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Distance to the pre-industrial technological frontier and economic development

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Abstract This research explores the effects of distance to the pre-industrial technological frontiers on comparative economic development in the course of human history. It establishes theoretically and empirically that distance to the frontier had a persistent non-monotonic effect on a country's pre-industrial economic development. In particular, advancing a novel measure of the travel time to the technological frontiers, the analysis establishes a robust persistent U-shaped relation between distance to the frontier and pre-industrial economic development across countries. Moreover, it demonstrates that countries, which throughout the last two millennia were relatively more distant from these frontiers, have higher contemporary levels of innovation and entrepreneurial activity, suggesting that distance from the frontier may have fostered the emergence of a culture conducive to innovation, knowledge creation, and entrepreneurship.

Keywords Comparative development · Geographical distance · Culture and technology · Innovation · Technological diffusion and imitation · Patenting activity · Entrepreneurship

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1 Introduction

The origins of comparative economic development across the world has been one of the most fundamental research agendas in the social sciences. The literature on the subject has focused on deep determinants such as geographical, institutional, cultural and human characteristics (Diamond 1997; Acemoglu et al. 2001; Guiso et al. 2009; Alesina et al. 2013; Ashraf and Galor 2013; Galor and Özak 2016). In particular, given their adverse effect on trade and technological diffusion, geographical isolation and distances to the technological frontier have been widely viewed as fundamental sources of the prevailing inequality among countries (Smith 1776; Redding and Venables 2004; Feyrer 2009; Spolaore and Wacziarg 2009; Ashraf et al. 2010). This conventional view is based on the fundamental role trade plays in the diffusion of technology and in creating economies of scale in the contemporary era. However, given the limited scope of trade in the pre-industrial era, the conventional channels through which distance could have generated negative effects on productivity, may not have been significant.

This research explores the effects of distance to the pre-industrial technological frontiers on comparative economic development in the course of human history. It proposes that during the pre-industrial era, while a country's remoteness from the frontier diminished imitation, it fostered the emergence of a culture conducive to innovation, knowledge creation and entrepreneurship, which may have persisted into the modern era. The contribution of these cultural values to productivity have counteracted the adverse effect of distance from the frontier via diminished technological diffusion. Thus, the theory proposes that the interaction of these opposing forces resulted in a U-shaped relation between economic development and the distance to the frontier in the pre-industrial era.

In line with the predictions of the theory, the analysis establishes both theoretically and empirically that distance to the frontier had a persistent non-monotonic effect on a country's pre-industrial level of economic development. In particular, advancing a novel measure of the travel time to the technological frontiers, the analysis establishes a robust persistent U-shaped relation between distance to the frontier and pre-industrial economic development across countries. Moreover, it demonstrates that countries, which throughout the last two millennia were relatively more distant from these frontiers, have higher contemporary levels of innovation and entrepreneurial activity, suggesting that distance from the frontier may have fostered the emergence of a culture conducive to innovation, knowledge creation, and entrepreneurship.

The proposed theory suggests that variations across countries in distance to the pre-industrial technological frontier generated differences in incentives for technological imitation, adaptation and innovation, which culminated in differences in innovative and entrepreneurial culture. In particular, since during the pre-industrial era, the usefulness and transferability of technologies decreased with the distance from the technological frontier, distant countries benefitted less from imitation and had to tinker and toil more in order to adapt existing technologies to their own environment. Additionally, geographically distant countries also tended to be culturally different from the frontier, which may have facilitated the application of existing technologies to uses not discovered or intended by the original innovators. Finally, for some countries the process of technological diffusion from the frontier may have been too slow or costly, which may have promoted the generation of native innovations. Thus, these forces diminished the usefulness and availability of foreign technology and increased the incentives for native innovation that distant countries faced. While all countries might have been imitating, adapting and innovating, the degree to which each activity was pursued was affected by their geographical location with respect to the frontier. Moreover, as successive generations faced similar incentives, a process of intergenerational learning-by-doing in the creation of knowledge may have reinforced this pattern of specialization, facilitating the emergence of an innovative and entrepreneurial culture.

The proposed theory generates several testable predictions regarding the effect of distance to the pre-industrial technological frontier on economic development across countries. First, the theory predicts the existence of a U-shaped relation between the distance to the frontier and economic development across countries in the pre-industrial era. Specifically, the theory suggests that during the pre-industrial era, countries located at intermediate distances from the technological frontier were less developed than countries closer to or more distant from it, making these intermediate distances the Least Desirable Distances from the technological frontier. Second, the theory suggests that increases in a country's distance to the frontier (e.g., due to a change in the location of the frontier) should have positively impacted its level of economic development, especially among countries that were distant. Third, the theory predicts that the more time a country was farther than countries located at the bottom of the U-shape, i.e., at the More Desirable Distances, the longer it benefitted from its incentives to imitate, adapt and innovate. Thus, the cumulative time a country spent at these distances (across technological frontiers in the pre-industrial era) should be positively associated with its level of development. Finally, the theory suggests that the more time a country was remote from the frontier, the longer it experienced conditions that may have facilitated the emergence of an innovative and entrepreneurial culture. Thus, the cumulative time a country spent at the More Desirable Distances (across technological frontiers in the pre-industrial era) should be positively associated with its innovative and entrepreneurial activities in the contemporary era.

To explore these predictions empirically, the research introduces a novel measure of the pre-industrial geographic distance between countries and pre-industrial technological frontiers. For each country, this measure estimates the potential minimum travel time to the pre-industrial technological frontiers, accounting for human biological constraints, as well as geographical and technological factors that determined travel time before the widespread use of steam power. This strategy overcomes the potential mismeasurement of distances generated by using geodesic distances (Özak 2010), for a period when travel time was the most important determinant of transportation costs (O'Rourke and Williamson 2001). Additionally, it removes the potential concern that travel time to the frontier reflects a country's stage of development, mitigating further possible endogeneity concerns. The research validates these measures by (1) analyzing their association to actual historical travel time; (2) examining their explanatory power for the location of historical trade routes in the Old World; and (3) analyzing their association to genetic and cultural distances.

Consistent with the predictions of the theory, the empirical analysis establishes the existence of a robust U-shaped relation between the distance to the technological frontier and pre-industrial economic development across countries. Additionally, it establishes the positive effect of increases in a country's distance to the frontier (due to changes in the location of frontiers) on pre-industrial economic development across countries. Moreover, the analysis establishes that the length of time a country was relatively more distant from the frontiers is positively associated with its economic development as well as its contemporary domestic patenting and entrepreneurial activities.

The analysis establishes these results in various layers: (1) a cross-country analysis of the relation between the distance to the pre-industrial technological frontier and technological sophistication in 1500CE; (2) a cross-country panel-data analysis of the relation between the distance to the pre-industrial technological frontier and population density in the pre-industrial era; (3) a cross-country panel-data analysis of the relation between changes in the distance to the pre-industrial technological frontier and changes in population density in the pre-industrial era; (4) a cross-country panel-data analysis of the cumulative effect of distance from the pre-industrial technological frontier on population density in the pre-industrial era; (5) a cross-country analysis of the relation between the distance to the last pre-industrial technological frontier and contemporary technological sophistication and income per capita; (6) a cross-country analysis of the cumulative effect of distance from the pre-industrial technological frontier on contemporary income per capita; and (7) a cross-country analysis of the cumulative effect of distance from the pre-industrial technological frontier on contemporary patenting and entrepreneurial activities.

The analysis accounts for a wide range of potentially confounding geographical factors that might have directly and independently affected a country's economic development (e.g., elevation, area, malaria burden, share of area in tropical, subtropical or temperate zones, caloric suitability, latitude, island and landlocked regions). Moreover, unobserved geographical, cultural, and historical characteristics at the continental, regional or country level may have codetermined a country's level of economic development. Hence, the analysis accounts for these unobserved characteristics by accounting for continental, historical region, and when possible country and period fixed effects. Furthermore, it accounts for other time-varying pre-industrial country characteristics (e.g. change in caloric suitability due to the Columbian Exchange, colonial status, lagged technology levels, the onset of the Neolithic Revolution). Additionally, the analysis accounts for period-region fixed effects and thus for unobserved time-varying regional factors.

The analysis exploits variations in the location of the pre-industrial technological frontier in order to: (1) mitigate potential concerns relating to omitted country characteristics; (2) analyze the effects of increases in distance to the frontier on a country's development; and (3) explore the persistent and cumulative effect of distance from the frontier on a country's development. First, changes in the location of the pre-industrial technological frontier permit the analysis to account for country fixed effects, and thus for omitted time-invariant heterogeneity at the country-level. This allows the analysis to differentiate the effect of distance from the frontier from other unchanging characteristics of a country. Moreover, changes in a country's distance to the pre-industrial technological frontier across different time periods are potentially less endogenous when exploring their association with differences in development, especially after accounting for period, region and period-region fixed effects. Second, changes in the location of the pre-industrial technological frontier permit the analysis to explore the effects of increasing distance on development across countries. Thus, allowing alternative tests of the theory. Third, changes in the location of the pre-industrial technological frontier generated variations in the length of time countries were relatively remote from the frontiers. These variations permit the exploration of the cumulative and persistent effect of distance from the frontier on economic development across countries.

