temperature on soil quality. While there have been fluctuations over time (e.g., the Little Ice Age, Global Warming) dendrochronological evidence indicates a remarkably stable climate for at least the past two millennia (Le Roy Ladurie 1971: 35).

[14] Low inputs are operationalized in GAEZ 3.0 as traditional cultivars, labor intensive techniques, no application of nutrients or chemical fertilizers, no use of chemicals for pest and disease control, and minimum conservation measures. We make an exception to the specification of "rain-fed, low inputs" in the

across crop groups we calculate the maximum potential yield across the 17 low moisture annual crops and the five high moisture perennial crops separately. For each crop group we allow each raster cell to produce the crop with the highest yield, and then sum across all cells in each hinterland. We convert metric tons to calories for each of the crops based on U.S. Department of Agriculture (2016).

2.3 The Constraints Imposed by Storability

There was a big difference between the ability to grow low moisture annual crops and the ability to store them. Basically stated, increases in humidity, especially when accompanied by increases in temperature, dramatically lower the number of days before cereals and pulses become unfit for human consumption because of the growth of mold, bacteria, and the intrusion of insects. As a first step in storage, the moisture content of the crop must be lowered, which historically was done by air drying. As a second step, the crop must be stored in a cool, dry enclosure, which historically was done in a silo or crib. The number of days that a crop could be stored was therefore a two-step function: the moisture content of the crop at the time it was placed in storage, which was a function of temperature and relative humidity; and the interaction of moisture content and temperature during storage.

The algorithm we employ to estimate the number of days that high moisture annual crops could be stored are based on studies of maize storability (Wilcke and Wyatt 2002). The literature on other low moisture annual crops indicates that, while their storage lives are not identical to maize, the temperature and humidity conditions that affect their storability are similar (Wilcke et. al. 1999; W. Pushpamma and Vimala 1985; Howell, Smith, and Dilday 2003; Wrigley, Batey, and Miskelly 2017). We employ data from the National Oceanographic and Atmospheric Agency on temperature and relative humidity

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case of Egypt. Because the Aswan dam prevents the yearly flooding that irrigated cropland in Egypt, we impute the value for irrigated, low input production for Egyptian hinterlands. See Appendix C.

covering the period since 1850 at the monthly level to estimate the number of days that maize could be stored in each hinterland.[15] We provide a discussion of the construction of this variable in Appendix D.

2.4 The Direct and Indirect Effects of Malaria

As an immense medical and social science literature shows, malaria shaped the availability and allocation of labor in agriculture more than any other pathogen (Marsh and Snow 1999; Carter and Mendis 2002; Chima, Goodman, and Mills 2003; Bleakley 2010; Hong 2011; Cowman et. al. 2016; McCord and Anttila-Hughes 2017). The direct effects of malaria on labor availability operate through its symptoms: uncomplicated (non-severe) malaria induces weakness, fatigue, prostration, fever, vomiting, and headaches that can persist from a few days to several weeks —sometimes persisting for months or years—requiring the infected person to cease work and other family members to redirect their efforts to caring for the sick person.[16]

Malaria is not, however, a one-time event; it can be a life-long process of progressive debilitation. Two of the five species of the mosquito-borne plasmodium that cause malaria—P. vivax and P. ovale—have dormant liver stage parasites that can reactivate, giving rise to a recurrence of the illness months or years after the initial infection. In addition, acquiring immunity from malaria comes at high cost. Innate immunity from malaria, which emerged through genetic polymorphisms in regions where malaria was endemic for millennia, come at the cost of debilitating anemias among homozygotes (individuals who inherited the gene from both parents), including ovalocytosis, thalassemias, Glucose-6-

[15] Our analysis assumes that differences across hinterlands in temperature and humidity in 1500-1800 are correlated with their cross-sectional differences for the period since 1850. See fn 13. There are a few extremely arid hinterlands with very limited production of low moisture annual crops, but in which it would have been possible to store these crops almost indefinitely. We set an upper limit at 5,000 days to prevent those extreme outliers from skewing the rest of the distribution.

[16] The length of incapacitation per episode varies widely, with most estimates between one and five days. One study of Ethiopian farmers, that accounts for both days lost by the sick person and by caregivers, came to an estimate of 21 days per adult episode (Chima, Goodman, and Mills 2003). It is possible, however, for malaria infections from a single bite to be prolonged over many months to years because the parasites undergo clonal "antigenic variation," requiring the human host to mount a new specific immune response to each of these variants as they arise (Carter and Mendis 2002: 567).

Phosphate Dehydrogenase Deficiency, hemoglobin C, and hemoglobin S (the sickle cell trait). Because homozygosity comes at a cost of reproductive losses, malaria immunity is found in only a small proportion of the relevant populations (Carter and Mendis 2002: 570-74). For most people achieving immunity against malaria is a hard-fought, life-threatening battle requiring recurrent infections by each strain of each local plasmodium species—and that immunity fades within a year unless the subject continues to be regularly "reinoculated" through recurrent reinfections.[17] Making matters more difficult still, immunity can only be maintained in regions of high endemicity; in low endemicity regions short-run changes in temperature and humidity that temporarily favor mosquito reproduction can induce devastating epidemics (Marsh and Snow 1999; Cowman et. al 2016; McCord and Anttila-Hughes 2017).

There are also substantial indirect effects of malaria on the productivity of labor, which operate through anticipatory coping strategies. One such strategy is for farmers to conserve work effort because of uncertainty regarding their health status. Another is to make crop choices that allow for flexibility of work effort in the expectation of illness (Chima, Goodman, and Mills 2003; Dillon, Friedman, and Serneels, 2020). A third is to make crop choices that reduce the reproduction rate of the mosquitos that carry the malaria plasmodium. Vansina (1990), for example, reports that farmers in Central Africa chose to plant banana trees, instead of tubers, because they did not require the clearing of forest cover, thereby reducing the standing pools of water necessary for the egg, larva, and pupa life stages of mosquitos.[18] That strategy entailed a costly tradeoff, however; bananas have even lower calorie yields per hectare, and even shorter storage lives, than tubers.

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[17] Recurrent infections of two plasmodium species—P. falciparum and P. malariae—give rise to enlargement of the spleen, chronic anemia, the wasting of body tissues, and damage to the lungs, liver, kidneys, and brain. Recurrent infections from all plasmodium species can have devastating effects on young children, who tend not to acquire immunity until age five. The most common effect is chronic anemia, which can result in permanent cognitive and developmental deficits. Malaria infections also affect pregnant women disproportionately, causing low birth weights among newborns, resulting in long term developmental deficits (Carter and Mendis 2002; Cowman et. al. 2016).

[18] Mosquitos were not identified as the vector of malaria until 1898, but the relationship between standing pools of water and malaria had been understood since antiquity.

The total direct and indirect effects of malaria on productivity are not straightforward to calculate, but the available estimates indicate that they are sizable. Bleakley (2010) estimates the productivity loss from recurrent childhood malaria at 50 percent of adult income. Hong (2011), based on comparative real estate prices, estimates a productivity loss of 75 percent.

To estimate the productivity impact of malaria we rely on an index of malaria transmission developed by McCord and Anttila-Hughes (2017) that combines ecological factors—rainfall and temperature—with biological ones such as the human biting rate of the mosquito species that serves as the vector for malaria transmission. While current infection rates of endemic malaria may be endogenous to the level of economic development, the malaria transmission index approximates the distribution of endemic malaria based on climatic and geographic characteristics.

2.5 The Effects of Trypanosomiasis

We have already discussed the effect of tsetse fly-transmitted trypanosomiasis on hinterland sizes in Section 2.1, but its effects went beyond the ability to employ draft animals in transport. Animal trypanosomiasis also forced farmers to substitute human labor for animal power in other agricultural tasks: hoes or digging sticks had to be used instead of plows; baskets had to be used instead of wagons. Human trypanosomiasis, however, reduced the availability of labor. Because there was no medical cure prior to the invention of Suramin in 1916, the disease progressed from a first stage, characterized by intermittent fevers, to a second stage that affected the central nervous system, causing progressive debilitation characterized by changes in personality, alteration of the circadian rhythm, confusion, slurred speech, seizures, and difficulty in walking and talking—ultimately leading to death. To estimate the impact of trypanosomiasis beyond its effects on hinterland sizes, we use a predicted distribution of tsetse fly groups and species developed and put online in raster format by the FAO.[19]

2.6 Temporally and Spatially Correlated Droughts

[19] http://www.fao.org/geonetwork/srv/en/main.home?uuid=f8a4e330-88fd-11da-a88f-000d939bc5d8

The populations of pre-modern societies, as Le Roy Ladurie (1971: 2) put it, “were constantly at the mercy of climatic benediction or calamity.” The most acute, as well as easy to measure retrospectively, such calamities were droughts. Where droughts were not temporally correlated, farmers could mitigate their anticipated effects by planting a variety of crops with staggered sowing and harvesting seasons. Where droughts were not spatially correlated, farmers could mitigate their anticipated effects by developing trade relationships with farmers in neighboring communities. Where droughts were temporally and spatially correlated, however, neither of these strategies could work; everyone was wiped out simultaneously and protractedly.

We operationalize droughts using a widely employed climate science metric, the Palmer Drought Severity Index, abbreviated as PDSI (Palmer 1965). More in Appendix E, but we employ the self-calibrating version of PDSI (sc-PDSI), which is calculated dynamically such that negative and positive sc-PDSI values represent departures from the norm for a particular place at a particular time of year. We retrieve monthly gridded sc-PDSI data with coverage from 1850 to 2014 at a resolution of 2.5° by 2.5° from Dai, Trenberth, and Qian (2004).[20] We operationalize a spatially correlated drought as values at or below -4 for every raster cell in a largest city hinterland. We operationalize a temporally correlated drought as values at or below -4 for a continuous period of at least six months for any raster cell in a largest city hinterland. A spatially and temporally correlated drought—one in which all farmers would lose all crops over an entire season—is therefore an event in which sc-PDSI is measured at or below -4 for every raster cell in a hinterland for a continuous six-month period. We sum the number of months of such extreme drought events for each hinterland and divide by the total number of months for which we have sc-PDSI data for that hinterland. As we explore in Appendix E, we validate our use of this worldwide 1850-2012 monthly data for the period 1500-1800 using annual PDSI tree ring data from Cook et. al., (2015) for Europe, the Middle East, and North Africa.

[20] We exclude the data from 2011 through 2014 because the values for those months are non-varying, which implies the data series stopped updating at the end of 2010.

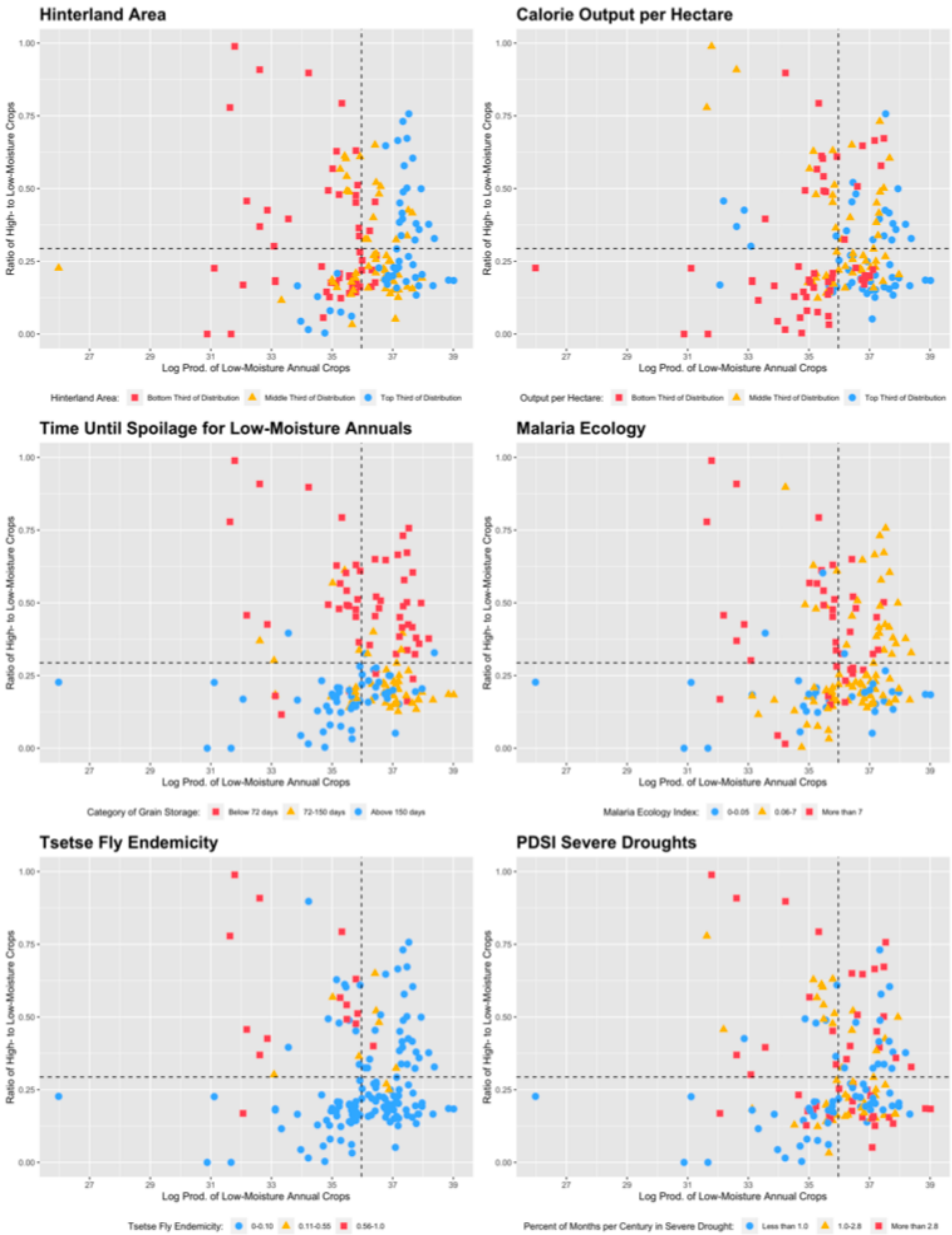
3. From Factor Endowments to Social and Institutional Ecologies

How did these factor endowments interact such that they gave rise to the different forms of social organization that we refer to as Self-Sufficient, Pastoral, Transactional, and Risk-Pooling ecologies? We employ machine learning techniques on continuous values of the factor endowment variables in Section 3.5 to show how complex combinations of them yield these four distinct clusters. To explain the intuition, however, we present a series of graphs of the data in Figure 3.

Figure 3 displays the risk-return tradeoff across the two basic crop groups: low moisture annuals and high moisture perennials. The unit of analysis is the hinterland of the largest city in 1800 for 163 present-day countries. Potential calorie production from low moisture annual crops for each hinterland, expressed as natural logs, is displayed on the X axis. The vertical dotted line represents the mean of this variable. The ratio of potential calorie production from high moisture perennials to potential calorie production from low moisture annuals is displayed on the Y axis. The horizontal dotted line represents the mean of this variable. Basically stated, as one moves from left to right, total potential output of low moisture annuals increases, and as one moves from bottom to top the ability to substitute toward high moisture perennials increases.

Each of the six panels of Figure 3 then displays the distribution of the other factor endowments—hinterland size, potential output of low moisture annual crops per hectare, storability of low moisture annual crops, malaria endemicity, tsetse fly endemicity, and the frequency of spatially and temporally correlated droughts—using colors and shapes. Each panel of Figure 3 therefore displays three factor endowments, two of which are always the potential output of low moisture annual crops and the output loss from substituting toward high moisture annuals, and a third factor that varies by panel. By following the color/shape coding of the other variables across the six panels, it is possible to visualize, albeit crudely, the interactions among the eight variables.