This research is the first attempt to analyze the effects of the geographical distance from the pre-industrial technological frontier on economic development. In doing so, it contributes to various literatures. First, it contributes to the literature on the effects of distance on development (Redding and Venables 2002; Feyrer 2009; Spolaore and Wacziarg 2009; Ashraf et al. 2010; Puga and Trefler 2010). This literature has focused mainly on the effects of distance on contemporary levels of trade and development across countries. An exception is Ashraf et al. (2010), which examined the impact of a country's prehistoric degree of isolation (i.e., its average isolation level from all locations in a continental mass prior to the advent of seafaring and airborne transportation technologies) on its economic development. Their cross-country analysis finds a positive relation between their measure of prehistoric isolation and population density in the years 1, 1000, 1500CE, and GDP per capita in 2000CE. In contrast, this research explores the effect of distance to the technological frontier during the pre-industrial era (i.e., after the introduction of seafaring technologies) on pre-industrial and contemporary economic development across countries. It is the first to establish the persistent U-shaped relation between distance to the frontier and development. Moreover, it provides evidence for a novel channel through which these pre-industrial distances may have had persistent effects on a country's development. In particular, it presents novel evidence on the persistent effect of pre-industrial distances on contemporary innovative and entrepreneurial activities.

Second, the research contributes to the literature on the determinants of entrepreneurship (Knight 1921; Schumpeter 1934; Hwang and Powell 2005; Guiso et al. 2015), which has stressed the role of personal traits as well as the cultural and institutional environment in the prevalence of an entrepreneurial spirit. In contrast, this paper sheds light on a deep historical determinant of innovative and entrepreneurial activities. Finally, the research sheds additional light on the geographical origins of comparative development (Diamond 1997; Gallup et al. 1999; Ashraf and Galor 2013; Galor and Özak 2016). Specifically, it provides novel evidence of the changing effects of geography in the course of economic development (Andersen et al. 2016) and suggests a novel geographical determinant of cultural and institutional differences and their persistent effect on economic development (Giuliano et al. 2006; Alesina et al. 2013; Galor and Özak 2016).

The rest of the paper is structured as follows: Section 2 presents anecdotal evidence supporting the proposed theory. Section 3 rationalizes the theory using an overlapping generations model and establishes the existence of a U-shaped relation between distance and economic development. Section 4 presents the data and the empirical strategy. Section 5 presents the empirical analysis for the pre-industrial era. Section 6 analyzes the persistent effect of distance from the frontier on contemporary economic development. Section 7 concludes. All additional supporting material is presented in the Appendix.

2 Anecdotal evidence

This section presents anecdotal evidence for the pre-industrial era that shows (1) the limited role trade could play in technological diffusion before 1850, (2) the importance of human mobility in technological diffusion, (3) the difficulty of technological diffusion across space, (4) the intertemporal links in the imitation and creation of technology, and (5) examples supporting the theory.

2.1 Importance of trade

Although trade plays a crucial role in the process of economic development in the modern era, historically its role seems to be more restricted, as high transportation costs during the pre-industrial era limited the amount and type of trade being conducted. For example, Maddison (1995) estimates that by 1820 world trade represented only 1% of world GDP. Clearly, trade in technological goods represented an even smaller share, especially since technologies embodied in goods were difficult to transport, as in the case of heavy machinery (e.g. clocks, steam engines, furnaces). Case in point, during its first 25 years of operation, the Boulton and Watt Co. constructed less than one additional steam engine per year in order to fulfill international orders, which represented 4% of their total sales during the period 1775–1800 (Tann 1978). These low trade volumes in the pre-industrial era suggest that the indirect gains from trade via learning-by-doing or the direct gains from trade in technology were small before 1850.

Furthermore, many technologies could not be embodied in tradable goods (e.g. canal systems, water mills, three-field rotation system, husbandry rules), or required access to tacit knowledge in order to produce them (Robinson 1974; Epstein 2006; Jones 2009). For example, Boulton and Watt had recurring problems securing the services of engineers or skilled mechanics who could travel and install their steam engines overseas (Tann 1978). To these impediments one must add any kind of state intervention, which forbade the trade in technologies considered fundamental to national security or for the comparative advantage of the nation (Jeremy 1977). British laws prohibiting the export of machinery and travel of skilled technicians during the eighteenth and nineteenth centuries, as well as the current embargo on the trade in nuclear weapons, technology, and knowledge, are examples of these types of measures.[1]

2.2 Transferability across space and time

Under such circumstances, most technologies had to be invented in situ or imported, not directly through the goods that embodied them, but indirectly through the people who knew the technology. For instance, Epstein (2006) after establishing that neither texts nor patents played a major role in technological diffusion in premodern times, argues that "[i]n practice, technological transfer could only be successfully achieved through human mobility". Mokyr (1990) highlights the importance of master-and-apprentice and father-and-son dynasties in the diffusion of technology, especially in the machine and engineering sector:

> From Nuremberg and Augsburg the art of instrumentmaking spread to Louvain in the southern Netherlands and from there to London. The London instrumentmaker Humfray Cole was apprenticed to the Liége craftsman Thomas Gemini. […] Gemini himself had studied in the south of Germany. […] Another German instrumentmaker, Nicholas Kratzer, lived in England for many years (Mokyr 1990, p. 71, fn. 9).

Similarly, Justus von Liebig, the German chemist whose innovations and book on organic chemistry gave birth to the fertilizer industry, studied in Paris under Joseph Louis Gay-Lussac. In turn von Liebig was the professor of August von Hoffman, who moved temporarily to London in order to head the creation of the Royal College of Chemistry and taught there for about 20 years before returning to Germany, teaching the first generation of professionally trained English chemists. Another example is Leonardo Pisano, more commonly known as Fibonacci, who learned mathematics from the Arabs as a boy during his father's trade missions in North Africa, and later introduced Europe to the use of algebra.[2]

[1] Furthermore, during the pre-industrial era most trade was based on goods that could not be produced locally due to agro-climatic, environmental or geological constraints.

[2] This last example exemplifies how trade's effect on the diffusion of innovation could be related more to the transmission of information than to the transmission of goods. Pacey (1990, p. vii) holds a similar view and offers as an example the Indian textile industry, "which had a profound influence in Britain during the Industrial Revolution even though there were few 'transfers' of technology. Just the knowledge that Indians could spin fine cotton yarns, weave delicate fabrics, and dye them with bright and fast colours stimulated British inventors to devise new ways of achieving these same results". Another role trade can play is in creating incentives to adopt certain technologies or to invest in certain types of capital which are conducive to economic development.

Besides the formal networks of scientists and apprentices, the dispersion of technologies was based also on the work of businessmen, merchants, diplomats, and spies, who many times were sent or travelled by their own initiative to the technological frontier in order to gain access to the most advanced products, ideas, processes, and the skilled workers who knew them (Robinson 1958, 1974; Mokyr 1990; Epstein 2006; Jones 2009). For example, Robinson (1958) notes that

> Eighteenth-century industry was conducted in an atmosphere of secrecy. The newspapers of Manchester, Birmingham and other industrial centres, during the seventeen-seventies and 'eighties, contain frequent references to foreign spies who were snooping in factories and warehouses to learn the trade secrets of the area and to entice away the workmen who knew them. Committees were formed to protect these trade secrets by warning the locality about foreigners and by enforcing the various acts against the exportation of tools and the enticing of artisans abroad, so that every manufacturer became spy-conscious and perhaps more deliberately secretive than he already was. (Robinson 1958, p. 3)

Similarly, in 1789, after a notorious spy was caught exporting drawings, plans and objects of industrial interest, the Birmingham industrialist, Samuel Garbett, complained to Matthew Boulton, Watt's partner, that

> [o]ur country [UK] is certainly considered as a School of the Arts and that great improvements in Manufacture are originating here. And it seems We are a common plunder for all who will take the trouble of coming here. And our Magazine of Secrets at the Patent Office is exposed to all Foreigners (Robinson 1974, p. 91).

These examples highlight the two central dimensions through which technology was accumulated, which are central to the mechanism highlighted in this paper. First, technology moved across space, from advanced to less advanced regions, by means of the people who travelled to the first, learning and copying the technology there, and bringing it back to the latter. Second, across time, between generations of innovators, fathers and sons, masters and apprentices.

Clearly the movement along the first dimension is easier the closer the two regions are geographically or culturally. For example, it was easier for Francis Cabott Lowell to visit the textile mills in Lancashire in 1810 and appropriate the new techniques, which would revolutionize manufacturing in the U.S., than it would have been to do so for the contemporaries of Willem Van Ruysbroeck in thirteenth century Mongolia, Marco Polo in thirteenth century China, Rabban bar Sauma in thirteenth century Europe or Matteo Ricci in sixteenth century China.[3]

Additionally, if the technology is not generally applicable across space, or requires modification in order to be useful in different locations and environments, the diffusion across space will be facilitated by the proximity to the frontier, requiring less tinkering and toiling in order to adapt the technology to its new location. For instance, the diffusion of the "new husbandry" in the Middle Ages was slowed by these differences, in part because "[d]ifferent

[3] Although the motives behind their voyages varied, and so did the circumstances with which they were received, it is clear that Lowell's endeavor was facilitated by him sharing a common language, customs, and religion with his hosts. On the other hand, the difficulties, the hostility, and general lack of trust with which these emissaries and ambassadors were received, gives an idea of how difficult the situation might have been for foreigners lacking their credentials. Van Ruybroeck, also known as Rubruquis, tells of how, in the beginning of his voyage, his guide distrusted him, and how at their arrival at Kûblâi Khân's court, his guide was well received and offered proper accommodations, while the friar and his companions were given a small hut, and they "were called and closely questioned as to the business which had brought" them there [van Ruysbroek 1900, pp. 166–167; Polo 1858, pp. 66–67]. Marco Polo notes that the people of Maabar distrust sailors [Polo 1858, p. 263; Beazley 1906, p. 138]. Similarly, Rabban bar Sauma, a Christian envoy of the Mongols, was initially treated as a heretic upon his arrival to Rome (Budge 1928, pp. 56–63).

crops have different requirements, and the same crop will use different inputs and technology depending on elevation, rainfall, soil type, and so on" (Mokyr 1990, p. 32).

Similarly, agricultural techniques, windmills, waterwheels, among other machines, required adaptation in order to work in different locations.[4] Jones (2009) mentions the impressions made by the visit of a skilled Welsh ironmaster to Tarnowitz in 1786 on the Prussian Commissioner for Affairs of War, Taxation, Mining and Factories, who concluded that "some ideas were made active in Silesia, old ones improved, some implemented in part, insofar as the differing location of German industry as compared to that of England permits". Similarly, the diffusion of the Bessemer and Siemens-Martin processes of steel production encountered many problems given that they could only be used with phosphorous-free iron ores, which were not abundant (Mokyr 1990). Also, Epstein (2006) mentions the problems of applying the structural theory for Gothic churches across regions in Europe, as well as other techniques, noting the difficulty of transferring "recipes", adding that "recipes, as opposed to machines, were hard to transfer, because their result depended critically on a combination of material ingredients, and atmospheric and other conditions that could not be easily controlled for, and thus, easily reproduced" (p. 23).

2.3 The mechanism and examples

Thus, distance to the technological frontier decreases the diffusion of technology across space by making it more difficult for people to move between their home location and the frontier, and by limiting the usefulness of the acquired knowledge and technology. At the same time, this lower usefulness demands additional innovative work in order to adapt the technologies to local conditions (Mokyr 1990; Epstein 2006; Immelt et al. 2009). So, a greater distance to the frontier decreases the offer of directly applicable technologies, but simultaneously increases the innovative effort of the distant receiving society. Additionally, a larger distance to the frontier, which increases the cultural distance to the frontier, expands the possible new uses of any given technology (Ehret 2002), resulting in more innovation in distant locations.

Moreover, for far enough locations it might be more economical to create the technology at those locations than to go through the process of imitation and adaptation. Thus, one can expect to observe independent innovation in multiple geographical locations, contrary to the diffusionist view (Blaut 1987, 2012). In particular, this process can potentially increase the innovativeness of distant economies, allowing them to accumulate skills and technology across time. Since the transmission of skills and technologies within a location is easier than across space, and also more efficient and effective the more experienced the master or elder is (Epstein 2006), the increased demand for innovative effort in distant locations may be accompanied by an improved intergenerational transmission of skills and technology.

All this is conducive to the independent and persistent creation of technologies and innovativeness in locations distant from the technological frontier. Case in point, the Old and New Worlds were mostly incommunicated between the last ice age and the modern discovery voyages, but in both landmasses people independently discovered agriculture and domestication (Diamond 1997), the compass (Carlson 1975), and the number zero (Kaplan 2000), among others. Similarly, research on African medicine has found that kingdoms, like the Bunyoro–Kitara in Uganda, which were isolated from the rest of the world until around the eighteenth century, had discovered the use of the Caesarean section and variolation through inoculation, among other medical technologies (Felkin 1884; Davies 1959; Dunn 1999). Moreover, distant cultures like the kingdoms of Mapungubwe and Great Zimbabwe were some of the

[4] Bazzi et al. (2016) present evidence that the problem of transferability across space in the agricultural sector is still prevalent in the modern period in developing countries.

most complex societies in Africa (Huffman 2009). Additionally, ethno-mathematicians have shown that some pre-colonial African and Amerindian cultures had advanced (native) mathematical knowledge in areas like congruences, boolean algebra, fractals, topology, graph theory, etc. (Zaslavsky 1999; Ascher 1991, 2002; Bangura and Bangura 2011; Selin 2003).[5] Similarly, many ancient Chinese mathematical innovations and results, like solutions to linear, quadratic and cubic equations, Horner's method and Descartes' rule of signs, were much later rediscovered in Europe (Smoryński 2008; Needham and Wang 2008; Joseph 2011).

Further evidence can be found in the improvement of non-native technologies. For example, around the year 1CE African iron-smelting, which had been introduced from the eastern Mediterranean around 500BCE, was technologically superior to European, Middle Eastern, and South Asian smelting techniques (Austen and Headrick 1983).[6] Analogously, the windmill, which had been invented in central Asia and imported to Europe by its contact with the technologically advanced Islamic world, was developed and attained its state of perfection in the Netherlands (Mokyr 1990). These last two examples defy conventional wisdom since it is in locations far away from the technological frontier and from the source of original innovation where these technologies attained their highest expression. Similarly, Great Britain's location made it one of the most distant places relative to the technological frontiers in the Old World until about the fourteenth century, when the "English had long been known as the perfecters of other people's ideas […]", to which "[a] Swiss calico painter remarked in 1766 of the English: 'they cannot boast of many inventions, but only of having perfected the inventions of others […]" (Mokyr 1990, p. 240). Finally, Nicholas (2011), Choi (2011), and Hashino (2012) have recently shown that local innovation played a mayor role in Japan's industrialization process during the twentieth century.

3 A model of technology imitation and creation

This section introduces a model that generates a U-shaped relation between the distance to the technological frontiers and economic development.[7] The model embeds the main elements of the proposed theory and of the historical evidence in a fairly standard overlapping generations model. The main features of the model are (1) the presence of imitation, adaptation and innovation processes, (2) the presence of negative spatial spillovers in the process of imitation, and (3) the presence of positive (sector specific) intertemporal spillovers in the processes of imitation, adaptation and innovation. The presence of negative spatial spillovers in the process of imitation, which captures the loss of functionality of pre-industrial technologies when moved across space, captures the essential force highlighted by conventional wisdom. Without it, there would not exist spatial variations in economic development in the model or economic development would otherwise be positively associated with the distance from the technological frontier. Similarly, the presence of positive intertemporal spillovers due to learning-by-doing or learning-by-watching in the processes of adaptation and innovation, which have characterized these processes during the pre-industrial and contemporary eras, play a fundamental role in the emergence of the U-shape. Without these positive spillovers,

[5] It is interesting to note that some of this knowledge is being currently used to understand modern mathematical problems. For example, the mathematical ideas inherent in the kola designs of the Tamil Nadu in southern India have influenced the development of modern computer science theory (Katz 2003). See also Selin (1997) and Joseph (2011).

[6] There still exists a debate among archeologists about the possibility of an independent discovery of iron smelting in Sub-saharan Africa (Ehret 2002), which would provide even stronger support to this paper's theory.

[7] Appendix C presents all the proofs and intermediate steps.

although larger distances would generate a reallocation of resources from imitation to innovation, the additional innovation would not be enough to counteract the negative effects of the spatial spillover. On the other hand, if the positive intertemporal spillovers in adaptation and innovation are sufficiently strong, especially stronger than any potential positive intertemporal spillovers in imitation, then a U-shaped relation between the distance to the technological frontier and economic development may exist.

3.1 Setup

The world consists of a set of economies $\mathcal{E} \subseteq \mathbb{R}^n$ and n technological leaders. Assume that all economies in $\mathcal{E}$ are identical except for their geographical distance $\mathbf{d} = (d_1, \ldots, d_n)$ from these leaders, and thus identify each economy with this distance vector $\mathbf{d}$. Each economy $\mathbf{d} \in \mathcal{E}$, is populated by overlapping generations of two-period lived individuals. Population is constant and is normalized so that its size is 1. Each individual is endowed with one unit of time when young and one unit of time when old. For simplicity, assume that young individuals can only engage in activities of imitation or creation of technology, and do not engage in consumption. On the other hand, old individuals can only engage in production and consumption activities, where their production possibilities are determined by their own technology, which is generated by their decisions when young and the technology inherited from their parents.[8] Under these assumptions the individual's only meaningful economic decision is how to allocate her labor when young between innovation and imitation from the n technological frontiers in order to maximize the growth rate of technology. Thus, to simplify notation, denote by the subscript t all variables corresponding to individuals born in $t-1$ who will be old in period t.