Figure 3: Factor Endowments and Ecology Types, Measured at the Largest City Hinterland in 1800



The upper left panel of Figure 3 displays the data on hinterland size by segmenting it into three groups: hinterlands in the top one-third of the size distribution are displayed as blue circles, those in the middle third as yellow triangles, and those in the bottom third as red squares. The figure shows a high degree of variance in the ability to produce each of the two basic staple food groups. To give a sense of the range, moving from the hinterland of Walvis Bay, Namibia, (located at roughly 26 on the X axis, and .20 on the Y axis) to Buenos Aires, Argentina (located at roughly 39 on the X axis, and .18 on the Y axis) produces a 400,000-fold increase in potential calorie output from low moisture annual crops. Moving from the hinterland of N'shenge, in the present-day Democratic Republic of the Congo (located at roughly 31 on the X axis and .99 on the Y axis) to Cairo, Egypt (located at 38 on the X axis and .001 on the Y axis) produces a 1,000-fold drop in the ability to substitute high moisture annual crops for low moisture annual crops.

The upper-right panel of Figure 3 repeats this exercise, but it uses colors and shapes to depict potential output of low moisture annual crops per hectare. Hinterlands in the top one-third of the distribution are displayed as blue circles, those in the middle third as yellow triangles, and those in the bottom third as red squares. It shows that both hinterland size (upper left panel) and land productivity (upper right panel) contributed to total potential agricultural output.

It was one thing to grow low moisture annual crops that were *potentially* storable, and quite another to store them successfully. We segment the data into three groups in the middle-left panel of Figure 3. We code as blue circles those hinterlands in the upper third of the distribution, as yellow triangles those hinterlands in the middle third of the distribution, and as red squares those hinterlands in the lower third of the distribution.

As we discuss in Section 2.4, endemic malaria reduced labor productivity. We segment the data into three groups in the middle-right panel of Figure 3, coding as blue circles those hinterlands where endemic malaria was absent (a score below 0.06), as yellow triangles those hinterlands below the median of the remainder (a score of 0.06 to 7.72), suggesting low endemicity, and as red squares those hinterlands above the median of the remainder (a score above 7.72), suggesting high endemicity.

As we discuss in Section 2.5, endemic trypanosomiasis forced farmers to substitute human labor for animal power, while simultaneously reducing the supply of human labor. We segment the data into three groups in the lower-left panel of Figure 3. We code as blue circles those hinterlands where tsetse flies did not prevent the use of horses or oxen (a score below .11), as yellow triangles those hinterlands below the median of the remainder (a score of .11 to .55), suggesting low endemicity, and as red squares those hinterlands above the median of the remainder (a score above.55), suggesting high endemicity.

The bottom-left panel of Figure 3 displays the data on the frequency of spatially and temporally correlated severe droughts. We code as blue circles hinterlands where such droughts never happened. We code as yellow triangles those hinterlands below the median of the remainder (above zero, but below 21 months per century), suggesting that spatially and temporally correlated droughts were rare events, and as red squares those hinterlands above the median of the remainder (21 months or more per century), suggesting that such droughts occurred at high frequency.

3.1 Self-Sufficient Ecologies

A reader who looks at the color coding across the six panels of Figure 3 will notice that several factor endowments tend to co-occur in the hinterlands located in the upper-left quadrant (above the horizonal dotted line, and to the left of the vertical dotted line). All those hinterlands were characterized by low potential output of low moisture annual crops. They were also able to substitute toward high moisture perennial crops, though doing so came with a loss in total potential calorie output because the substitution ratio was always less than 1.0. They also tended to be characterized by small size, climates that made it difficult to store whatever low moisture annual crops could be produced, high malaria endemicity, and high tsetse endemicity. Many of the same factors co-occur in the upper-right quadrant (above the horizonal dotted line, and to the right of the vertical dotted line), particularly the ability to substitute toward high moisture perennial crops, limited ability to store low moisture annual crops, and high malaria endemicity.

Nature pushed farmers away from producing low moisture annual crops toward high moisture perennial crops in those upper-left and upper-right hinterlands of Figure 3. Why would a farmer grow a low moisture annual crop whose yield was subject to the vagaries of the weather and her own malarial health status when that harvest was likely to be lost to molds, bacteria, and insects in a short period? Why not, instead, insure against starvation by growing perennial crops, such as tubers and corms that are drought-resistant and can be left in the ground until they are needed, or by growing starchy fruits that produce year-round? Those incentives would have been magnified in hinterlands with high tsetse fly endemicity; animal traction could not have been substituted for human labor during the fixed periods for plowing, planting, and harvesting low moisture annuals.

The rational decision to focus on high moisture perennial crops generated pressures and tensions that affected the form of social organization. Most directly, it limited population size and density. As Figure 3 shows, as one moves down along the Y axis, the ratio of potential calorie output from high moisture perennials to low moisture annuals declines; at the mean of that ratio (the dotted horizontal line), a farmer specializing in high moisture perennials incurred a potential calorie output loss of 70 percent. The incentive to focus on high moisture perennials also limited the extent of non-agricultural economic activities. Labor dedicated to manufacturing, mining, and commerce must be financed by surplus agricultural production, but high moisture perennials, once harvested, were a rapidly depreciating asset; they could not serve as a unit of account, a medium of exchange, or a store of value. Finally, a focus on high moisture perennials limited investments in institutions related to trade, such as bodies of commercial law or specialized courts to adjudicate contract disputes, as well as limited investments in forms of human capital useful for engaging in trade, such as numeracy and literacy. Why make those costly investments if there was little to trade? A rational agent in this environment was a self-sufficient producer.

The basic unit of social organization that emerged from this system of self-sufficient production was not a market, it was a village composed of autonomous households. Crafting a state out of such a society was not impossible, but low fiscal capacity limited the degree to which it could centralize power. It could not be financed through the appropriation of a stock of storable food calories that could serve as a unit of account, a medium of exchange, and a store of value. Rather, a state in a Self-Sufficient Ecology had to be financed by capturing a flow; a continuous stream of rapidly decaying food.

3.2 Pastoral Ecologies

A reader who now looks at the color coding across the lower-left quadrant (below the horizonal dotted line, and to the left of the vertical dotted line) in the six panels of Figure 3 will notice another set of factor endowments that tend to co-occur. Hinterlands in this quadrant were poorly suited to growing crops of any kind, and also tended to be characterized by the absence of malaria, the absence of tsetse flies, and by being well-suited to the storage of whatever low moisture annual crops might be grown. A few of the hinterlands in this quadrant—such as that of Bergen, Norway—shared these characteristics because they had cold climates. Most, however, dis so for quite another reason; aridity.

Where climates were too cold or arid to grow crops of any type, humans adapted by moving up the food chain. They domesticated large herbivores—sheep, goats, camels, horses, or cattle—that could convert wild grass into muscle tissue and milk. Moving up the food chain came, however, at a large cost in terms of potential calorie production per hectare. As a general rule of ecology, each step up a food chain entails an energy loss to metabolism of roughly 90 percent.

Survival through pastoralism therefore generated pressures and tensions that affected the form of social organization. Most directly it implied mobility; people insured against starvation by moving their animals to greener pastures. It also implied low population density; most of the calories produced were consumed by animal metabolism. Finally, it implied a low level of political centralization. As Barfield (1989: 45) points out, animals as stores of wealth could not be concentrated: they had to be dispersed to take advantage of grass and water. Unless the animals could be converted into some more stable product, a ruler could not successfully engage in taxation.

The basic unit of social organization that emerged in a Pastoral Ecology was a mobile kinship-based camp, which was limited in size by the number of animals that could be grazed on a pasture. Camps aggregated into clans and tribes based on common lineage. Camps, clans, and tribes had strong incentives to compete with one another over access to pastures, as well as strong incentives to appropriate one another's animals. While conflicts among camps or clans could be adjudicated on the basis of customary law, conflicts among tribes had to be settled with violence—because a Pastoral Ecology did not generate the fiscal basis for a state that could arbitrate property rights (Barfield 1989).

A rational agent in a Pastoral Ecology was therefore incentivized to invest in human capital related to mobility and violence potential which, in the context of the period 1500 to 1800, meant the ability to shoot a bow and arrow from the saddle of a horse at the gallop. Until improvements in firearm and artillery technologies gradually undid the advantage of calvary-archery, Pastoral Ecologies posed serious military threats to the Transactional, Risk-Pooling, or Self-Sufficient ecologies at their borders, provided that a charismatic leader was able to forge a coalition of feuding tribes. When that occurred, a pastoralist empire, based on the appropriation of a stock of wealth generated by a Transactional or Risk-Pooling ecology, or based on the appropriation of human muscle power generated by a Self-Sufficient ecology, could emerge.

3.3 Transactional Ecologies

A reader who looks at the color coding across the lower-right quadrants (below the horizonal dotted line, and to the right of the vertical dotted line) in the six panels will notice another set of factors that tend to co-occur. Hinterlands in this quadrant were well-suited suited to growing low moisture annual crops and poorly suited to substituting toward high moisture perennial crops. They also tended to be large, had highly productive soils, were able to store low moisture annual crops for extended periods, and were free of malaria and tsetse flies.

What pressures and tensions were generated by nature in the hinterlands located in this lower-right quadrant? The answer depends on the factor that varies significantly in this quadrant: the frequency of spatially and temporally correlated droughts.

Let us focus first on those hinterlands in which spatially and temporally droughts never occurred. As Figure 3 shows, farmers in those hinterlands would have been able to produce, store, and move large quantities of low moisture annual crops. This does not mean, however, that they lived in an idyll. The seasonal nature of those crops exposed them to the risk of crop failure from idiosyncratic weather events. They could, however, insure against such idiosyncratic risks by planting a mix of annual crops with staggered sowing and harvesting periods, and then compensate for shortfalls by trading with farmers in neighboring communities.

Insurance through local trade generated a unique set of pressures and tensions. Storable food calories could serve as a unit of account, a store of value, and a medium of exchange. They could therefore finance non-agricultural activities, such as mining and manufacturing. Insurance through trade also incentivized investments in legal structures that facilitated trade—such as property registers, commercial codes, and courts—as well as incentivized investments in human capital related to trade, such as numeracy and literacy.[21] Agents with specialized human capital, in turn, had incentives to economize on transaction costs by collocating, giving rise to cities and towns.

A system of insurance through trade also created pressures and tensions in respect to the distribution of power. Anything that can serve as a unit of account, a store of value, and a medium of exchange is an attractive target for appropriation. An entity with police power that could arbitrate property and contract rights among agents internal to the society, and that could defend them against neighboring societies, was therefore necessary. The problem was that any entity with the power to carry

[21] In Western Europe, for example, literacy and numeracy were already widespread among merchants, professionals, tradesmen, and farmers during the early modern period. Farmers kept account books and followed price changes in other regions. These human capital investments appear to have been made through informal teaching in the household (Tollnek and Baten 2017).

out those tasks was also strong enough to appropriate the surplus it was supposed to protect. Insurance through trade therefore generated a tension between the need for a strong government and a government that was limited in its authority and discretion. In short, the political institutions that underpinned a market economy, such as parliaments and independent judiciaries, were endogenous outcomes of a particular complex combination of factor endowments.

3.4 Risk-Pooling Ecologies

How did the dynamics that gave rise to a Transactional Ecology change if spatially and temporally correlated droughts occurred at high frequency? When all crops failed simultaneously across an entire hinterland for an extended period there were no surpluses from staggered harvests to trade; farmers had to rely on hoards that they had amassed from previous years in anticipation of such catastrophes. A hoard, however, incentivized opportunistic and predatory behavior. Why should Farmer A limit his consumption today to save for tomorrow, when he could appropriate the hoard of Farmer B tomorrow? Why, then, should Farmer B save for tomorrow, when he knows that his hoard will be appropriated by Farmer A?

One solution to this coordination problem is risk pooling—the creation of a centralized hoard to which everyone contributes during good times and makes claims during bad times. Risk pooling systems generate, however, a classic public goods problem; participants have incentives to free ride. Thus, to be viable, a risk pooling system needs police power to compel the payment of premiums. It also needs the administrative capacity to accommodate claims rapidly during bad times; otherwise, agents will not have incentives to pay premiums during good times.

A Risk-Pooling Ecology therefore generated pressures and tensions that favored the emergence of entities with considerable coercive power and administrative authority. Unlike a Transactional Ecology, where it was in the interest of agents to decentralize power to constrain the authority and discretion of rulers, in a Risk-Pooling Ecology it was in the interest of agents to centralize power. It was also in the interest of agents to invest in specialized skills in demand by the system: tax collecting, record keeping, and punishing free riders.

A Risk-Pooling Ecology did not foreclose the emergence of markets, but it did create a counterweight to them. Arbitrage opportunities generated by local comparative advantages or idiosyncratic weather events continued to exist, and surpluses not allocated to the centralized hoard were available to finance non-agricultural activities. An authority with considerable power and discretion, that by design stood above any coalition of private agents, could, however, suffocate markets—and it would have been common knowledge that it could do so.

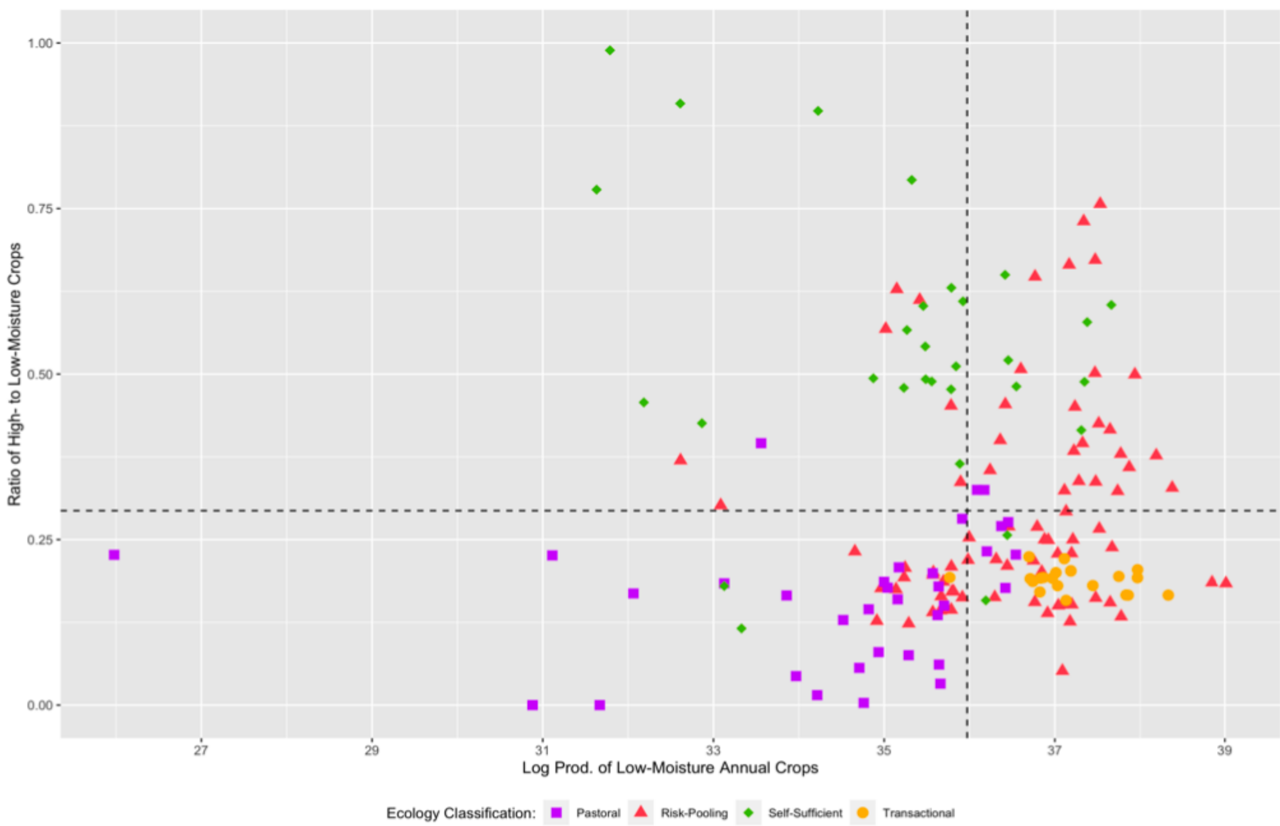
3.5 Naïve Bayes Classification

How do we know that this vector of exogenous factor endowments really generates four distinct ecologies? We employ a supervised Naïve Bayes classification algorithm, which takes as inputs each of the continuous exogenous variables discussed above and then determines groupings based on their joint distributions. More in Appendix F, but we hand code 15 hinterlands as canonical cases of the different ecology classes, and then let the algorithm estimate the probability distribution over the set of four ecology classes for all 163 hinterlands based on the values of their factor endowments. This ties our hands regarding the distributions of the variables and the functional forms of their interactions; the process of classification is carried out by a probabilistic algorithm. The algorithm yields four distinct bins: 135 of the 163 hinterlands are placed into a single bin at greater than 95 percent probability, 141 at greater than 90 percent, and 150 at greater than 75 percent; there are no hinterlands that are placed into more than two bins at a probability of greater than five percent.