An individual born in period $t-1$ inherits a level of technology A_{t-1} from her parents. She increases her stock of technology, which will be available for production in period t, using two types of intermediate activities. In particular, she produces an intermediate input, $\tilde{I}$, by imitation from the technological frontiers, and a second one, $\tilde{R}$, through independent creation. Her productivity in each activity depends not only on the amount of labor she allocates to it, but also on sector specific intertemporal spillovers due to learning-by-doing or learning-by-watching in imitation and creation of technologies by her ancestors. Importantly, the individual does not take into account the effect of her own allocations on the sector specific productivities of her descendants. In particular, let l_t denote the amount of labor she allocates to independent creation and i_{jt} denote the amount of time she allocates to imitating from frontier j, so that, $\sum_j i_{jt} = 1 - l_t$. Additionally, denote by $\mathbf{l_t} = (l_t, l_{t-1}, \ldots)$ and $\mathbf{i_{jt}} = (i_{jt}, i_{jt-1}, \ldots)$ the history of allocations up to generation t. She produces a quantity $\tilde{R}_t = aS_R l_t^\alpha A_{t-1}$ of independent knowledge, where $a > 0$, $\alpha \in (0, 1)$ and $S_R = S_R(\mathbf{l_{t-1}})$ captures the positive intertemporal spillovers in innovation. She devotes the rest of her time, $(1 - l_t)$, to creating intermediate knowledge through imitation from the frontiers. Assume that the intermediate knowledge from each frontier is generated using similar technologies, namely

$$\tilde{I}_{jt} = b(d_j) S_{Ij} i_{jt}^\beta A_{t-1}, \quad j = 1, \ldots, n \tag{1}$$

[8] These assumptions are made for convenience and in order to simplify the analysis. Changing them would not alter the main qualitative results since the underlying mechanism does not depend on them. For example, one could allow young individuals to produce and consume, or old individuals to engage in additional research activities, without affecting the main results. Additionally, allowing for endogenous population growth in a Malthusian framework would generate similar results.

where $\beta \in (0, 1)$, the function $b : \mathbb{R}_+ \to \mathbb{R}_{++}$ is continuous, decreasing, twice differentiable. $b(d_j)$ captures the negative effect of distance on the productivity of imitation, while $S_{Ij} = S_{Ij}(\mathbf{i_{jt-1}})$ captures the positive intertemporal spillovers in imitation from frontier j. She combines the intermediate knowledge she gained from the frontiers through a constant elasticity of substitution production function to produce her aggregate knowledge from imitation

$$\tilde{I}_t = \left(\sum_{j=1}^{n} \lambda_{2j} \tilde{I}_{jt}^{\rho_2} \right)^{\frac{1}{\rho_2}} \tag{2}$$

where $\sum_{j=1}^{n} \lambda_{2j} = 1$, $\lambda_{2j} \in [0, 1]$, $0 < \rho_2 \equiv \frac{\eta_2 - 1}{\eta_2} < 1$, and η_2 is the constant elasticity of substitution of knowledge between any two frontiers. The new knowledge she gains from imitation and independent creation are aggregated through another constant elasticity of substitution production function to produce total new knowledge, which is added to her existing stock of technology. Letting $R_t = \tilde{R}_t / A_{t-1}$ and $I_t = \tilde{I}_t / A_{t-1}$, the growth rate of technology can be written as

$$g_t = \frac{A_t - A_{t-1}}{A_{t-1}} = \left[\lambda_1 R_t^{\rho_1} + (1 - \lambda_1) I_t^{\rho_1} \right]^{\frac{1}{\rho_1}}, \tag{3}$$

where $\lambda_1 \in (0, 1)$, $0 < \rho_1 \equiv \frac{\eta_1 - 1}{\eta_1} < 1$, and η_1 is the constant elasticity of substitution between imitation and creation. Let $u(c_t)$, be the utility an individual born in period $t - 1$ derives from consumption, where $u'(c) > 0$, $u''(c) < 0$. She chooses $l_t \in [0, 1]$ and $i_{jt} \in [0, 1]$ for $j = 1, \ldots, n$, in order to maximize her lifetime expected utility, i.e. she solves the following problem

$$\max_{(l_t, (i_{jt})_{j=1}^{n}) \in [0,1]^{n+1}} \quad u(c_t) \quad \text{subject to} \quad c_t = (1 + g_t) A_{t-1}, \; l_t + \sum_{j=1}^{n} i_{jt} = 1, \tag{4}$$

which amounts to maximizing the growth rate g_t.

From the individual's point of view, the only difference between frontiers is their distance, so, in order to maximize her lifetime expected utility, her time allocations when young, l_t and $\{i_{jt}\}_{j=1}^{n}$, have to equalize the marginal product of labor across sectors. Importantly, increasing the distance d_j lowers the marginal product of labor in imitation from frontier j, without affecting the marginal productivity of labor in any other activity. Thus, increases in d_j generate a reallocation from imitation from j to all other activities, including innovation. This reallocation process lies at the heart of the mechanism highlighted in this paper.

Furthermore, the sector specific intertemporal spillovers play an essential role in the effects of this reallocation across sectors in the model. In particular, without them the steady state growth rate of the economy would be a decreasing function of distance. To see this, notice that the growth rate can be rewritten as a strictly concave function of the labor allocation in innovation l_t, so that the optimal growth rate in a steady state is $g(l^*(d), d) \equiv g^*(d)$. Without any sector specific intertemporal spillovers, the envelope theorem implies that $g'^*(d) = g_d < 0$, where g_d is the partial derivative of the growth rate with respect to distance. Thus, without spillovers, the model would predict that distance has a negative monotonic relation with development as in the conventional wisdom. On the other hand, if the sector specific intertemporal spillovers are present, then $g'^*(d) = g_{S_R} + g_{S_I} + g_d \lesseqgtr 0$, where g_{S_R} and g_{S_I} are the effects of the spillovers on the growth rate. This opens up the possibility for the emergence of a U-shape in the steady state, depending on the signs and relative sizes of g_{S_R} and g_{S_I}.

In order to simplify the analysis, assume that the sector specific intertemporal spillovers due to learning-by-doing, $S_R(\mathbf{l_{t-1}})$ and $\left\{S_{Ij}(\mathbf{i_{jt-1}})\right\}_{j=1}^{n}$, are continuous, bounded, differentiable and concave functions of its elements, and satisfy the following property: for any steady state allocations $\mathbf{l} = (l, l, \ldots)$ and $\mathbf{i_j} = (i_j, i_j, \ldots)$, $j = 1, \ldots, n$, $S_R(\mathbf{l}) \propto l^{\alpha'}$ and $S_{Ij}(\mathbf{i_j}) \propto i_j^{\beta'}$, where $\alpha', \beta' \in (0, 1]$. I.e., in a steady state the intertemporal sector specific spillovers are proportional to a concave function of the steady state allocation in each sector.[9]

The steady state growth rate of economy $\mathbf{d}$ generated by the individual's optimal decisions is given by[10]

$$g^*(\mathbf{d}, \lambda_2) = R^*(\mathbf{d}, \lambda_2)\left[\lambda_1 + (1-\lambda_1)\left(\frac{I}{R}(\mathbf{d}, \lambda_2)\right)^{\rho_1}\right]^{\frac{1}{\rho_1}}, \tag{5}$$

where $\lambda_2 = (\lambda_{2j})_{j=1}^{n}$, and $R^*(\mathbf{d}, \lambda_2)$ and $I/R(\mathbf{d}, \lambda_2)$ are the optimal levels of imitation and of the ratio of imitation to creation. Furthermore, the first factor is increasing and the second one is decreasing in all the components of $\mathbf{d}$. This implies, in particular, that increasing the distance to frontier j, d_j, increases the amount of creation while lowering the aggregate amount of imitation. As shown below, this trade-off, which is caused by individual's desire to equalize the marginal product of labor, can generate under some conditions a U-shape in the level of development.

3.2 Steady-state growth in a world with a unique frontier

Clearly, economies that are equidistant from all frontiers, effectively only have one frontier. Thus, individuals in these economies behave as if they lived in a world with a unique frontier. For these economies, $\mathbf{d} = d \cdot \mathbf{e}$ and $g^*(\mathbf{d}, \lambda_2) = G(d)$, where $\mathbf{e}$ is the n dimensional vector of ones, $d \in \mathbb{R}_+$, and $G(d)$ is the steady state growth rate for an economy at distance d in a world with a unique frontier. Assume that

$$(\alpha' + \alpha)\rho_1 < 1, \qquad (\beta' + \beta)\rho_1 < 1, \tag{ES}$$

$$\frac{\rho_1 \beta\left[\frac{\alpha'}{\alpha} - \frac{\beta'}{\beta}\right]x}{\big(1 - (\alpha' + \alpha)\rho_1\big)(1 - x) + \big(1 - (\beta' + \beta)\rho_1\big)x} = 1 \text{ for some } x \in (0, 1). \tag{U}$$

Condition (ES) ensures that in a steady state the marginal productivity of labor of young and old individuals is "jointly" decreasing in the production of intermediate products. Condition (U) gives a measure of the strength of intertemporal spillovers across sectors, and imposes limits on the differences in labor productivities across them. Clearly, $\alpha'/\alpha > \beta'/\beta$ is a necessary condition for (U) to hold, which implies intertemporal spillovers are stronger in creation than imitation. Additionally, it implies that if in the production of each intermediate input the same quantities of current and past labor are used, then the marginal rate of technical substitution between current and past labor is larger in I than in R. So, as the distance d increases, the lower productivity of labor in imitation generates a substitution out of imitation

9 The following functions satisfy these conditions: (1) $S(\mathbf{x_{t-1}}) = x_{t-1}^{\beta'}$, (2) $S(\mathbf{x_{t-1}}) = \lim_{T\to\infty} \frac{1}{T} \sum_{\tau=0}^{T} x_{t-1-\tau}^{\beta'}$, (3) $S(\mathbf{x_{t-1}}) = (\lim_{T\to\infty} \frac{1}{T} \sum_{\tau=0}^{T} x_{t-1-\tau})^{\beta'}$, (4) $S(\mathbf{x_{t-1}}) = \sum_{\tau=0}^{\infty} \delta^\tau x_{t-1-\tau}^{\beta'}$, and (5) $S(\mathbf{x_{t-1}}) = (\sum_{\tau=0}^{\infty} \delta^\tau x_{t-1-\tau})^{\beta'}$. Clearly, these are not the only functions that satisfy these conditions, but they are commonly used in the literature.