Figure 4 displays the ecology classes, distributed over the same X and Y axes as Figure 3. We employ the probability distributions when we estimate Naïve Bayes regressions in Section 5, but for the purpose of visualizing the data we code each hinterland by the ecology class with the highest probability. It shows that the ecology classes are distributed along the lines we hypothesize: Self-

Sufficient ecologies cluster at the top of the figure; Pastoral ecologies cluster on the lower left; and Risk-Pooling and Transactional ecologies are interspersed on the lower right.

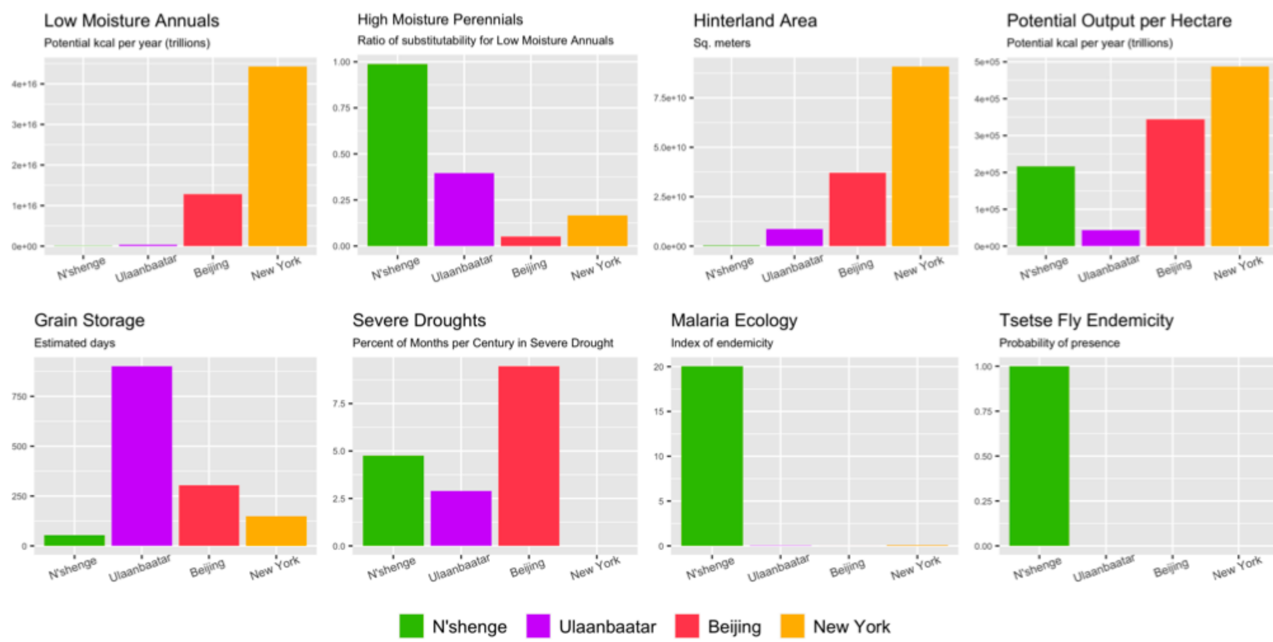
Figure 4: Naïve Bayes Classification of Hinterlands, by Ecology Type



4. Outlier Analysis

Ecologies are not reified entities with sharp boundaries but are continua; adjacent cases might be only marginally different from one another, but the extremes are quite distinct. It follows that one way to put the predictions of our theory to a test against evidence is to focus on hinterlands at the extremes of the factor endowment distributions. We therefore focus on the histories of four hinterlands—those of N'shenge, New York, Beijing, and Ulaanbaatar—that should be canonical cases of Self-Sufficient, Transactional, Risk Pooling, and Pastoral ecologies, respectively. Figure 5 presents a bar graph showing the values of their factor endowment variables. For readers who wish to locate them across the panels of Figures 3, the hinterland of N'shenge is at roughly 32 on the X axis and .99 on the Y axis, Ulaanbaatar is at roughly 34 and .4, New York is at roughly 38 and .17, and Beijing is at roughly 37 and .05.

Figure 5: Factor Endowments of the N'shenge, Ulaanbaatar, Beijing, and New York Hinterlands



4.1 The N'shenge Hinterland as a Self-Sufficient Ecology

The largest city in 1800 in the present-day Democratic Republic of the Congo was N'shenge, the capital of the Kuba Kingdom. Nestled between the Sankuru, Lulua, and Kasai rivers, at the point where the great equatorial forest of West Central Africa met the dry savanna of eastern Angola, N'shenge's location deep in the interior of continent placed it outside of the Atlantic slave trade (Vansina 1978, 236; 2010, 14-16). This location allowed N'shenge's farmers to grow low moisture annuals in the drier regions bordering the savanna, and high moisture perennials in the wetter regions bordering the rainforest. N'shenge was nestled *between* three rivers, but it was not actually situated *on* a riverbank, and because it was in a zone of high tsetse fly endemicity, farmers could not move staple foods to the riverbanks using horse or ox-drawn wagons. These factors generated, as Figure 5 shows, a very small hinterland. When coupled to the low productivity of its soils, N'shenge's very small hinterland meant that its potential calorie output from low moisture annuals was roughly six, 200, and 700 times lower than the hinterlands of Ulaanbaatar, Beijing, and New York, respectively—even before considering the effects of high levels of malaria and tsetse fly endemicity on the productivity of labor. N'shenge's hot, humid climate then made it difficult to store those crops; low moisture annuals stored in N'shenge deteriorated roughly three times faster than in New York, six times faster than in Beijing, and 17 times faster than in Ulaanbaatar. N'shenge's farmers could, however, substitute away from low moisture annuals to high moisture perennials with only a one percent loss in calorie production, compared to losses of 60 percent, 83 percent, and 95 percent in Ulaanbaatar, New York, and Beijing, respectively. In short, if there was a place where a Self-Sufficient Ecology should have emerged, N'shenge was it.

The factor endowments of the N'shenge hinterland implied that its farmers could not insure against its frequent droughts—roughly speaking, one every 20 years—by stockpiling food or by relying on trade. It should not, therefore, come as a surprise that the historical record provides abundant evidence about the existence of markets for luxury goods in the Kuba Kingdom, but there is silence as to the existence of markets for food (Vansina 1978: 187, 191). In fact, the Kuba king and the numerous titleholders residing in his court in N'shenge were fed by villages obligated to transport a continual supply of food to them, not by food purchased in a market (Vansina 1978: 140, 184).

N'shenge's food corvee emerged with the Columbian Exchange. Until the introduction of maize, sweet potatoes, and cassava from the New World, the region surrounding N'shenge could not support a large population. When those crops replaced millet, sorghum, yams, and plantains, the productivity of land and labor jumped dramatically (Vansina 1978: 176, 236). One result was an increase in population. Another was that ethno-linguistic groups were incentivized to conquer one another to enslave or enserf their populations, as well as appropriate their land (Vansina 1978: 191). One group, the Bushong, prevailed over the others in this competition. What had been a society of independent villages, became by 1620 the Kuba Kingdom, run by a Bushong king with its capital at N'shenge (Vansina 1978: 49).

High transport costs, low agricultural productivity, and difficulty in storing what could be grown translated into a low level of economic development. The basic social and economic unit of the Kuba kingdom was the village, with populations ranging from ten to 400 occupants. These moved every five years or so because the region's thin soils were easily exhausted (Vansina 1978: 169). The kingdom was therefore composed of clusters of settlements, with large uninhabited expanses between clusters (Vansina 2010: 49). Even though the kingdom stretched over an area two-thirds the size of Belgium, its population, including the conquered peoples from which the Bushong drew slaves, tribute labor, and food, totaled only 120,000 to 160,000, almost all of whom were engaged in subsistence agriculture (Vansina 1978:3). The only town of any size was N'shenge, which had a population of 5,000 to 10,000.

A taxation system based on the appropriation of labor in the context of a small population implied a small tax base, and hence a limited ability to centralize political authority. To the degree that the Kuba king had a source of revenue, it was the royal monopoly he maintained on ivory, whose high-value-to-bulk ratio allowed it to be traded at a distance (Vansina 2010: 30, 47). The low level of political centralization is belied by the structure of decision-making; the king ruled in consultation with a set of councils, staffed by more than 100 ranked titleholders, who were elected by the Bushong villages. Titleholding among the Bushong, in turn, was widespread. Kinship glued the political system together: each village was obliged to have at least one of its women married to the king. The king was, in short, the head of a confederacy of villages, not an absolute monarch (Vansina 2010: 46-47).

This economic and political system endured for more than 250 years, but it neither generated a market that could coordinate, nor a centralized political authority that could engineer, the rapid absorption of the technologies of the modern era as a broad suite. When a small Belgian force arrived in N'sheng in 1900 it quickly overran the town, forced the kingdom to submit to foreign rule, and ushered in the tragedy of King Leopold's Congo Free State.

4.2 The Hinterland of New York as a Transactional Ecology

As Figure 5 shows, the soils, climate, and disease environment of the New York hinterland were the opposites of the N'shenge hinterland. If there was a place where a Transactional Ecology should have emerged, it was the hinterland of New York.

The New York hinterland is interesting for two additional reasons. First, its agricultural system circa 1800 was the product of the Columbian Exchange. Prior to European contact there were no draft animals to pull barges, plow fields, or haul wagons, no boats powered by the wind, no iron tools to clear the region's hardwood forests and till the soil, and no wheat, oats, barley, or rye to sow. There was also no tuberculosis, cholera, influenza, measles, or smallpox. The Columbian Exchange therefore resulted in a dramatic increase in agricultural productivity and the decimation of the Native American population.[22]

Second, the initial political structures of the New York hinterland were not established with the goal of creating a democratic society. James, the Duke of York, brother of King Charles II, who would later become King James II, did not bankroll a British fleet to capture New Netherland from the Dutch for the benefit of free yeoman farmers. His goal was to re-create the English manorial system, which had long since disappeared from England. What had been New Netherland was granted to James as a proprietary colony, making him essentially a monarch in his own realm. A Lord Proprietor ran an outlying part of the kingdom with authority to establish courts, appoint judges, impose martial law, pardon crimes, call up the men of fighting age to wage war, grant land titles, levy duties, and collect tolls, so long as he agreed to maintain allegiance to the king (Galenson 1996). James, in turn, sold what is currently the state of New Jersey to two of his friends, Lord Berkeley and Sir George Carteret, who were already the Lords Proprietors of Carolina. What is now Eastern Pennsylvania and Delaware was granted by Charles II to William Penn as a proprietorship. The southern portion of the New York hinterland—the present-day state of Maryland—was already a proprietary colony run by Cecil Calvert, the 2nd Baron Baltimore, who had received a grant from Charles I in 1632.

The manorial vision of the Lords Proprietors quickly proved to be incompatible with the incentives generated by the factor endowments of the New York hinterland. Once its hardwood forests were cleared with axe and saw and the land turned over by heavy ploughs, the New York hinterland had immense amounts of land suitable for wheat, rye, oats, barley, and maize. Growing those crops was not attractive to the gentlemen that the Lords Proprietors hoped would establish rural manors, but it did

[22] Jones (2008: 86) estimates the pre-conquest Iroquois population, spread across present-day central New York State, at 18,300 to 21,900. By 1660 the population was only 6,810.

prove to be a draw for common people that came as freemen and indentured workers, who were able to advantage of the "headright system" that permitted them to obtain family-sized tracts in fee simple.[23]

Much to the shock of the Lords Proprietors, the free farmers soon began to take advantage of the fact that most proprietary charters called for the establishment of colonial assemblies. The initial conception of the Lords Proprietors was that they, or governors acting on their behalf, would decree laws, "with the advice, assent, and approbation of the freemen of the same province" (Land 1981: 4). The assembled freemen, however, had a rather different idea; they began to draw up their own laws, challenged the Lords Proprietors to veto them, and gave one another proxies to represent them at assembly meetings.[24] That is, independent farmers created the right to vote for representatives on the fly in the 17th century; no one "granted it."[25]

The New York hinterland not only lacked a dependent peasantry, it also—except for its southernmost reaches around the Chesapeake—lacked plantation slavery. In the colonies of Connecticut, New York, Pennsylvania, and New Jersey the basic economic unit was the household, growing a mix of cereals and pulses, with cattle-raising as an adjunct. Additional labor was provided by workers on five-year indenture contracts or laborers hired on the spot market (Vickers 1996: 226). Slavery certainly existed, but its use in agriculture was atypical outside of the tobacco plantations of Delaware and Maryland.[26]

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[23] The system was adopted to incentive immigration to the colonies. Each grantee received 50 hectares of land for each person they brought to the colony, whether as settler, indentured servant, or slave. The Lord Proprietors received an annual "quitrent" from the grantees (Land 1981; 25).

[24] In some colonies, such as Maryland, New Jersey, and Pennsylvania, the resistance of the colonial assemblies to the Lord Proprietor and his agents occurred almost immediately (Land 1981; Murrin 1984). The initial charter for New York did not include a colonial assembly, but the farmers agitated for one and were successful by 1691.

[25] Formal restrictions on suffrage began to be established in the late 17th century, but they were not onerous (Morgan 1975: 145). Adult male suffrage was widespread; 40 to 50 percent of early 18th century white male colonists were eligible to vote for colonial assemblies in the mid-Atlantic region (Keysaar 2000:7).

[26] Data from the first U.S. population census in 1790 provides a sense of the differences in social structure as one moved from north to south within the New York hinterland. Slaves accounted for one percent of the

The agricultural surpluses of the New York hinterland financed the emergence of specialists in trade, finance, and manufacturing. By the early 18th century, the region had "merchants in the full sense of the term: owning and managing ships, providing banking and insurance services for other dealers, financing local industries, and buying and selling in a multitude of different markets." (Vickers 1996: 230). Industrialization was well underway by the middle of the 18th century; sawmills, gristmills, paper mills, textile mills, breweries, distilleries, tanneries, and iron works dotted the region (Scranton 1983: 75-83). The collocation of merchants and manufacturers gave rise to growing cities; the first U.S. census in 1790 showed 21 cities and towns with at least 2,500 inhabitants in the New York hinterland.

One of the striking features of the population of the New York hinterland was its investment in transaction-specific human capital; the level of literacy was probably the highest in the world (Galenson 1996). It should hardly be surprising that this independent-minded, commercially oriented, literate society gave rise to the world's first successful rebellion against British colonial rule.

It should also not be surprising that the society that emerged in the New York hinterland quickly absorbed the broad suite of technologies of the modern era. Joint stock banks were set up in the early 1780s, including the Bank of North America, the Massachusetts Bank, and the Bank of New York. Those banks were followed by the founding of the Philadelphia and New York stock exchanges to trade their shares, as well as those of other companies. New legal technologies were absorbed as well, most particularly the U.S. Patent Act of 1793, which improved on the British patent system by simplifying the process of securing a patent and lowering the costs to five percent of the British level (Khan 2008).

Manufacturers, craftsmen, and merchants in the New York hinterland soon went beyond the absorption of technologies developed in Britain. They created, by an act of the New York State legislature, the world's first general incorporation law in 1811 (Seavoy 1972). Craftsmen in the New York hinterland also succeeded in making interchangeable parts manufacturing—a French concept,

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population in Connecticut, six percent in New York, six percent in New Jersey, and one percent in Pennsylvania—and then jumped to 15 percent in Delaware and 32 percent in Maryland.

employed by the British for making wooden pulley blocks—a practical reality. The invention of jigs and milling machines for cutting metal to precise tolerances, such that parts made from them would fit into any assembly of the same type, came out of workshops in Connecticut, Rhode Island, New York, and Pennsylvania in the 1810s. The combination of interchangeable parts and mass production came to be known as the "American system" and served as the model for late nineteenth-century industrialization around the world (Engerman and Sokoloff 2000).

4.3 The Hinterland of Beijing as a Risk Pooling Ecology

As Figure 5 shows, the hinterland of Beijing was much more like the hinterland of New York than the hinterland of N'Shenge, with one exception; it was highly subject to spatially and temporally correlated droughts. The archival record is consistent with our data: drought-induced mortality crises on the North China Plain, the cradle of Chinese civilization and essentially coterminous with our estimated Beijing hinterland, were considered regular and inevitable occurrences (Li 2007: 5, 24-25, 33).

One does not have to search hard to find evidence of a Risk Pooling political and economic system. The concept of the "Mandate from Heaven," a doctrine holding that heaven conferred legitimacy on a dynasty in exchange for its maintenance of earthly harmony, one of whose obvious markers was an absence of famine, dates to the Western Zhou dynasty (1045 to 771 BCE). Government purchases of grain and the reduced-price sale or loan of those stocks to the public when droughts or floods caused prices to rise began in the Warring States period (5th century BCE). During the Sui dynasty (581 to 618 CE) the state established an empire-wide system of famine relief granaries. The Sui also built the Grand Canal to link its capital of Luoyang with the rice-growing region of the lower Yangtze River valley far to the south. The canal was enlarged during the Yuan dynasty (1271 to 1368 CE), so that rice could be transported the 1,200 miles to the Yuan capital of Beijing (Von Glahn 2016: 55, 178, 183-84; Li 2007: 15-16).

This state-run insurance system generated surplus that could easily be steered into luxury consumption by political elites, thereby creating a target for appropriation by the nomadic and seminomadic peoples of Mongolia and Manchuria. The military technology of the steppe, the cavalry-archer, proved so superior to infantry on the flat, open terrain of the North China plain that Chinese dynasties from the 3rd century BCE to the 17th century CE were forced to "buy peace" by paying tribute to the pastoral confederations and empires on their northern border. In fact, Xianbei, Jurchen, and Mongolian armies invaded China and established imperial dynasties of their own on five occasions: the Northern Wei (386-534 CE), Liao (916-1125 CE), Jurchen Jin (1115-1234 CE), Yuan (1271 to 1368 CE), and Qing (1644-1911 CE). In doing so, they transformed themselves from military extortionists into tax-collecting rulers little different from the Han dynasties they replaced.[27]

Until China's conquest of Mongolia in the late 18th century—and with the notable exception of the Yuan dynasty, which was part of the Mongolian Empire—all Chinese dynasties faced the same strategic problem of invasion by pastoralists, and they all hit upon the same solution: a wall along the northern border. By the end of the Ming dynasty (1368-1644 CE) the Great Wall was a 3,900-mile-long structure with thousands of watchtowers manned by 600,000 troops. The peacetime army of France at this time—the largest standing army in Europe—numbered 22,000 (Robinson 2017a: 303, 318-19).

The provisioning requirements of this force were immense. Chinese governments met some of the food demand by creating military farms; state-owned lands were allocated to soldiers in exchange for a share of the grain produced. The Yuan dynasty expanded this system by creating hereditary military households; lands were allocated to a household, in exchange for which an able-bodied male member performed military service and the household turned over the equivalent of the food requirements of that member to a military granary. By the Ming dynasty, this system accounted for 10 to 20 percent of all registered households (Robinson 2017a).

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[27] The Yuan dynasty, established by the Mongolian conqueror Kublai Khan, provides an out of equilibrium episode that allows us to assess the impact of factor endowments on forms of social organization. Kublai Khan initially distributed huge tracts of land in North China to his generals, who envisioned driving out the region's farmers to create vast horse pastures. He soon realized, however, that his wealth would be greater if the land was worked by tax-paying farmers. He therefore confiscated the lands he had distributed and encouraged the farmers to return to their fields and villages.

Population growth required the Ming dynasty (1368-1644 CE) to extend the system of government grain procurement to cover the civilian population. It funded those purchases by selling official titles, degrees from the imperial national academy, and other privileges, as well as levying taxes on rice. By the mid-15th century, 11,775 barges manned by 121,500 officers and soldiers transported the taxed Yangtze Valley rice to Beijing on the Grand Canal (Perkins 1998: 188).

The Qing dynasty (1644-1911 CE) faced similar pressures: a population of 150 million in 1700 ballooned to 300 million by 1800. (Li 2007: 3).[28] The Qing therefore responded with an expansion of the public granary system. As Will and Wong (1991) show, the Qing "ever normal" granary system was incredibly sophisticated; it built granaries at the county level, levied taxes in grain, sold older grain stocks to avoid spoilage, conducted annual audits, and gathered information on grain prices and weather to predict shortages. It then donated grain to the poor, sold stocks into the market at reduced prices, and made loans in grain to keep prices stable during crop failures. Rowe (2002: 479, 512) estimates that in the 18th century the volume of grain commanded by government instruments was on the order of 20 percent of the grain that was distributed through the market. Myers and Wang (2002: 602) state that in the 18th century the reserves held by the state's granaries "probably amounted to some 5 to 10 percent of total foodgrain production." Shiue (2004: 105) estimates that in the 1750s annual civilian grain stocks averaged 1.5 billion liters of husked rice, which was equivalent to one-fifth of government revenue.

The logic inherent in this government-run risk pooling system required that it repress private market intermediaries; arbitrage opportunities by private agents were effectively taken off the table. As Li (2007: 161-164, 175-180) documents, government officials forced merchants to sell their grain to state granaries at below market prices and limited the size and location of grain shops.

The system that emerged—labor-intense production by small farmers with usufruct rights to land, taxation in grain, the purchase of additional grain by government agents, storage in government

[28] These stresses were relieved somewhat by the Columbian Exchange, which allowed lands unsuited to rice, wheat, and millet to be sown with New World maize, peanuts, potatoes, and sweet potatoes (Li 2007: 97-99).

granaries, the repression of private grain dealers, and the smoothing of supply shocks through government loans, donations, and below-market-price sales—implied a high degree of political centralization. China had neither representative assemblies, nor voting of any kind. Rather, there was an emperor, chosen through rules of dynastic succession, and his court, which was made up of family members, ministers, other officials, and tens of thousands of eunuch administrators. In the provinces, governors appointed by the emperor served as viceroys. A bureaucracy of prefects, magistrates, and their staffs reported to the governor, conscripted men for military service, collected taxes on agricultural output, and kept track of stored grain.

This political and economic system served China well, in the sense that it allowed for a large population, maintained social stability, and permitted the flourishing of an urban high culture, but it did come at a cost to the rate of economic growth. During the Song dynasty (960-1279 CE) a growing commercial economy powered numerous innovations, such as the use of coal in iron and steel smelting, water-powered clocks, gunpowder, and the cannon. The fiscal burden of defending China against Jurchen and Mongol invasions toward the end of the Song, however, slowed the pace of this commercial revolution. The Yuan dynasty then brought it to a halt by expanding the number of government monopolies, increasing taxation, and inducing a hyper-inflation through the issuance of fiat money (Rosabi 1994). Ming emperors continued to throttle the commercial economy. In 1371, the first Ming emperor decreed that all foreign trade had to be conducted by official "tribute missions;" private foreign trade was punishable by death. Between 1613 and 1684, the government forbade coastal trade even among Chinese between the lands north and south of the Yangtze River, the goal being to force all North-South trade through the Grand Canal, where it could be taxed (Myers and Wang 2002: 587).

The history of the market for salt certificates, explored by Faure (2006), provides an example of how Ming emperors preyed on markets. In the late 15th century, the emperor mortgaged his monopoly on salt production to finance the transport of rice from the lower Yangtze valley to the troops that protected the northern border. The basics of the market were that merchants from the lower Yangtze who specialized in grain transport received a salt certificate upon delivery of rice to the north, which they then sold to merchants who specialized in salt distribution, who, in turn, made a claim on an allotment from the imperial salt fields. Salt certificates became, in effect, a government bond with a market price. Precisely because they were valuable, however, the government granted certificates to members of the imperial court without requiring them to transport any grain at all. It therefore could not always meet claims on the salt certificates, requiring it to periodically "regrade" them. In 1617 the emperor abolished the certificates altogether, effectively defaulting on the national debt.

There is debate among Chinese historians regarding the degree to which the Ming policies that repressed private enterprise continued during China's last dynasty, the Qing (1644-1911). One view is that Qing era policies were similar to those of the Ming. In this view, the risk-pooling granary system prevented the emergence of large-scale grain dealers (Li 2007), the emperor discouraged the emergence of a robust and independent merchant class by forcing all foreign trade to go through Canton, where it was handled by merchant guilds that had exclusive trading rights (Meyers and Wang 2002), and a legal system built around the idea that business enterprises were outgrowths of families, owned by lineage trusts (a legal maneuver to prevent state expropriation by holding title to property in the spirit of an ancestor), limited the mobilization of impersonal sources of capital for large-scale business enterprises (Kirby 1995, Faure 2006). Another view is that the Qing were much friendlier to private enterprise than the Ming. In this view, restrictions on commodities trading were relaxed over time (Zhang 2021), the zihao (a commercial entity similar to a limited liability partnership) mobilized impersonal sources of capital for multi-branch trading houses, banks, breweries, and salt mining operations (Zelin 1988, 2006, 2019), and lineage trusts often acted as institutional investors in enterprises not controlled by family members (Pomeranz, 1997; Miller 2020; Zhang, 2021). In addition, as Lowenstein (2021) shows, the Qing economy boasted a broad range of private banks, some of which specialized in financing long-distance trade and others of which focused on agricultural credit. Underpinning these banks, as well as the zihao, was a legal system that respected private property and enforced contracts

There are, however, a set of facts about which there is no debate, and they point to a slow growing economy and a quite limited response to the challenge of modernity. The best estimates suggest that China's per capita GDP fell by roughly 40 percent from 1700 to 1850, at which point it was only one-fifth that of Great Britain (Broadberry, Guan, and Li 2018). That divergence in economic development was reflected in crushing defeats in the Opium Wars of 1839-42 and 1856-60. Those losses induced Chinese elites to take note of the broad suite of new technologies that comprised modernity. China's "Self Strengthening Movement" was, however, perfunctory when compared to Japan's response. Meiji Japan adopted the US patent system (Kahn 2008), the British banking system (Calomiris and Haber 2014), German civil and corporate law (Kirby 1995), German military organization (Ravina 2017), and parliamentary government on the German model (Ramseyer and Rosenbluth 1998). China built a few factories, primarily aimed at armaments production. Broad scale industrial development was held back by the Qing doctrine of "official supervision and merchant management," under which private actors were expected to put up the capital and bear all the risk, but "…were required to work under the thumb of supervising government officials who often followed their own, not necessarily government-directed business agendas and who introduced bribes, corruption, and inflexible management into these enterprises." (Goetzmann and Koll 2005). Railroads, which would have tied markets together and permitted the government to project military power at a distance, were actively discouraged, such that railway construction did not get underway until the 1890s, six decades after the first lines had been laid in Britain, the United States, Belgium, France, and Germany (see Appendix J). The reform of China's educational system was similarly half-hearted. The system had been crafted over the course of centuries to train young people to be imperial bureaucrats; the emphasis was on preparation for a three-day long examination on "the Four Books and Five Classics of Confucianism…." (Ferguson 2011: 43). Rather than broad educational reform designed to build the human capital necessary to compete with the West, the Chinese government sent 120 students to study in the United States in 1872. The students were called back to China three years later because they were becoming overly familiar with Western political ideas (Kuo 1978). Underpinning all these missteps was a system of decision making that depended on a very high degree of competence by a very small group of people governing a very large polity. These are difficult conditions to satisfy, and there is broad agreement that the emperor and his court were not exceptions to the general rule. The result was a series of internal rebellions, defeat in the Sino-Japanese War of 1894-95, and the overthrow of the dynastic system in 1911.

4.4 The Ulaanbaatar Hinterland as a Pastoral Ecology

Few Pastoral ecologies survived the challenge of modernity; most were conquered and absorbed by the nation states based on Transactional or Risk Pooling ecologies that emerged at their borders. Our dataset does, however, provide a few examples of present-day countries that emerged from pastoral ecologies, one of which is Mongolia, whose largest city in 1800 was Ulaanbaatar.

Ulaanbaatar was founded in 1639 as a mobile, yurt-based, Buddhist monastic center, and only became a permanent settlement in 1778, when the monastic center settled in the town of Khuriye, which had emerged as a way station for traders along the Tea Road connecting the fur-producing areas of Russia with the silk and tea markets of China. Its location at the edge of the Gobi Desert made it a convenient place for caravans heading south to offload their cargos from horses to camels, while those heading north did the opposite. The town's proximity to BogKhan mountain to its south shielded it from cold winter winds, while the forests to the north provided wood to build permanent structures. Its location near the confluence of the Tuul and Selbe rivers provided a source of water, while also making some agriculture possible (Christian 2018: 293, 297)—though as Figure 5 shows, the hinterland of Ulaanbaatar could produce only trivial quantities of agricultural staples. The primary source of calories came from livestock, of which sheep tended to be the most important, because they could digest a wide variety of grasses, reproduced rapidly, and provided milk and meat for food, wool for clothing and tents, and dung for fuel (Barfield 1989: 20-21). The result was a hinterland characterized by low population density; circa 1820, Ulaanbaatar had only 7,000 inhabitants (Christian 2018: 293, 297).

The basic social unit that emerged in the hinterland of Ulaanbaatar—and elsewhere on the Mongolian Plateau—was an extended family of shepherds. While there was private property in animals, it was not possible for a single person to look after separate herds of small and large stock simultaneously. Animals of similar species were therefore combined into larger herds that were managed collectively. A group was also better able to protect the herds from theft, as well as enforce claims to the use of specific pastures at specific times of the year. Both women and men developed remarkable proficiency with bow and arrow (Barfield 1989: 24-25).