10 See Appendix C for the proof.

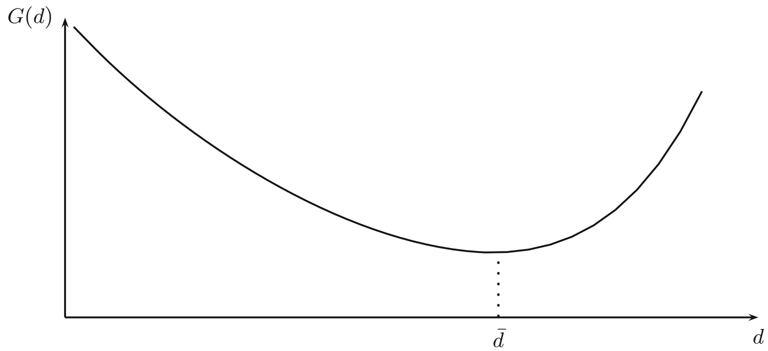


Fig. 1 The steady state relationship between distance and economic growth in a world with one frontier

and into research. Under these assumptions, in a world with a unique frontier, $G(d)$ is U-shaped with the lowest growth rate attained at the *Least Desirable Distance* $\bar{d} > 0$.[11] Figure 1 depicts the relation between distance d and steady state growth rates in a world with a unique frontier.

3.3 Steady-state growth in a world with a many frontiers

Since any $d \in \mathbb{R}_+$ can be written as $d = \bar{d} + z$, for some $z \in \mathbb{R}$, the previous result implies that in a world with n frontiers, the growth rate of equidistant economies is given by $g^*\Big((\bar{d}+z)\cdot \mathbf{e}, \lambda_{\mathbf{2}}\Big) = G(\bar{d}+z)$, so that the growth rate for these economies is also U-shaped. Also, since the set of economies $\mathcal{E}$ in the world can be partitioned by the z-isogrowth sets

$$D(\lambda_{\mathbf{2}}, z) = \left\{\mathbf{d} \in \mathcal{E} \mid g^*(\mathbf{d}, \lambda_{\mathbf{2}}) = G(\bar{d}+z)\right\}, \tag{6}$$

which is the set of economies that grow at rate $G(\bar{d}+z)$, a similar non-monotonicity holds for all other economies as well (see Appendix C). These results imply that the steady state profile of growth rates looks like a valley with the economies belonging to $D(\lambda_{\mathbf{2}}, 0)$ at its bottom. Figure 2 depicts two general isogrowth maps in a world with two frontiers when (a) $b(d)$ is convex or (b) $b(d)$ is concave. Clearly, the shape and direction of the valley will depend on the functional forms and parametrization chosen. For example, for the CES functions above, Fig. 3 plots the $g(\mathbf{d}, \lambda_{\mathbf{2}})$ and $G(\bar{d}+z)$ functions for an artificial economy in which $b(d) = b_0 e^{-b_1 d}$. The distance $\bar{d}$ is the least desirable distance (LDD) from the technological frontiers and is located where the 45-degree line intersects $D(\lambda_{\mathbf{2}}, 0)$.

Notice that the non-monotonicity does not imply that being far from the frontiers *always* increases the growth rate. On the contrary, it only implies that there must exist economies which are farther from the frontiers and have higher growth rates than others which are closer to them. Furthermore, conventional wisdom can be seen as a special case of this theory in which either (1) $\bar{d} = \infty$, so that $D(\lambda_{\mathbf{2}}, z) = \emptyset$ for all $z \geq 0$, or (2) the observable world is too small, so that $D(\lambda_{\mathbf{2}}, 0)$ is not observable. In either case, any empirical analysis would find a monotonic relation between distance and development.

[11] See Appendix D for the proof.

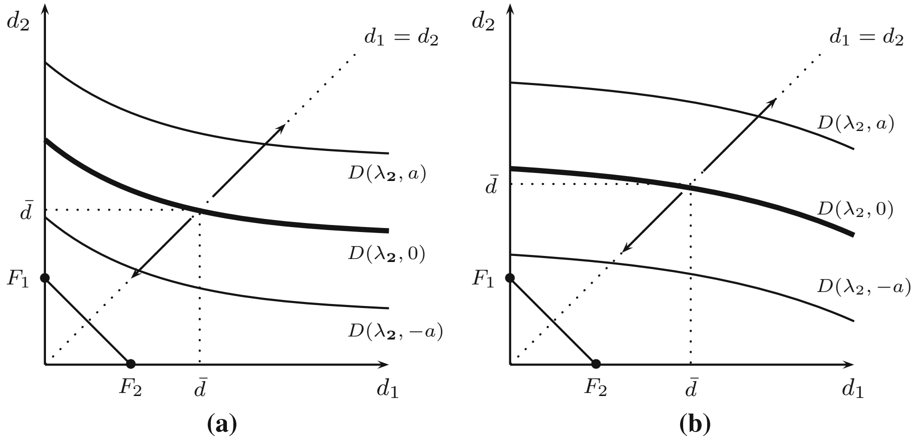


Fig. 2 Isogrowth maps in a world with two frontiers. These figure depict the isogrowth maps in a world with two frontiers. F_1 and F_2 denote the locations of frontiers 1 and 2, which are at a distance d_{12} from each other. Every point (d_1, d_2), which does not belong to the triangle generated by the frontiers and the origin, represents an economy located at a distance d_1 from frontier 1 and d_2 from frontier 2. Every isogrowth curve $D(\lambda_2, a)$ represents the set of economies that have the same growth rate. $D(\lambda_2, 0)$ is the set of economies that have the lowest growth rate. The arrows show the direction of increase in the growth rate. **a** Convex $b(d)$, **b** concave $b(d)$

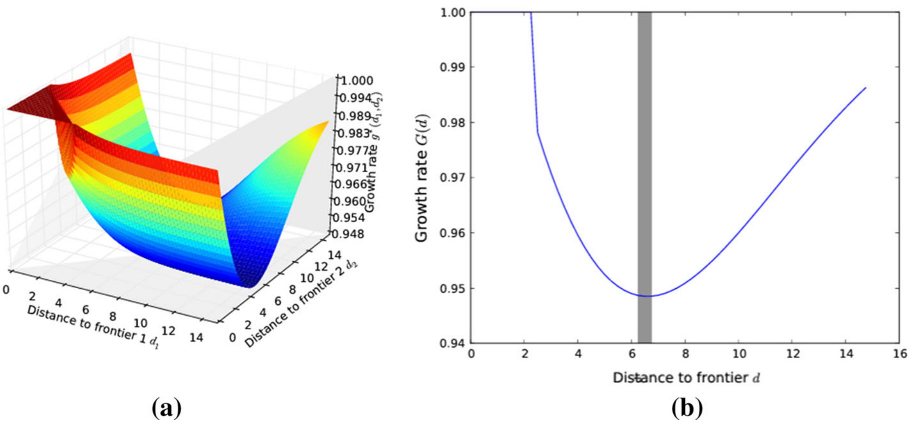


Fig. 3 Artificial world with two frontiers. **a** Steady state growth rates for all economies. **b** Steady state growth rates for equidistant economies or a world with only one frontier. Least Desirable Distance $\bar{d}$ in gray

3.4 Testable predictions

The previous analysis suggests that if the theory proposed in this paper is valid, then for at least one frontier j the Least Desirable Distance, LDD_j, is positive, statistically significant, and smaller than the maximum distance to frontier j in the sample. In particular, if all frontiers are identical and so the model is fully symmetric, there should exist a U-shaped relation with respect to the distance to each one of them, as depicted in Fig. 3a. Clearly, any asymmetry due to differences in the way frontiers affect imitation, may cause the U-shape with respect to some frontier to not be identifiable.[12] On the other hand, if conventional wisdom holds, then for all frontiers $j = 1, \ldots, n$, the estimated LDD_j lies outside the sample and is statistically insignificant, i.e. $LDD_j = \infty$.

These predictions and Monte Carlo simulations presented in Appendix E suggest using the following empirical specification to explore the relation between economic development and the distance to the technological frontier during the pre-industrial era across countries:

$$y_{it} = \beta_0 + \sum_{j=1}^{n} (\beta_{1j} d_{ijt} + \beta_{2j} d_{ijt}^2) + \gamma' x_{it} + \epsilon_{it} \tag{7}$$

where for each country i, y_{it} is its level of economic development in period t, d_{ijt} is its distance to the jth pre-industrial technological frontier in period t, x_{it} are other covariates in period t, and ϵ_{it} is an error term. The proposed theory implies that for at least one frontier j $\beta_{1j} < 0$, $\beta_{2j} > 0$, and the implied Least Desirable Distance ($LDD_j = -0.5\beta_{1j}/\beta_{2j}$) is positive, statistically significant, and smaller than the maximum distance to frontier j in the sample of countries.