The political system reflected the kin-based social structure. Camps aggregated into clans and clans aggregated into tribes through patrilineal descent. Political authority was a function of genealogical closeness to the common male ancestor, and internal disputes were settled based on a complex genealogical charter. Disputes with other tribes were settled by collective violence; membership in a clan or tribe came with military obligations (Barfield 1989: 26-27).

This political system tended to be unstable: low-ranking siblings had incentives to murder their older brothers; low ranking, but charismatic, men had incentives to create their own followings; and low-ranking clans had incentives to defect to other tribes by manufacturing a fictitious genealogical tie. Instability proved to be an even greater problem in forging stable confederations of tribes (Christian 2018: 293, 297). The Mongol Empire created by Genghis Khan and his descendants in the 13th and 14th centuries—the largest territorial empire in world history, stretching from the Mediterranean to the Pacific—is an exception that proves the rule. The empire was not crafted out of a tribal confederation. Rather, Genghis Khan destroyed the existing tribal links, and built an organization based on a personal following (Barfield 1989: 188-97).

Inherent instability made it difficult for Mongolian tribes to coordinate a society-wide response to the threat posed by the growing Risk-Pooling ecologies to their northwest and southeast, the Russian and Chinese empires. Gradual improvements in firearms and artillery during the 16th and 17th centuries eroded the military advantages of Mongolian cavalry archery—so much so that when the border between Mongolia and Russia was established by the Treaty of Kiakhta in 1727 its signatories were emissaries of Tsar Peter the Great and the Yongzheng Emperor of the Qing dynasty; Mongolians were not represented (Perdue 2005). That same treaty also regulated trade along the Tea Road, without which Ulaanbaatar would not have emerged as a caravan city.

Mongolia's emergence as a nation state in the 20th century, with Ulaanbaatar as its capital, was, in fact, a by-product of its location between China and Russia. Mongolia was conquered by the Qing dynasty in the 18th century. The collapse of the Chinese dynastic system in 1911 created, however, an opportunity for Mongolian nationalists to declare independence. Chinese armies sent to recapture Mongolia in 1919 were repulsed with the help of Russian forces, who then engineered the creation of a pro-Soviet satellite state, the Mongolian People's Republic (Christian 2018).

5. Statistical Tests

5.1 Current Levels of Economic Development

An implication of our theory is that the countries that grew out of largest city hinterlands with Transactional ecologies should be more prosperous than all the others. It should also be the case that countries that emerged from largest city hinterlands with Risk-Pooling ecologies should be more prosperous than those that emerged from Self-Sufficient or Pastoral ecologies.

5.1.1 Naïve Bayes Regressions

A test of this hypothesis is to estimate the average effect of being in one ecology classification rather than another. A challenge to this approach is that ecologies are not reified entities with sharp boundaries; they are continua. We therefore run a series of OLS regressions that estimate the average effect of being in each ecology type, in which the classifications of each hinterland vary based on the probabilities assigned by the Naïve Bayes algorithm. We run 10,000 iterations for each model, so an observation such as Copenhagen, Denmark that the algorithm classifies as transactional with 100 percent probability enters all 10,000 iterations as transactional, while an observation such as Potosi, Bolivia that the algorithm classifies as pastoral with 70 percent probability and risk pooling with 30 percent probability enters 7,000 iterations as pastoral and 3,000 as risk pooling. This approach, which we refer to for the remainder of the paper as Naïve Bayes regression, generates an estimate of the average effect of being in one of the four ecology classifications, an average robust standard error for each coefficient, and an average adjusted R^2 across the 10,000 model iterations. It also generates estimates of the standard deviation around the mean across the 10,000 ecology coefficients and the standard deviation around the mean across the 10,000 standard errors (displayed in Appendix G).

Table 1 presents the results of this procedure where the dependent variable is log GDP per capita, and each column represents the results for the years 2014, 2000, and 1990. We present all three to show that the results are robust to the year chosen. The independent variables are dummies for Transactional, Risk-Pooling, and Pastoral ecologies (Self-Sufficient ecologies are the reference category, captured by the intercept). We show two results for each year, one including the natural log of per capita oil production over the prior decade, to control for the fact that some countries have very high levels of per capita GDP because they produce prodigious amounts of petroleum and have very small populations, and another without that control.

Table 1: Ecological Classifications Predict GDP/c

Ln GDP/c in:	**2014**	**2014**	**2000**	**2000**	**1990**	**1990**
Mean of Transactional Coefficients	1.579	1.565	1.824	1.832	1.745	1.776
Mean of Transactional Std. Err.	(0.233)	(0.223)	(0.266)	(0.256)	(0.236)	(0.228)
Mean of Risk-Pooling Coefficients	0.512	0.379	0.588	0.457	0.661	0.529
Mean of Risk-Pooling Std. Err.	(0.204)	(0.301)	(0.22)	(0.224)	(0.204)	(0.214)
Mean of Pastoral Coefficients	0.25	0.379	0.336	0.405	0.362	0.428
Mean of Pastoral Std. Err.	(0.233)	(0.301)	(0.236)	(0.296)	(0.216)	(0.274)
Mean of Oil Coefficients	0.172	–	0.174	–	0.157	–
Mean of Oil Std. Err.	(0.024)	–	(0.03)	–	(0.025)	–
Mean of Intercept Coefficients	8.178	8.727	7.643	8.087	7.513	7.937
Mean of Intercept Std. Err.	(0.197)	(0.189)	(0.201)	(0.18)	(0.181)	(0.171)
Avg. Adjusted R^2	0.335	0.141	0.324	0.186	0.347	0.193
Avg. N	152	152	152	152	152	152
Models Run	10.000	10.000	10.000	10.000	10.000	10.000

Our framework predicts that the coefficient for Transactional should be positive, statistically significant, and of large magnitude, while the coefficient for Risk-Pooling should be positive, statistically significant, and of smaller magnitude than that for Transactional. Broadly speaking, the regressions yield the predicted results. Focusing on the specification that includes oil production per capita, the coefficient for Transactional is roughly 1.6 to 1.8 natural log points (depending on the year) above the (Self-Sufficient) reference group coefficient of 7.5 to 8.7 and is statistically significant at one percent. The coefficient for Risk-Pooling is roughly 0.5 to 0.6 log points (depending on the year) above the coefficient for the reference group and is statistically significant at five percent. Converting logs to natural numbers provides a sense of the magnitude of the effect of moving across ecology classifications: the average GDP per capita in 2014 for a non-petroleum producing country that emerged from a largest city hinterland with a Self-Sufficient Ecology works out to $3,562$ (1990 dollars), while that for a non-petroleum producing country that emerged from a largest city hinterland with a Pastoral ecology is $4,573, that of a Risk-Pooling Ecology is $5,943, and that for a Transactional Ecology is $17,275. To the degree that our results do not meet our predictions, it is that the coefficient for Risk Pooling, while of larger magnitude, is not statistically different from that for Pastoral at conventional levels of significance.[29]

5.1.2 Random Forests

One limitation of a Naïve Bayes regression is that it imposes a structure on the data. We therefore employ a Random Forest, an ensemble machine learning method, that allows us to be agnostic regarding the distributions of the variables and functional form. We estimate the Random Forest on the

[29] We display plots of logged coefficients, showing 95 percent confidence levels, in Appendix G. They show that the difference between the coefficient for Transactional and the other three categories are statistically significant at five percent in 1990, 2000 and 2014, both with and without controlling for petroleum production per capita. They show that the difference between the coefficient for Risk Pooling and Subsistence (captured by the intercept term) is statistically significant at five percent in 1990, 2000, and 2014 when controlling for petroleum production per capita, and significant at five percent even without that control in 1990 and 2000. The difference between the coefficient for Risk Pooling and Pastoral does not, however, reach statistical significance at the five percent level of confidence in any specification.

continuous values of the variables for each year twice—once including per capita petroleum production over the prior decade, and again without this control. We provide a brief discussion of the tuning of our Random Forests in Appendix H.

Table 2: Random Forest Models using Ecological Variables to Predict Economic Development

Ln GDP/c	**2014**	**2014**	**2000**	**2000**	**1990**	**1990**
Pseudo-R^2	0.63	0.569	0.576	0.547	0.521	0.491
Out-of-Bag Mean Squared Error	0.53	0.617	0.654	0.699	0.664	0.705
N	152	152	152	152	152	152
Oil Used as Control:	✓	–	✓	–	✓	–

The results, displayed in Table 2, indicate that the vector of exogenous ecological variables relating to the hinterland of the largest city in 1800 accounts for roughly half to three-fifths of the variance in per capita GDP across countries in recent decades. The inclusion of the per capita oil variable improves model fit, as measured by the decline in the out of bag mean squared error. The VIMs for each model, reported in Appendix I, indicate that all the variables contribute to the result.

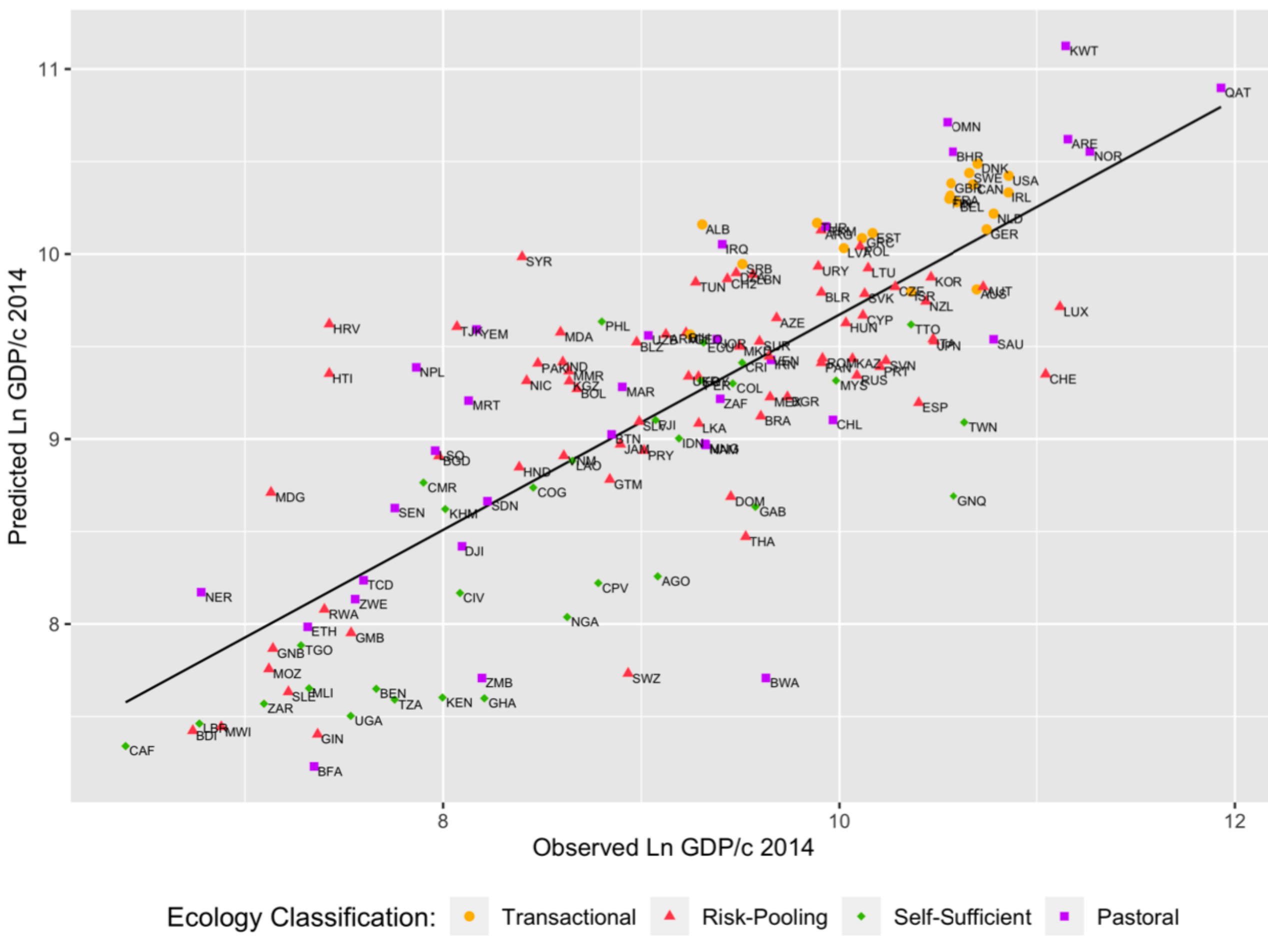
In Figure 6 we graph the Random-Forest predicted values (using the model that includes oil per capita) against the observed (actual) values for log GDP per capita in 2014.[30] This allows us to validate our Random Forest results. We also color code each observation based on the dominant ecology type from the Naïve Bayes classifier developed in Section 3.5. This allows us to cross-validate the results of the Random Forest against the Naïve Bayes regressions reported in Table 1.

There are two notable features of Figure 6. The first is that most of the observations fall close to the regression line. The second is that the Random Forest and the Naïve Bayes regression yield broadly similar results. Except for a small number of countries that emerged from Pastoral ecologies that produce prodigious amounts of petroleum per capita (e.g., Qatar) the countries that cluster at the highest

[30] We display the results for 2000 and 1990 in Appendix I.

predicted and observed levels of economic development tend to be classified as Transactional by the Naïve Bayes algorithm. The countries that cluster at the lowest levels of economic development tend to be classified as Self-Sufficient or Pastoral by the Naïve Bayes algorithm, while the countries classified as Risk Pooling tend to cluster between the two extremes.

Figure 6: Random Forest Predicted vs Observed GDP per Capita, 2014 (Natural Logs)



5.2 Economic Development Over Time

It is one thing to show that countries that we can classify into four different groups based on their factor endowments tend to cluster based on their current levels of economic development, and it is quite another to show that this pattern only emerged over the past two centuries. The GDP series that provide cross-sectional coverage before 1950 tend to be of doubtful reliability, while those with coverage from 1950 to 1990 tend to be characterized by non-random missingness. We therefore employ the urbanization ratios we develop in Appendix A, covering 1500, 1600, 1700, 1800, 1850, 1900, 1950, and 2000, in the models below.