Monte Carlo simulations (Appendix E) suggest that this empirical specification tends to over-reject the proposed theory. In particular, using simulations, the analysis finds that in artificial economies in which the theory proposed in this paper is true, the estimation might not be able to capture this non-monotonic relation. Specifically, this test tends to over-reject the null hypothesis of the existence of a non-monotonicity. Thus, the presence of a non-monotonicity in the estimation is strong suggestive evidence that the underlying relation is non-monotonic.

Additionally, a corollary of the theory suggests that countries that are located farther than the Least Desirable Distance (LDD) at the More Desirable Distances (MDD) should be more developed. This in turn implies that if the location of the frontier changes exogenously, the more time an economy spends at the MDD (across technological frontiers), the more developed it should be. Furthermore, the theory suggests that remote economies, which become even more remote after the change in the location of a frontier should get a boost in their economic performance.

4 Data and empirical strategy

This section develops the empirical strategy and describes the data used to explore the existence of a U-shaped relation between the pre-industrial distance to the technological frontier and economic development across countries.

[12] Symmetry conditions need not hold for all frontiers since imitation from different frontiers can be affected by linguistic, cultural, institutional or geographical differences. In particular, it can be shown that variations in the parameters of the model, e.g. $\lambda_{\mathbf{2}}$ or ρ_2, can disrupt the symmetry of the model and cause estimates not to find a U-shaped effect on development of the distance from certain frontiers. For example, consider the case when $\lambda_{2j} \rightarrow 0$ for some j. In this case, the effect of the distance to such a frontier will tend to appear monotonic. Additionally, as suggested in Appendix E, even in a symmetric world randomness and sample composition can cause asymmetries in the estimates. Reassuringly, simulations suggest that if the empirical analysis finds at least one frontier with an LDD estimate that satisfies this condition, then with high probability the non-monotonicity exists.

4.1 Empirical strategy

The analysis surmounts significant hurdles in the exploration of the relation between pre-industrial distance to the technological frontier and economic development across countries. First, the results may be biased due to potential measurement error in historical data on economic development. In order to mitigate this concern, the analysis explores the relation using different measures of economic development for the pre-industrial era. In particular, the research explores the relation using the level of technological sophistication in 1500CE and also population density levels for the years 1CE, 1000CE, 1500CE and 1800CE. This allows it to analyze the relation in data constructed from independent sources, over different samples, minimizing the potential effects of mismeasurement and sample selection on the analysis. Additionally, it permits the analysis to exploit cross-country and cross-period variation to explore the non-monotonic effect of distance to the frontier.

Second, the results may be biased by omitted geographical, institutional, cultural, or human characteristics of countries that might have determined their economic development and are correlated with their pre-industrial distance to the technological frontier. This research employs various strategies to mitigate this potential concern. In particular, the analysis accounts for a large set of possible confounding geographical characteristics (e.g., elevation, area, malaria burden, share of area in tropical, subtropical or temperate zones, average caloric suitability, latitude and its square, being an island or landlocked). Moreover, it accounts for continental fixed effects and thus for any unobserved time-invariant heterogeneity at the continental level. In addition, it accounts for common history fixed effects controlling for any unobserved time-invariant heterogeneity due to common historical experience across countries within a region. Additionally, when possible it accounts for country fixed effects and thus for unobserved time-invariant country-specific factors. Furthermore, it accounts for other time-varying country characteristics (e.g. change in caloric suitability due to the Columbian Exchange, colonial status, lagged technology levels), as well as period-region fixed effects and thus for unobserved time-varying regional factors.

Third, the analysis further mitigates the potential concern that the results may partially reflect the effect of omitted geographical, institutional, cultural, or human characteristics, by exploiting the variation in the location of the western technological frontier in the Old World. In particular, changes in the location of the technological frontier permit the research to account for country fixed effects and thus for time-invariant characteristics of a country. Moreover, it is plausible that the change in a country's distance to the frontier may be exogenous to its characteristics, especially once region-period fixed effects are accounted for. If this were the case, the first difference estimator of Eq. (7) would be unbiased.

Fourth, variations in the location of the western frontier permit the analysis to mitigate various potential concerns by exploring the effects of changes in the distance to the frontier on changes in population densities across countries. In particular, as mentioned above, differences across periods in Eq. (7) account for omitted time-invariant determinants of population density across countries. Additionally, analyzing changes across different periods mitigates the potential concern that a particular period or technological frontier drives the results. Another potential concern is that the results may not reflect the effect of being far from the frontier, but of countries that were distant from the frontier in one period and became closer to it in another period. Exploration of the differential effect of larger distances (to the technological frontiers) on population density in countries located far from the technological frontiers mitigates this concern.

Fifth, the analysis exploits the variation in the location of the western frontier in order to explore the cumulative and persistent effect of the distance to the pre-industrial frontier on development across countries. In particular, the theory suggests that the more time a country was farther than the LDD, the longer it benefitted from its incentives to imitate, adapt and innovate. Thus, the cumulative time a country spent at the MDD (across technological frontiers in the pre-industrial era) should be positively associated with its level of development.

Finally, the results may reflect the European expansion in the post-1500CE era or other time-varying characteristics of a country. The analysis mitigates this potential concern by using various strategies. In particular, it restricts the analysis to the Old World, where European population replacement was less prevalent. Additionally, it establishes that the results hold for the pre-colonial period, before European expansion. Furthermore, it accounts for time-varying characteristics of a country (years since the Neolithic Revolution, lagged technological sophistication) as well as other changes generated in the Old World during the colonial period (e.g. changes in colonial status, changes in caloric suitability). In addition, it accounts for the interaction between region and period fixed effects, which control for the effects of time-varying region-specific unobserved heterogeneity, and thus partially account for the potential effects of European expansion and other omitted time-varying characteristics of a country.

4.2 Independent variable: an economic measure of pre-industrial distance

This section[13] introduces a novel cross-country measure of the pre-industrial distance to the technological frontier in the pre-industrial era, which is the main independent variable employed in the analysis. This distance is based on a novel measure of geographical distance during pre-industrial times: the Human Mobility Index with Seafaring (HMISea). The HMISea measures the time required to cross any square kilometer on land and on some seas accounting for human biological constraints, as well as geographical and technological factors that determined travel time before the widespread use of steam power. Based on HMISea, the analysis estimates distances as the potential minimum travel time between locations (measured in weeks of travel). This strategy overcomes the potential mismeasurement of distances generated by using geodesic distances (Özak 2010), for a period when travel time was the most important determinant of transportation costs (O'Rourke and Williamson 2001).

The estimated time required to cross each square kilometer on land is based on data on the maximal sustainable speeds of dismounted infantry movement under different climatic, topographical, and terrain conditions (Hayes 1994). In particular, Hayes 1994 estimates the maximal sustainable speeds of dismounted infantry movement under different temperature, relative humidity, slope, and terrain conditions. Hayes focused on the levels of metabolic rates and speeds that can be sustained for long periods of time without causing a soldier to become a victim of heat-exhaustion.

Based on this data, the analysis estimates the relation between the maximum sustainable travel speeds and these conditions using Ordinary Least Squares (OLS). Given these OLS coefficients, the analysis proxies the time required to cross any square kilometer on land, given the average geographical conditions prevalent in it. Additionally, it complements this Human Mobility Index (HMI) by estimating the time required to cross any square kilometer on seas in the Old World, by constructing average times for each sea from primary and

[13] Given space limitations, a more complete presentation of the material covered in this section is given in Appendix A. The interested reader can find additional material regarding the construction and testing of the measure there. See also Özak (2010). Data and software for distance calculations based on this measure available on the author's website.

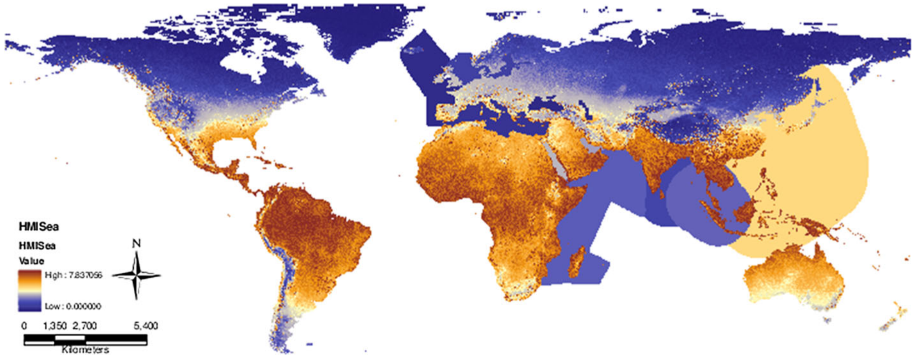


Fig. 4 Human Mobility Index with Seafaring (HMISea) cost surface. The figure depicts the number of hours required to cross each square kilometer on land and on seas in the Old World. Low values in dark lila, high values in dark brown, intermediate values in intermediate tones. See text or Özak (2010) for construction

secondary historical sources (see Appendix A for a more complete description). Figure 4 depicts the resulting HMISea cost surface.