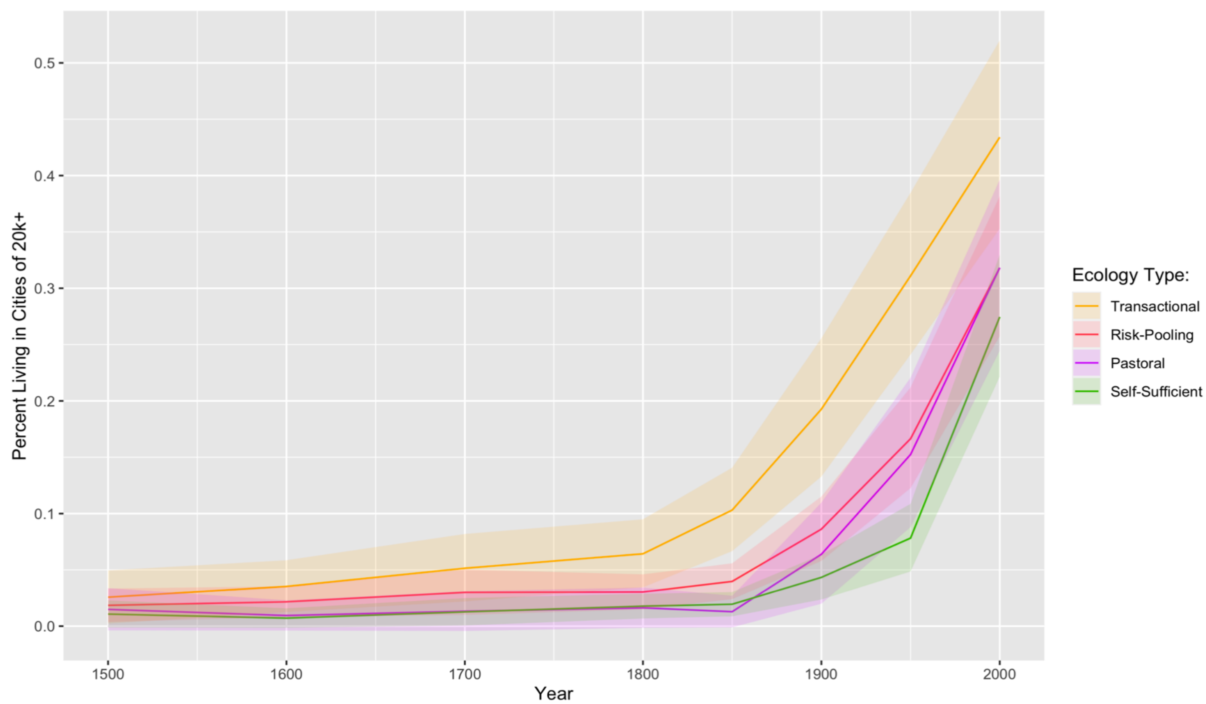
5.2.1 Naïve Bayes Regressions

We follow the same approach to the data as in Section 5.1.1. We present the results in Table 3, and graph them in Figure 7 (using the specification that controls for petroleum production per capita and two-tailed T tests to estimate 95 percent confidence intervals). The table and figure, along with the box and whisker plots showing 95 percent confidence intervals for each year (presented in Appendix G), reveal three patterns. First, in 1500, there are no statistically significant differences in levels of development across ecology types. In 1600 and 1700 countries that emerged from largest city hinterlands with Transactional ecologies display higher levels of development than the reference group (countries that emerged from Subsistence ecologies) as well as countries that emerged from Pastoral ecologies but are not statistically different from Risk-Pooling ecologies. As of 1800, countries that emerged from Transactional ecologies display higher levels of development than countries that emerged from all ecology types—a divergence that grows in magnitude over time. Importantly, countries that emerged from Risk Pooling ecologies display higher levels of development than the reference group (countries that emerged from Subsistence ecologies) in 1850, 1900, and 1950—that is, during the period after the technology shock of modernity. The difference between countries that emerged from Risk Pooling ecologies and those that emerged from Pastoral ecologies only reaches conventional levels of significance, however, in 1850.

Table 3: Percent of Population Living in Cities of at least 20k

Percent Urban in:	2000	2000	1950	1950	1900	1900	1850	1800	1700	1600	1500
Mean of Trans. Coefs.	0.118	0.123	0.195	0.195	0.134	0.136	0.079	0.045	0.038	0.028	0.015
Mean of Trans. Std. Err.	(0.029)	(0.028)	(0.028)	(0.028)	(0.026)	(0.026)	(0.017)	(0.014)	(0.014)	(0.011)	(0.012)
Mean of Risk-Pooling Coefs.	0.034	0.015	0.079	0.075	0.04	0.041	0.02	0.012	0.017	0.014	0.008
Mean of Risk-Pooling Std. Err.	(0.024)	(0.026)	(0.019)	(0.02)	(0.013)	(0.013)	(0.008)	(0.008)	(0.01)	(0.007)	(0.007)
Mean of Pastoral Coefs.	0.034	0.037	0.067	0.075	0.019	0.019	−0.007	−0.001	0.001	0.002	0.004
Mean of Pastoral Std. Err.	(0.029)	(0.035)	(0.029)	(0.032)	(0.021)	(0.021)	(0.007)	(0.009)	(0.009)	(0.007)	(0.009)
Mean of Oil Coefs.	0.022	–	0.024	–	0.011	–	–	–	–	–	–
Mean of Oil Std. Err.	(0.004)	–	(0.007)	–	(0.004)	–	–	–	–	–	–
Mean of Intercept Coefs.	0.243	0.301	0.075	0.092	0.042	0.043	0.019	0.018	0.013	0.007	0.011
Mean of Intercept Std. Err.	(0.021)	(0.021)	(0.014)	(0.015)	(0.01)	(0.01)	(0.005)	(0.005)	(0.006)	(0.004)	(0.006)
Avg. Adjusted R^2	0.239	0.058	0.241	0.159	0.173	0.174	0.24	0.085	0.033	0.047	−0.001
Avg. N	163	163	163	163	163	163	156	160	147	148	145
Models Run	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000

Figure 7: Urbanization Ratios by Ecological Classification, 1500-2000 (95 percent confidence intervals shown as shaded regions)



5.2.2 Random Forests

We follow the same method as in Section 5.1.2 and present the results in Table 4. The results are materially similar to those we obtain using Naïve Bayes Regressions. The Random Forest indicates that the vector of ecological factor endowments accounts for less than 10 percent of the variance in levels of development in 1500, 1600, and 1700. In 1800, however, those factor endowments account for 10 percent of the variance, and then jump to 34 percent in 1850, 25 percent in 1900, 43 percent in 1950, and 33 percent in 2000.[31] When we graph the data for each cross section, following the same procedure as in Figure 6 in order to cross-validate the results of the Random Forest and the Naïve Bayes classifier, we find that, except for countries that produce prodigious amounts of petroleum per capita, the countries classified as Transactional tend to cluster at the highest levels of economic development in 1950 and 2000, the countries classified as Self-Sufficient or Pastoral tend to cluster at the lowest levels of economic development, and the countries classified as Risk Pooling fall between the other groups. This pattern progressively deteriorates when we graph the data for earlier cross sections, such that there is no clear pattern prior to 1800. (Results presented in Appendix I).

Table 4: Random Forest explains progressively less variation in urbanization ratios going back in time

Percent Urban in:	**2000**	**2000**	**1950**	**1950**	**1900**	**1900**	**1850**	**1800**	**1700**	**1600**	**1500**
Pseudo-R^2	0.327	0.279	0.434	0.426	0.252	0.263	0.34	0.097	0.011	0.059	0.071
Out-of-Bag Mean Squared Error	0.028	0.03	0.017	0.017	0.01	0.01	0.002	0.002	0.004	0.002	0.001
N	163	163	163	163	163	163	156	160	147	148	145
Oil Used as Control:	✓	–	✓	–	✓	–	–	–	–	–	–

5.3 Technology Absorption, Markets, and Human Capital

For our framework to hold we need to show that countries that emerged from largest city hinterlands with Transactional ecologies were better suited than all others circa 1800 to absorb the technologies of the modern era as broad suite because a network of markets had emerged endogenously to coordinate the activities of agents that had been incentivized to invest in transaction-specific human capital. We also need to show that countries that emerged from largest city hinterlands with Risk-Pooling ecologies were better suited than those that emerged from Pastoral or Self-Sufficient ecologies circa 1800 to absorb the technologies of the modern era—but not because a network of markets had emerged endogenously or because agents had invested in transaction-specific human capital.

[31] A straightforward interpretation of the decline in the Pseudo R^2 from 1950 to 2000 is the growth of mega-cities in poor countries, a phenomenon examined by Glaeser (2014). This interpretation is consistent with the increase in the coefficient on the intercept from 1950 to 2000 in the Naïve Bayes regressions.

We follow the same approach to the data as in Section 5.1.1, above, by estimating Naïve Bayes regressions on variables that proxy for the growth of markets from 1500 to 1800, investments in transaction-related human capital circa 1800, and the rate of absorption of post-1800 technologies. We estimate the growth of markets in two ways: the number of new secondary towns and cities with at least 20,000 population that emerged between 1500 and 1800 within each countries' largest city hinterland; and the change in the population of those new cities and towns from 1500 to 1800. We estimate investments in transaction-related human capital by employing two different measures: the Whipple Index for 1820 from Crayen and Baten (2010) as a measure of numeracy; and the percentage of the population enrolled in primary school in 1820 from Lee and Lee (2016). We operationalize the rate at which modern technologies were absorbed by estimating the year in which countries began to operate a railroad network of at least 250 kilometers within their present-day borders by expanding upon data in Comin and Hobjin (2009; see Appendix J).[32]

The Naïve Bayes regressions presented in Table 5 (with box and whisker plots presented in Appendix G) yield results that are consistent with our hypotheses. First the results indicate more rapid growth of markets, as proxied by the growth of secondary cities, in largest-city hinterlands with Transactional ecologies. The average largest-city hinterland with a Transactional Ecology added nearly three secondary cities over the period 1500-1800, while the number of secondary cities that emerged in Pastoral, Risk Pooling, and Self-Sufficient hinterlands were not statistically different from zero. We obtain materially similar results when we substitute the growth of secondary city populations as the dependent variable.

[32] We focus on the railroad because it is a canonical case of mutual dependence. On the one hand, it multiplied the impact of new industrial and war-fighting technologies by lowering transport costs. On the other hand, its financing, construction, and operation required the absorption of a suite of new technologies, such as steel rolling, metal cutting and joining, the telegraph, universities to train engineers and managers, general incorporation laws to mobilize capital, and political institutions to limit the ability of government to appropriate the quasi-rents generated by sunk investments.

Second, investments in transaction-related human capital, as measured by the percentage of the population enrolled in primary school, were significantly higher in countries that emerged from largest city hinterlands with Transactional ecologies, as compared to countries that emerged from Pastoral, Risk Pooling, and Self-Sufficient ecologies. The effect is of large magnitude; roughly 22 percentage points higher. The results for the Whipple Index do not point to the same conclusion, however. There is no difference across ecology types, a result we think is due to the small number of observations.

Finally, countries that emerged from largest-city hinterlands with Transactional ecologies absorbed the railroad 41 years earlier, on average, than countries that emerged from largest-city hinterlands with Pastoral ecologies (the reference group). Countries that emerged from largest-city hinterlands with Risk-Pooling ecologies absorbed the railroad more slowly than those that emerged from Transactional ecologies (roughly 25 years later, a result that is significant at five percent), but still faster than those that emerged from Pastoral or Self-Sufficient ecologies (roughly 16 years earlier, significant at five percent).[33] In short, the data are consistent with our predictions

Table 5: Ecology Classifications Predict Differences in 19th Century Markers of Human Capital & Technological Absorption

	Year 250km of railroad surpassed	**Percent enrolled in primary school, 1820**	**Numeracy in 1820 (Whipple Index)**	**Number of New Cities 1500-1800**	**Pop. Growth in Cities 1500-1800***
Mean of Trans. Coefs.	−41.444	21.695	−37.632	2.525	101269
Mean of Trans. Std. Err.	(10.116)	(7.136)	(41.287)	(0.748)	(33325.6)
Mean of Risk-Pooling Coefs.	−15.655	1.134	32.193	0.261	10386.2
Mean of Risk-Pooling Std. Err.	(7.983)	(3.281)	(39.902)	(0.192)	(9260.3)
Mean of Self-Suff. Coefs.	3.263	−4.401	–	0.041	−3197.1
Mean of Self-Suff. Std. Err.	(8.85)	(2.525)	–	(0.202)	(7280.7)
Mean of Intercept Coefs.	1911.322	4.922	198.45	0.233	7343.2
Mean of Intercept Std. Err.	(6.89)	(2.649)	(35.55)	(0.125)	(4708.9)
Avg. Adjusted R^2	0.148	0.204	0.053	0.204	0.155
Avg. N	132	104	47	163	163
Models Run	10,000	10,000	10,000	10,000	10,000

*Excluding centroid city

5.4 Democratic Consolidation

Our framework makes sharp predictions about the consolidation of democracy. Countries that emerged from largest city hinterlands with Transactional Ecologies should be more democratic today

[33] Table 5 employs largest city hinterlands with pastoral ecologies as the reference category because the Whipple dataset does not include any Self-Sufficient ecologies.

than those that emerged from Risk-Pooling, Self Sufficient, or Pastoral ecologies. In addition, we should observe that difference emerging over time. Finally, the level of democratic consolidation of countries that emerged from largest city hinterlands with Risk-Pooling ecologies should not be higher than that of countries that emerged from Self-Sufficient and Pastoral ecologies, even though they display higher levels of economic development. The ability to engineer the absorption of chemical, electrical, and mechanical technologies from above could permit economic growth in fits and starts, but it could also block the absorption of educational, organizational, legal, and governance technologies.

We operationalize the level of democratic consolidation by combining two variables from the Polity IV dataset: Polity2 (a measure of the level of democracy/autocracy); and Durable (the number of years since the most recent regime change), which we convert to natural logs and add to Polity2 when it meets the threshold for democracy (a value of 7).[34] Our measure, Durable Polity, therefore captures both cross sectional differences in democratic institutions, as well as the length of time that a country has been democratic. Ideally, our coverage of Durable Polity would extend back to 1500. Polity IV only provides coverage, however, since 1800, and until 1850 there are very few reporting countries. We therefore estimate our models for 1850, 1900, 1960, 2000, and 2017.

5.4.1 Naïve Bayes Regressions

We follow the same approach to the data as in Section 5.1.1, and present the results in Table 6 and Figure 8. They reveal four patterns. First, in 1850 and 1900, the level of democratic consolidation in countries that emerged from Transactional ecologies is not different from those that emerged from other ecology types. Second, in 1960, 2000, and 2017 countries that emerged from largest city hinterlands with Transactional Ecologies demonstrate much higher levels of democratic consolidation than all others. The estimated mean of Transactional in 2000 of 10.6 (the Transactional coefficient plus the intercept), for example, is roughly twice the other estimated means. Fourth, the coefficients for countries

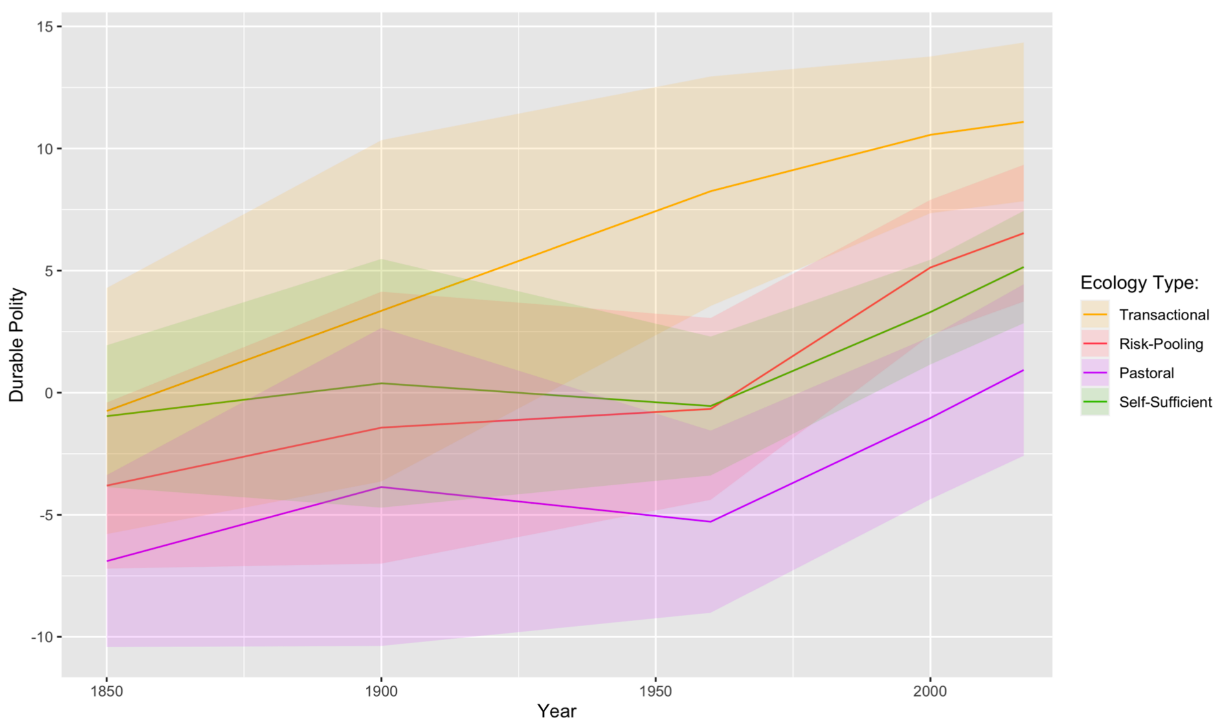
[34] For information on Polity IV see http://www.systemicpeace.org/polity/polity4x.htm. See Appendix K for a discussion of back coding of Polity2 and Durable, as well as a discussion of our coding rules in cases of the political unification of two or more states.

that emerged from hinterlands with Risk-Pooling ecologies are never statistically different from the reference category (Self-Sufficient ecologies).