In order to validate this index, Appendix A applies the HMISea measure to estimate distances during the pre-industrial era (see also Özak 2010). In particular, it estimates the total time required to travel along the optimal paths that connect all modern day capitals and the average optimal time required to travel to each capital from all locations on a contiguous continental mass. Using these estimates, the analysis validates the measures by comparing them with data on ancient trade routes (Ciolek 2004). As established in Appendix A, the optimal paths among capitals predict the locations of ancient trade routes in the Old World (500BCE–1900CE). Additionally, it explores the relation between these historical migratory distances and genetic, religious, and linguistic distances (Fearon 2003; Mecham et al. 2006; Spolaore and Wacziarg 2009). Reassuringly, the optimal time required to travel among regions is strongly positively associated with these cultural distances.[14] Finally, using data on the historical speed of diffusion of news to Venice between the sixteenth and eighteenth century from a sample of cities (Braudel 1972), the analysis establishes that HMISea travel time to Venice approximate these historical data. These results suggest that HMISea based migratory routes are good proxies for the minimum total travel time between the capital of each technological frontier in the pre-industrial era and the capitals of countries in the Old World.

Economic historians suggest that during the pre-industrial, the eastern technological frontier in the Old World era was located in China. On the other hand, the historical record suggests that the western technological frontier changed location during this era from the Eastern Mediterranean (≈1CE), to Iraq (≈1000CE), to the Low Countries (≈1500CE), and to the UK (≈1750CE) (Abu-Lughod 1989; Maddison 1995; Mokyr 1990; Pomeranz 2000; Maddison 2003; Findlay and O'Rourke 2007; Davids 2008; Blaut 2012). For each contemporary country the analysis estimates the HMISea migratory distance to all technological frontiers. Figure 5 depicts the travel time to each western pre-industrial technological frontier in the Old World. In particular, for each western frontier it depicts the iso-chronic lines

[14] Further supportive evidence of the validity of this method has been provided elsewhere. In particular, as predicted by the Out-of Africa Theory of the dispersion of modern humans, estimated HMI and HMISea migratory distances to East Africa have been shown to have a high explanatory power for the level of expected heterozygocity both at the ethnic and country levels (Ashraf and Galor 2013; Depetris-Chauvin and Özak 2015b). Similarly, differences in other cultural values have been linked to these estimated migratory distances (Spolaore and Wacziarg 2014; Becker et al. 2014; Depetris-Chauvin and Özak 2015b).

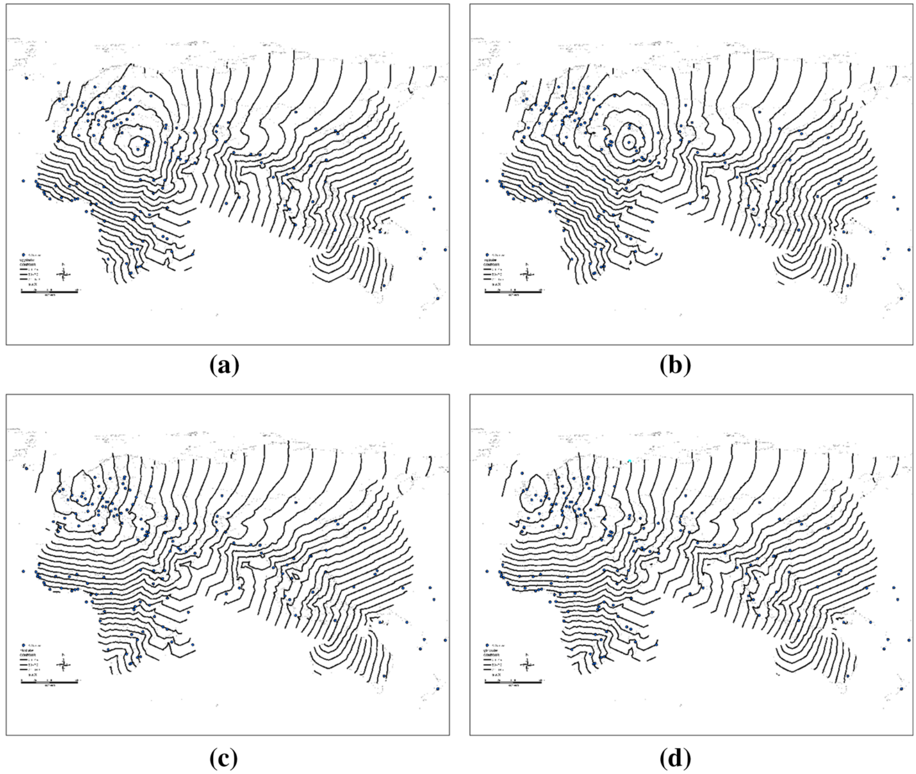


Fig. 5 Potential travel time to western pre-industrial technological frontiers (Old World). **a** Eastern Mediterranean, **b** Iraq, **c** Netherlands, **d** UK. *Note* Each panel depicts iso-chronic lines of travel time to a western pre-industrial technological frontier in the Old World. Each iso-chronic line represents half a week of continuous travel time along the optimal path to the frontier

generated by the HMISea measure, where each line corresponds to half a week of continuous uninterrupted travel.

4.3 Dependent variables and additional controls

In order to implement the empirical strategy, the analysis employs as independent variables various country-level measures of economic development for the pre-industrial era as well as measures of innovativeness and development during the contemporary era. First, the analysis employs an index of countries' technological sophistication in 1500CE and 2000CE (Comin et al. 2010), which documents around each era whether a certain set of technologies was used or known by the residents of the region where a contemporary country is located. Second, the analysis employs a measure of population density for each contemporary country in 1CE, 1000CE, 15000CE and 1820CE (McEvedy and Jones 1978). Third, in order to explore the persistence of the effect into the modern era, the analysis uses countries' average level of GDP per capita, patents per capita and new firms per 1000 people during the 2000–2015 period from the World Bank's Development Indicators.

The distance from the technological frontier is correlated with other geographical characteristics of a country that may have affected its development. Hence, the analysis accounts for the potential confounding effects of a range of geographical factors such as absolute latitude, area, average elevation, mean distance to nearest waterway, malaria risk, caloric agricultural suitability, climatic volatility and correlation, share of area within 100 km of sea, length of coastline, tropical, subtropical and temperate zones, as well as islands and landlocked regions. Furthermore, the analysis accounts for continental as well as historical region fixed effects, controlling for unobserved continent-specific geographical and historical characteristics that may have affected a country's economic development.

The onset of agriculture has been associated with a technological head-start that persisted during the Malthusian era (Diamond 1997; Ashraf and Galor 2011). Thus, the empirical analysis considers the confounding effect of the advent of sedentary agriculture, as captured by the years elapsed since the onset of the Neolithic Revolution (Putterman 2008), on countries' economic development.

The analysis also considers the confounding effect of a country's distance to other potential sources of economic development. In particular, it accounts for the effects of distance from a country to the closest pre-industrial trade route, which may reflect a country's ability to trade goods or information during this era. Additionally, it accounts for the effects of countries' distance to local technological frontiers as well as their distance to East Africa, which may independently have affected a country's development (Ashraf and Galor 2013; Depetris-Chauvin and Özak 2015a). Also, the empirical analysis accounts for the effect of the Columbian Exchange during the post-1500CE era. Specifically, it accounts for the effect of changes in caloric suitability (Galor and Özak 2016) as well as colonial status, legal origin and religious composition on economic development across countries. Appendix B provides the description, source and summary statistics of all variables used in the analysis.

5 Distance to the pre-industrial technological frontier and pre-industrial development

This section analyses the relation between the pre-industrial distance to the technological frontiers in the Old World and economic development across countries.[15] In particular, the predictions of the theory and Monte Carlo simulations (Sects. 3 and 4.1, Appendix E) suggest that the theory can be tested using variations of the following empirical specification

$$y_{it} = \beta_0 + \sum_{j=1}^{n} (\beta_{1j} d_{ijt} + \beta_{2j} d_{ijt}^2) + \sum_j \gamma_{0j} x_{it} + \sum_c \gamma_{ci} \delta_c + \sum_t \gamma_t \delta_t + \sum_{ct} \gamma_{ct} \delta_{ci} \delta_t + \epsilon_{it} \qquad (8)$$

where y_{it} is a measure of its economic development in period t for country i, d_{ijt} is the number of weeks of travel from country i to the jth pre-industrial technological frontier in period t, x_{it} are additional characteristics of country i in period t (including geography), $\{\delta_{ci}\}$ is a complete set of continental/regional/historical/country fixed effects, $\{\delta_t\}$ is a complete set

[15] As explained in Sect. 4.1, the analysis excludes the New World and Oceania in order to overcome various concerns. In particular, since the development process in both the New World and Oceania was strongly affected by other forces during the pre-1500 and post-1500 eras, their exclusion overcomes potential concerns due to, e.g., the potential confounding effects of population replacement and colonization, as well as the extinction of great mammals. Additionally, the lack of interaction between the Old and New World raises methodological issues regarding the estimation of distances. Reassuringly, Appendix F establishes the robustness of the inclusion of these regions into the analysis. In particular, it establishes the presence of a non-monotonicity when the New World has its own technological frontiers or when distances between the Old and New World are assumed to be larger than within each region.

of period fixed effects, and ϵ_{it} is an error term.[16] The theory predicts that $\beta_{1j} < 0$, $\beta_{2j} > 0$, and the implied Least Desirable Distance ($LDD_j = -0.5\beta_{1j}/\beta_{2j}$) is positive, finite and statistically significant for at least one frontier j.[17]

5.1 Historical evidence I: technological sophistication (cross-country analysis)

This section explores the relation between a country's level of technological sophistication in 1500CE and the distance to the technological frontiers in the Old World during that period, namely the Netherlands and China. The technology indices for the year 1500 proxy a country's stock of technology and innovativeness.[18] Thus, the dependent variable in these regressions measures the relevant channel through which remoteness affects economic development according to the proposed theory.