Table 6: Ecology Classifications Predict Consolidation of Democracy Over Time (As Measured by Durable Polity)

	Polity 2017	**Polity 2000**	**Polity 1960**	**Polity 1900**	**Polity 1850**
Mean of Transactional Coefficients	5.942	7.259	8.797	2.969	0.21
Mean of Transactional Std. Err.	(1.645)	(1.623)	(2.37)	(3.483)	(2.501)
Mean of Risk-Pooling Coefficients	1.385	1.826	−0.118	−1.816	−2.844
Mean of Risk-Pooling Std. Err.	(1.417)	(1.402)	(1.877)	(2.775)	(1.688)
Mean of Pastoral Coefficients	−4.215	−4.337	−4.738	−4.247	−5.936
Mean of Pastoral Std. Err.	(1.777)	(1.683)	(1.881)	(3.247)	(1.749)
Mean of Intercept Coefficients	5.148	3.301	−0.545	0.386	−0.96
Mean of Intercept Std. Err.	(1.164)	(1.085)	(1.433)	(2.538)	(1.44)
Avg. Adjusted R^2	0.142	0.181	0.212	0.072	0.137
Avg. N	158	155	111	57	49
Models Run	10,000	10,000	10,000	10,000	10,000

Figure 8: Estimated Democratic Consolidation by Ecology Type, 1850-2017 (95 percent confidence intervals shown as shaded regions)



5.4.2 Random Forests

We follow the same method as in Section 5.1.2 as a second approach to the data. The results, presented in Table 7, are materially similar to those we obtain using Naïve Bayes Regressions. The

Random Forest indicates that the vector of ecological factor endowments accounts for virtually none of the variance in levels of Durable Polity in 1850, but then accounts for progressively more over time—20 percent in 1900, 21 percent in 1960, 29 percent in 2000, and 27 percent in 2017.

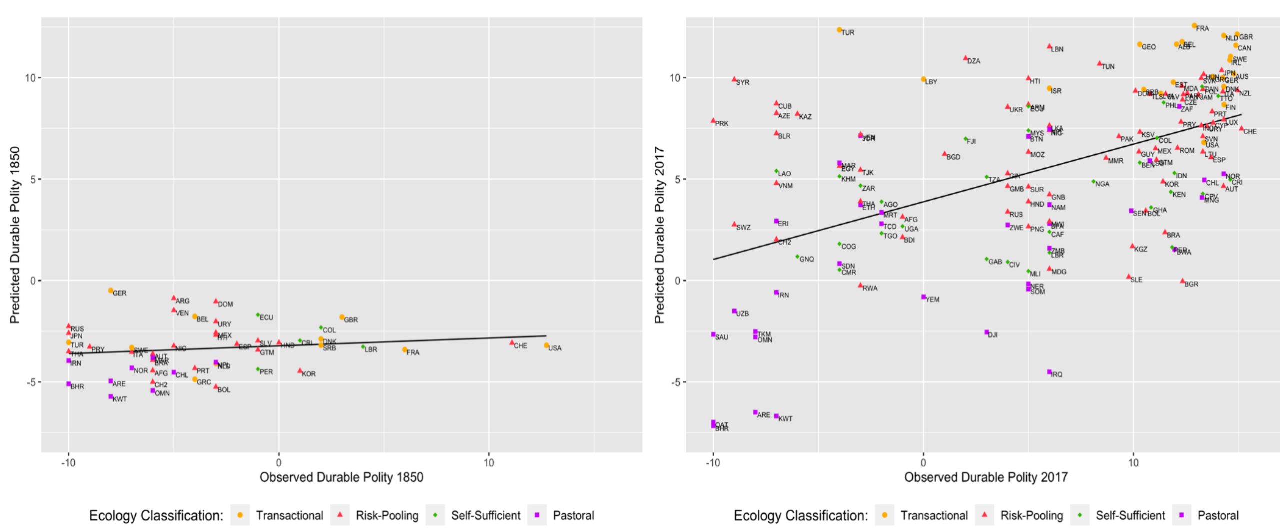
Table 7: Random Forest explains less and less variation in democratic consolidation back in time

	Polity 2017	**Polity 2000**	**Polity 1960**	**Polity 1900**	**Polity 1850**
Pseudo-R^2	0.273	0.288	0.214	0.197	0.041
Out-of-Bag Mean Squared Error	43.02	44.591	60.109	42.416	25.276
N	158	155	111	57	49

As we did in Section 5.1.2, we cross-validate the results of the Random Forest and the Naïve Bayes regressions by graphing the Random-Forest predicted values against the observed values for Durable Polity, color coding each observation based on the dominant ecology type from the Naïve Bayes classifier. We show the results for 1850 and 2017 in Figures 9A and 9B, respectively (and all other years in Appendix I). They indicate that the ecological variables do a far better job accounting for variance in levels of democratic consolidation in 2017 than in 1850, and that the countries classified as Transactional cluster at the highest levels of both observed and predicted democratic consolidation in 2017, but not in 1850.

Figure 9: Comparing Predicted Democratic Consolidation in 1850 and 2017

(a) Random Forest Model, Durable Polity 1850 (b) Random Forest Model, Durable Polity 2017



5.5 The Geography of "The New Imperialism"

Historians divide the history of imperialism into two periods. In the first period, from roughly 1500 to 1800, Spain, Portugal, Sweden, the Netherlands, England, France, and Russia colonized the Americas and Siberia, relying mostly on private enterprises to do so because of their limited fiscal capacities. Those enterprises also set up trading posts on the coasts of Africa, South Asia, and Southeast Asia, but their attempts to expand inland were turned back by mortality from tropical diseases and armies fielded by indigenous kingdoms and empires. In the second period, from roughly 1800 to 1945—often referred to as the New Imperialism—Great Britain, France, Germany, Belgium, the Netherlands, Portugal, Sweden, Italy, Spain, Russia, Japan, and the United States drew on the technologies of the modern era to colonize Africa, Central Asia, South Asia, Southeast Asia, East Asia, and Australasia.

Our theory generates predictions about who colonized who during the New Imperialism. If countries that emerged from largest-city hinterlands with Transactional ecologies were able to absorb the technologies of the modern era more rapidly than the others, it follows that they should have been more likely than others to be colonizers. Conversely, countries that emerged from largest city hinterlands with Pastoral or Self-Sufficient ecologies should have been more likely than others to be colonized. Countries that emerged from largest city hinterlands with Risk-Pooling ecologies should have fallen between the Transactional and Pastoral/Self Sufficient groups; their ability to engineer technological absorption from above should have allowed them to resist colonization better than countries that emerged from Pastoral or Self-Sufficient ecologies, while permitting them to undertake imperial projects themselves.

We find that the data matches the predictions.[35] The conditional probability of being a colonizer was 33 percent for countries that emerged from a largest city hinterland with a Transactional ecology, versus six percent for Risk Pooling, 0 percent for Pastoral, and 0 percent for Self-Sufficient. The

[35] We code a country as colonized if according to the Correlates of War dataset it meets one of the following criteria: it was colonized or made a protectorate during the 19th or 20th centuries; it was made part of another state by force during the 19th or 20th centuries; or it was a League of Nations mandate.

conditional probability of being colonized was 77 percent for Self-Sufficient, 71 percent for Pastoral, 41 percent for Risk Pooling, and 33 percent for Transactional. Conditional on being colonized, the probability that the colonizer had emerged from a Transactional ecology was 76 percent, from a Risk Pooling ecology 24 percent, from a Pastoral Ecology 0 percent, and from a Self-Sufficient ecology 0 percent (see Appendix R for calculations).

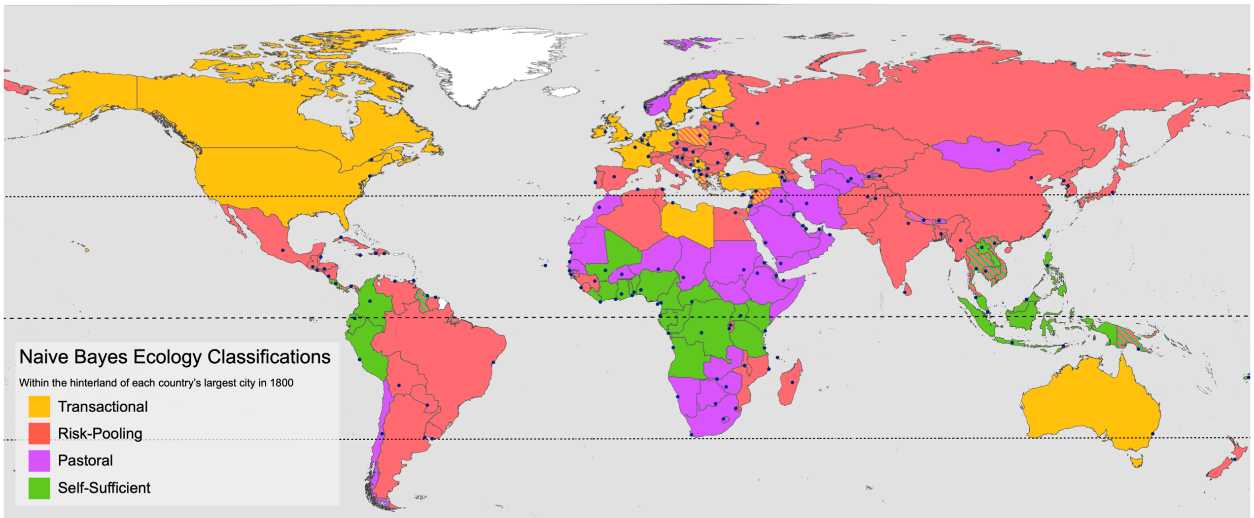
5.6 The Geographic Clustering of Economic Development

Scholars have long observed that countries with high levels of economic development are located in the temperate latitudes (35° to 66° N/S of the Equator), while those with low levels are located near the Equator. There are, however, numerous exceptions to this general pattern; Russia, China, Mongolia, Kazakhstan, Tajikistan, Kyrgyzstan, Uzbekistan, Chile, and Argentina are all located in temperate latitudes, but they are middle and lower middle-income countries.

Our framework not only explains the general pattern, but also explains the exceptions to it. Figure 10 presents a Mercator projection in which countries are color coded by the dominant ecology classification of their largest-city hinterland from the Naïve Bayes procedure in Section 3.5, above, the Equator and the beginning of the temperate latitudes at 35° North and 35° South are marked, and the location of the largest cities around which the hinterlands are estimated are shown. In cases of hinterlands that are classified as having at least a 25 percent probability of falling into more than one ecology type, both colors are shown.

Self-Sufficient ecologies, which as Table 1 shows tend to have low per capita incomes, clustered near the Equator. This was a consequence of an equatorial heat engine known as the Hadley Cell. Steady and direct sunlight near the Equator produces high temperatures relative to the poles, which in turn cause the evaporation of ocean water, with the warm, moist air rising via convection into the atmosphere. Once there, it cools, producing a belt of clouds and heavy rainfall several hundred miles wide that extends around the planet, known as the Intertropical Convergence Zone (ITCZ). The resulting hot, humid climate gave rise to wet soils suited to high moisture perennial crops, shortened the storage lives of low moisture annual crops, and favored the reproduction of mosquitos that carry malaria—factors that generated pressures and tensions that favored the emergence of Self-Sufficient ecologies.

Figure 10: The Spatial Distribution of Ecology Classes



The prevalence of Pastoral ecologies in the subtropics (the region just south of the line demarcating 35° North, and the region just north of the line demarcating 35° South in Figure 10), which as Table 1 shows tend to have low per capita incomes, was also driven by the Hadley Cell. The warm, moist air that rises near the Equator reaches an altitude of 10 to 15 kilometers at which point it cools, can ascend no longer, and is pushed toward the poles by the rising air behind it. That cool, dry, high-altitude air begins to sink at roughly 30° North and 30° South. As it falls it is compressed by the air on top of it, causing it to warm, thereby decreasing its relative humidity. That now warm, dry air gets pulled back toward the Equator at low altitude by the same convection current that pushed it into the atmosphere when it was water laden. The result is a region of deserts and savannas too dry to support crop production but wet enough to sustain grasslands—and hence sustain Pastoral ecologies—at the boundaries of the ITCZ. The Sahara Desert and the South African Veld, on either side of Central African Rainforest, are canonical example. Because the earth's axis is tilted 23.5 degrees relative to the plane of its orbit around the sun, the boundaries of the ITCZ, and hence the boundaries of subtropical grasslands, shift north and south with the seasons, thereby creating pressures and tensions that favor nomadism or semi-nomadism.

Large scale climatologic forces interacting with geographic features generated Risk-Pooling ecologies, which as Table 1 shows tend to fall in the middle of the distribution of per capita incomes. Temperature imbalances produced by differential rates of heating and cooling of oceans and large land masses, and which invert with the seasons as the ITCZ shifts north and south, give rise to monsoonal climates: moisture laden air moves from ocean to land in the summer, and dry air moves from land to ocean during the winter. When the moisture-laden summer winds are pushed to higher altitude by mountain ranges they cool and drop their moisture. The resulting rainy summers on the windward side of the mountains permit the cultivation of low moisture annual crops. When the winds reverse, the resulting cold dry winters facilitate their storage. Northern India, on the windward side of the Himalayas, and the North China Plain, on the windward side of the Yan mountains, are canonical examples. Slight perturbations in the earth's rotation about its axis, however, produce interannual variation in the boundaries of the ITCZ, and hence variation in the strength of the Indian Ocean, East Asian, Indo-Australian, West African, and Mexican monsoons. That variation in monsoon intensity produced the spatially and temporally correlated droughts that affected largest city hinterlands in South Asia, East Asia, East Africa, the Sahel, North Africa, the Middle East, Mexico, Central America, and the East Coast of South America, giving rise to the Risk-Pooling ecologies that cluster there.

The same large-scale climate systems that gave rise to Risk-Pooling ecologies on the windward side of mountain ranges produced Pastoral ecologies on the leeward side. Because almost all the moisture had already been dropped in the mountains the soils on the lee side were too dry for crops but wet enough to sustain wild grasses. A canonical case is the Mongolian plateau, on the lee side of the Yan Mountain Range.[36]

[36] A non-monsoonal, but nonetheless planetary-scale climate system is the El Niño Southern Oscillation (ENSO) of the equatorial Pacific. It interacts with the Cordillera de la Costa in Chile, the Andes in Bolivia,

There are, in fact, only a few regions on the planet that are both temperate (between 35° and 66° N/S), and hence were comparatively well-suited to growing and storing low moisture annual crops, and that are only minimally affected by large-scale climate systems that generate spatially and serially correlated droughts. Many of those regions are also characterized by flat terrains, slow-moving rivers, and long coastlines that facilitated transport prior to the steam-powered technologies of the 19th century. We would suggest that it is not an accident that forms of social organization characterized by decentralized markets—what we refer to as Transactional ecologies— emerged where these climatologic and geographic features co-occurred: the Mid-Atlantic and New England regions of the United States; the provinces of Upper and Lower Canada; Western and Central Europe; Scandinavia, the Baltic Rim, and Japan. As Table 1 shows, largest city hinterlands located in these regions tended to give rise to nation states with very high per capita incomes today.

6. Robustness Tests

6.1 Excluding New World Colonizers

This insight about large-scale climatologic forces and geographic features offers an explanation for the geographic clustering of present-day levels of economic development, but it also poses a challenge to statistical inference. How can we know that complex combinations of factor endowments, and their associated ecologies, explain variance in long-run development outcomes, rather than some other factor that correlates with geographic location?

The "Atlantic Economy" offers one such alternative theory. A set of emergent European nation states that faced the Atlantic Ocean colonized the Western Hemisphere during the 16th, 17th, and 18th centuries, and grew wealthy by exploiting the New World's natural resources, its native peoples, and the African slaves transported there. We therefore re-estimate the Naïve Bayes Regressions and Random Forests excluding hinterlands located in present-day European countries that held New World colonies:

Peru, and Ecuador, and the North and South Coast Ranges in California to produce spatially and temporally correlated droughts that shift over periods of years.

Britain, France, the Netherlands, Belgium, Spain, and Portugal. We present the results in Appendix L. To the degree that these differ from our main results, it is that we no longer detect a small, but statistically significant, difference between countries that emerged from Transactional ecologies and those that emerged from Pastoral or Self-Sufficient ecologies in 1600 and 1700; but we still detect that result in 1800 and all later years. The other results are materially the same. This does not mean that the Atlantic Economy had no effect; rather it indicates that our results are robust to controlling for it.

6.2 Excluding Hinterlands Affected by the African Slave Trade

The African Slave Trade might also explain geographically clustered development outcomes. The societies from which slaves were forcibly exported did not just suffer a loss of population; social trust might have been undermined and extractive institutions implanted (Nunn 2008). We therefore re-estimate the Naïve Bayes Regressions and Random Forests excluding hinterlands located in present-day African countries that, according to Nunn (2008), exported more than 10,000 slaves during the period 1400-1900. The results, which we present in Appendix M, tend to be materially the same as our main results. To the degree that they differ, it is that coefficient for Risk Pooling in the Naïve Bayes regressions on per capita GDP in 2000 and 2014, as well as the coefficient for Risk Pooling in the Naïve Bayes regressions on railroads, while retaining the same sign, no longer reach statistical significance at conventional levels. This does not mean that the African Slave Trade had no effect; rather it indicates that our results are robust to controlling for it.

6.3 Second Largest Cities

An additional concern is that our results might be sensitive to the choice of the densely populated nuclei from which modern nation states emerged. We therefore repeat the procedures and analyses in sections 5.1 through 6.2, above,[37] but, when available, substitute the second largest city in

[37] We use the same 15 manually-coded hinterlands as in Section 3.5 to train the Naïve Bayes classifier for second larges city hinterlands. Thus, the probability distributions of all 163 observations in this set of Naïve Bayes regressions are estimated by the algorithm.

1800 to estimate hinterland sizes, shapes, and factor endowments.[38] The results, which we present in Appendix N, tend to be materially the same as our main results. To the degree that they differ, it is that the coefficient for Risk Pooling in the Naïve Bayes regressions on Durable Polity in 2000 and 2017 reaches conventional levels of statistical significance, though it remains of smaller magnitude than the coefficient for Transactional.

7. Accommodating other Theories

A powerful test of a theory is whether it can account for the theories advanced by other researchers and the fact patterns that support those theories. Hall and Jones (1999) hypothesize that growth-enhancing institutions are a product of the emergence of capitalism and private property rights in Western Europe, and therefore employ latitude as an instrumental variable to capture the extent of Western European influence on the rest of the world. Engerman and Sokoloff (1997) argue that differential paths of development across the Americas were driven by soils and climates, drawing a distinction across places well-suited to growing sugar cane versus those well-suited to growing cereals. Acemoglu, Johnson, and Robinson (2002) argue that institutional choices made by Europeans centuries ago explain variance in levels of development today. They develop an index of settler mortality as an instrument to account for the endogenous component of institutions. Easterly and Levine (2016) hypothesize that property rights institutions were carried by people, and therefore construct a measure of the percentage of the population of Western European origin.

We introduce the variables of interest from those theories into our models. We first estimate their independent effect on development outcomes today by estimating OLS regressions. We then estimate our Random Forest ecological models but truncate the samples to match those employed in the analyses of latitude, sugar versus cereals, settler mortality, and European population share. We next re-estimate the Random Forest models, but include, serially and independently, latitude, potential sugar

[38] There are 16 cases of modern countries for which we have not been able to identify a second largest city in 1800. Because missingness is not random, we use the data for the largest city hinterland for those cases.

production, settler mortality, and European population share. Finally, we graph the values predicted by our ecological model against those predicted by our models plus each of the alternative variables.

Three things should be true if an alternative theory is accommodated by our ecological framework: 1) the percent of variance in present-day development outcomes accounted for by the alternative variable by itself should be less than the percent of variance accounted for by our ecological model; 2) the percent of variance accounted for when the alternative variable is added to the ecological model should not increase substantially, and the out of bag mean squared error should not decrease substantially; and 3) a graph that compares the results predicted by our ecological model against the results predicted by our model plus the alternative variable should display data points falling on the 45 degree line. We hasten to add that the failure of alternative variables to account for more variance than our ecological models does not imply that the other theories that are operationalized by those variables are wrong. Rather, it suggests that factors that other scholars have hypothesized as causal either proxy for our vector of factor endowments or were endogenous outcomes of the equilibrium paths of development posited by our framework.

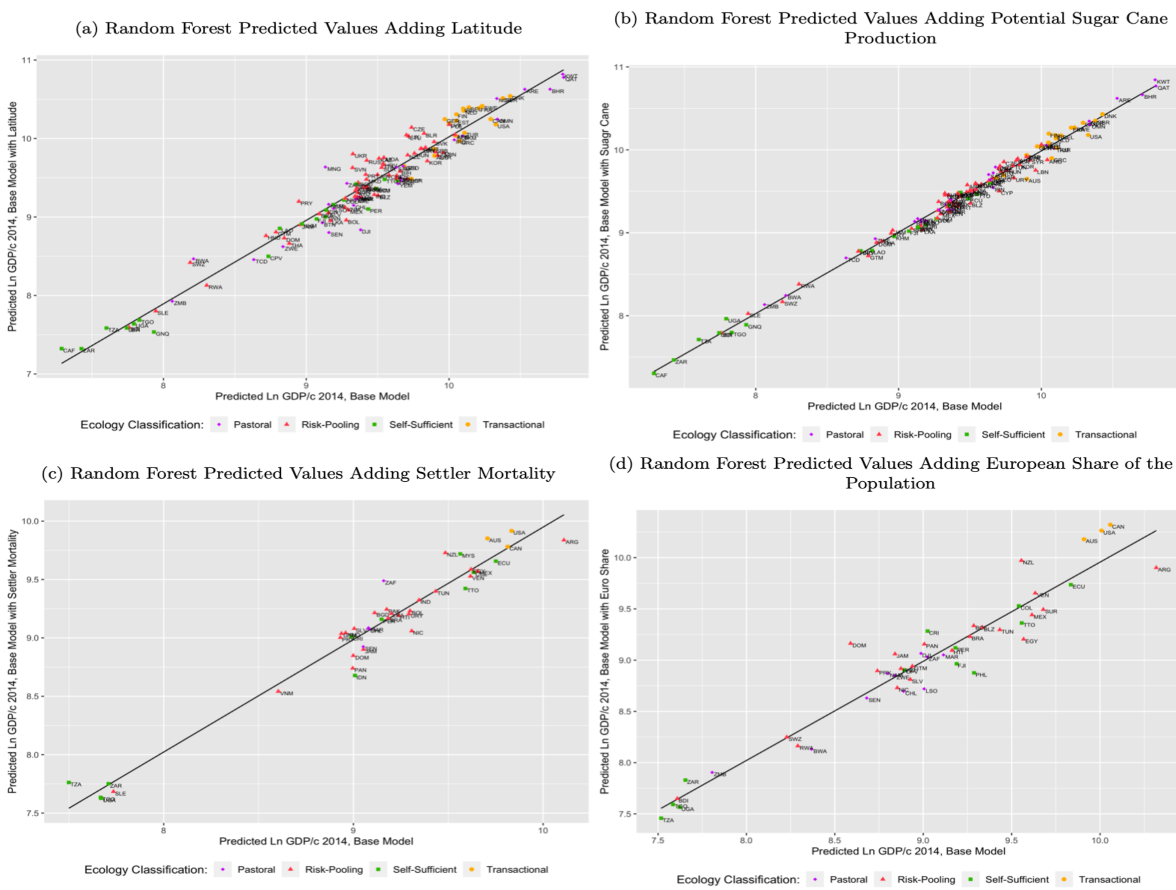
We present the results for three dependent variables—GDP per capita in 2014, the urbanization ratio in 2000, and democratic consolidation in 2017—in Table 8. We graph the predicted values of GDP per capita in 2014 from our ecological models against the predicted values from our ecological models plus the variable(s) from other theories in Figures 11A, 11B, 11C, and 11D, while presenting the urbanization ratio and democratic consolidation graphs, as well as the results for GDP per capita in 2000 and 1990, urbanization from 1500 to 1950, and Durable Polity from 1800 to 1960 in Appendix O. We then repeat all of these analyses using the restricted samples that exclude New World Colonizers (Section 6.1) and countries effected by the African Slave Trade (Section 6.2), as well repeat all of these analyses using the hinterlands of second largest cities (Section 6.3), and show those results in Appendix P. We find that: none of the alternative variables alone account for more of the variance in development outcomes than our ecological models; the addition of those variables to our models does not improve the goodness of fit; and the data points of the predicted values from our models versus those models plus the alternative variables tend to lie along the 45-degree line. The results, in short, suggest that our ecological framework accommodates the theories that have been advanced by other researchers.

Table 8: Random Forests, Incorporating Variables from Other Theories

Percent Urban 2000	**Latitude OLS**	**Base RF**	**RF w/ Latitude**	**Sugar OLS**	**Base RF**	**RF w/ Sugar**	**Euroshare OLS**	**Base RF**	**RF w/ Euroshare**	**Mortality OLS**	**Base RF**	**RF w/ Mortality**
Pseudo-R^2	0.137	0.327	0.338	0.114	0.327	0.33	0.222	0.404	0.412	0.177	0.308	0.313
Model MSE	0.189	0.166	0.165	0.192	0.166	0.166	0.175	0.152	0.151	0.175	0.159	0.159
N	163	163	163	163	163	163	58	58	58	60	60	60
GDP/c 2014												
Pseudo-$R^2$1	0.373	0.63	0.671	0.228	0.63	0.632	0.388	0.519	0.567	0.45	0.662	0.667
Model MSE	0.951	0.728	0.687	1.059	0.728	0.726	0.835	0.734	0.696	0.783	0.609	0.605
N	152	152	152	152	152	152	56	56	56	59	59	59
Durable Polity 2017												
Pseudo-$R^2$2	0.081	0.273	0.316	0.061	0.273	0.28	0.072	0.147	0.117	0.113	0.215	0.208
Model MSE	7.396	6.559	6.36	7.499	6.559	6.524	6.137	5.83	5.932	5.942	5.54	5.566
N	158	158	158	158	158	158	57	57	57	60	60	60

Latitude is from Hall and Jones (1999), measured as absolute latitude from the equator and is operationalized from the centroid city of each hinterland. Sugar is from Engerman and Sokoloff (1997), measured as the natural log of potential rainfed production within each largest city hinterland, with data provided by FAO GAEZ 3.0. Euroshare is from Easterly and Levine (2016), measured as the natural log of the percent of Europeans living in each country during that nation's formative colonial period. Mortality is settler mortality from Acemoglu, Johnson, and Robinson (2001), measured as the natural log of each country's mortality rate during the colonial period.

Figure 11: Comparing Random Forest Predictions with Alternative Explanatory Variables



8. Discussion and Conclusion

Three schools of thought dominate the literature explaining variance in levels of economic development across countries. One focuses on the direct effects of climate and geography, another on the impact of institutional choices made in the past, and a third on investments in human capital.

Our findings are inconsistent with the view that institutions or human capital, independent of climate and geography, shaped development outcomes. If they did, our vector of exogenous ecological factors for the economic hinterlands of modern countries' largest city in 1800 (conditional on 18th century technologies) would not account for roughly 60 percent of the variance in levels of per capita GDP today. Our findings are also inconsistent with the view that climate and geography shape development outcomes directly. If they did, our vector would account for more of the variance in levels of development in the past than they do today, rather than the other way around.

Our results are, however, consistent with the view that climate and geography operated on long run economic development indirectly, by generating pressures and tensions that gave rise to different forms of social organization around the planet between the Columbian Exchange and modernity. No one chose those forms of social organization in any meaningful sense of the word. Rather, in a world in which starvation always loomed, and in which solutions had to be found close at hand, human beings experimented. Some of the things they did—the choice of one crop over another, a deal struck with a neighbor, an appeal to a powerful individual—kept hunger away until the next harvest. People could not, however, experiment just any way they liked—at least if they wanted to live to see the next harvest. The result of countless agents making decisions over hundreds of years under the hard constraints imposed by nature yielded very different legal systems, stocks of human capital, social structures, lifeways, moral systems, and distributions of power. Because these features of societies coevolved with one another, societies could not jettison them overnight without cost once they faced a new challenge to survival; the technology shock of the modern world. Societies therefore absorbed the new, mutually dependent technologies at very different rates, giving rise to divergence in economic development.

Lest isolated arguments be misinterpreted, our results should not be read as suggesting that climate and geography *determined* long run paths of economic development, in the sense that they laid down tracks from which societies could not deviate. If they did, our vector of factor endowments would account for more than 60 percent of the variance in present-day levels of economic development. Our interpretation is that the variance that remains unaccounted for is the product of idiosyncratic events, individual action, and human foresight. How else might one explain cases far off the regression line in Figure 6, such as Botswana, whose success despite its factor endowments has been studied by Acemoglu, Johnson, and Robinson (2003).

We would suggest, however, that it would be a mistake to ignore the weight of the past in understanding why things are the way they are. A simple thought experiment perhaps makes the point. In the numerous decisions, small and large, you make—where to live, what to ask of your coworkers, which charities to support—how often do you take account of how they will position your society such that it can absorb a future technology shock whose parameters you do not know? Adam Ferguson, writing in 1782, was perhaps timeless in his insight: "The crowd of mankind, are directed in their establishments and measures, by the circumstances in which they are placed; and seldom are turned from their way, to follow the plan of any single projector. EVERY step and every movement of the multitude, even in what are termed enlightened ages, are made with equal blindness to the future; and nations stumble upon establishments, which are indeed the result of human action, but not the execution of any human design."

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