Table 1 explores the existence of a non-monotonic relation between the pre-industrial distance to the technological frontier and technological sophistication across countries. In particular, it uses ordinary least-squares (OLS) regressions to analyze the empirical association between a country's pre-industrial distance to the western technological frontier, the square of this distance and a country's technological sophistication in 1500CE. Column (1) shows the unconditional relation between the distance to the western technological frontier in the Old World and technological sophistication. In particular, the estimated Least Desirable Distance (LDD) is statistically and economically significant, and is located at 8.3 weeks. The estimates suggest that an economy located 1-standard deviation (SD) away from the LDD has a technological sophistication 19% higher than at the LDD.

Column (2) accounts for the confounding effect of a country's geographical characteristics. In particular, it accounts for a country's latitude and its square, pre-1500CE caloric suitability, percentage of land area in tropics and subtropics, mean elevation above sea level, land area, malaria burden, and dummies for being landlocked or an island. Reassuringly, the estimated LDD remains statistically and economically significant. The estimated location of the LDD is 5.4 weeks and implies that an economy located 1-SD away from the LDD has a technological sophistication 44% higher than at the LDD.

Columns (3) and (4) consider the confounding effects of the advent of sedentary agriculture and of unobserved time-invariant omitted variables at the continental level on technological sophistication across countries. In particular, column (3) accounts for the years elapsed since the a country experienced the onset of the Neolithic Revolution, which previous research has suggested had a positive impact on its economic development (Diamond 1997). Additionally, column (4) accounts for continental fixed effects and therefore for any unobserved time-invariant omitted variable at the continental level. The estimated LDD remains statistically

[16] The analysis includes the largest set of countries in the Old World for which all the data in the most general specification being studied is available. Appendix B contains the descriptive statistics for all the samples and variables used in the analysis.

[17] Appendix E explores the performance of this empirical specification using Monte Carlo simulations. In particular, it explores whether the null-hypothesis that $\beta_{2j} = 0$ for all frontiers j is rejected in favor of the alternative hypothesis that $\beta_{2j} \neq 0$ for some frontier j and its LDD_j is finite and smaller than the sample maximum. In these simulations the null-hypothesis was not rejected whenever it was assumed that the null-hypothesis was true. On the contrary, the null hypothesis was only rejected if the alternative hypothesis was assumed to hold. Moreover, even when the alternative hypothesis was true, the null-hypothesis was not always rejected. These findings suggest that rejection of the null-hypothesis in this specification provides strong support for the proposed theory.

[18] These measures were constructed independently of historical or contemporaneous income levels, covering a wide range of sectors, technologies, and countries. Thus, these measures try to prevent biases caused by a country's development. Still, they may be subject to Eurocentric biases due to the choice of technologies and knowledge on which they focus (Selin 1997; Blaut 2012).

Table 1 Distance from the pre-industrial frontier and technological sophistication in 1500 CE

	Technological sophistication in 1500CE							
	Unadjusted						Migration adjusted	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-industrial distance to NLD	− 0.15***	− 0.10***	− 0.10***	− 0.10***	− 0.13***	− 0.13***	− 0.13***	− 0.13***
	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Sq. Pre-industrial distance to NLD	0.01***	0.01***	0.01***	0.01**	0.01***	0.01***	0.01***	0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Pre-industrial distance to CHN					− 0.03***	− 0.04	− 0.03***	− 0.04
					(0.01)	(0.04)	(0.01)	(0.04)
Sq. Pre-industrial distance to CHN						0.00		0.00
						(0.00)		(0.00)
LDD NLD	8.25***	5.37***	5.63***	6.42***	7.66***	7.73***	7.28***	7.41***
	(0.89)	(0.50)	(0.36)	(1.25)	(1.26)	(1.62)	(1.13)	(1.52)
LDD CHN						124.61		61.21
						(1456.00)		(325.44)
Geographical controls	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time since Neolithic Revolution	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Continental FE	No	No	No	Yes	Yes	Yes	Yes	Yes
AET		1.87	2.15	3.51	13.05	14.95	10.24	12.88
δ		1.35	1.37	1.26	1.08	1.07	1.10	1.08

Table 1 continued

	Technological sophistication in 1500CE							
	Unadjusted						Migration adjusted	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
β^*		3.97	4.78	5.86	7.51	7.59	7.09	7.26
R^2	0.48	0.83	0.87	0.88	0.89	0.89	0.89	0.89
Adjusted-R^2	0.46	0.80	0.85	0.85	0.86	0.86	0.86	0.86
Observations	84	84	84	84	84	84	84	84

This table establishes the statistically and economically significant U-shaped relation between the distance to the frontier and technological sophistication in 1500CE across countries. Estimation by OLS. It additionally shows the Altonji et al. (2005) AET ratio as extended by Bellows and Miguel (2009). It also shows the δ and $\beta^*(1, 1)$ statistics suggested by Oster (2017). All statistics suggest that the results are not driven by unobservables. Pre-industrial distance to Netherlands/China is the minimum total travel time (in weeks) along the optimal path between a country's capital and the Netherlands/China (see text for construction). Additional controls include latitude and latitude squared of the country's capital, Pre-1500CE caloric suitability, percentage of land area in tropics and subtropics, mean elevation above sea level, land area, island and landlocked dummies, and malaria (falciparum) burden. Least desirable distance (LDD) is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests significant at the 1% and implies an economically significant effect of the distance to the technological frontier. In particular, after accounting for a country's geography, the advent of the Neolithic Revolution, and continental fixed effects, the estimated LDD is 6.4 weeks and implies that an economy located 1-SD away from the LDD has a technological sophistication 31% higher than at the LDD.

Furthermore, columns (5) and (6) account for countries' distance to the eastern technological frontier in the Old World. If conventional wisdom were valid, then accounting for the distance to China should eliminate the non-monotonicity with respect to the distance to the western technological frontier (see Appendix E). Reassuringly, the U-shape remains statistically and economically significant. Finally, columns (7) and (8) use an alternative measure of technological sophistication that corrects for possible migration in the pre-1500 era. Reassuringly, the results remain qualitatively similar, with the estimated LDD at 7.3 weeks, which implies that an economy located 1-SD away from the LDD has a technological sophistication 24% higher than at the LDD.

These findings suggests that after accounting for a country's geography, onset of the Neolithic Revolution and continental fixed effects there exists a U-shaped effect of the pre-industrial distance to the technological frontier on economic development. A potential concern with these results is that omitted factors might bias the results. In order to explore this issue, Table 1 additionally analyzes the potential bias generated by omitted variables. In particular, using statistics on selection on observables and unobservables (Altonji et al. 2005; Oster 2017), it establishes that the degree of omitted variable bias is low and is unlikely to explain the magnitude of the estimated LDD. In fact, omitted factors would need to be 1–13 times more strongly and positively correlated with distance from the frontier, in order to account for the estimated LDD. This suggests that the estimated LDD is not downward biased, which would be a concern for the proposed U-shaped relation. Furthermore, the bias-corrected LDD (Oster 2017), which assumes that the unobservables are as strongly correlated with distance as the set of observables that are accounted for columns (2)–(8), remains strictly positive, smaller than the sample maximum, and economically significant. These results suggest that it is unlikely that omitted country characteristics are significantly biasing the results.

Figure 6a, b depict the conditional relation between a country's technological sophistication and its distance from the frontier based on column (5) in Table 1. The figures show that the estimates generate a U-shape and a valley as predicted by the theory. Importantly, as shown in Fig. 6a, the semi-parametric regression and the fitted quadratic relation are almost identical, suggesting that the quadratic functional form is a good approximation to the non-monotonicity. A potential concern with these estimates is that the location of the LDD with respect to the Netherlands might depend on the distance from China. Reassuringly, as depicted in Fig. 6c, allowing for this interaction in the specification of column (5) does not affect the results qualitatively.

Another potential concern is that these results may reflect the aggregation of the sophistication measure across sectors. In order to mitigate this concern, Table 2 replicates the analysis for individual sectors. Reassuringly, as established in Table 2, the results remain qualitatively similar and suggest that the U-shape is not generated by aggregation and on the contrary holds for all sectors.

5.2 Robustness to alternative theories

This section explores the robustness of the results to alternative theories of development, omitted variables and mismeasurement. In particular, if the distance from the technological

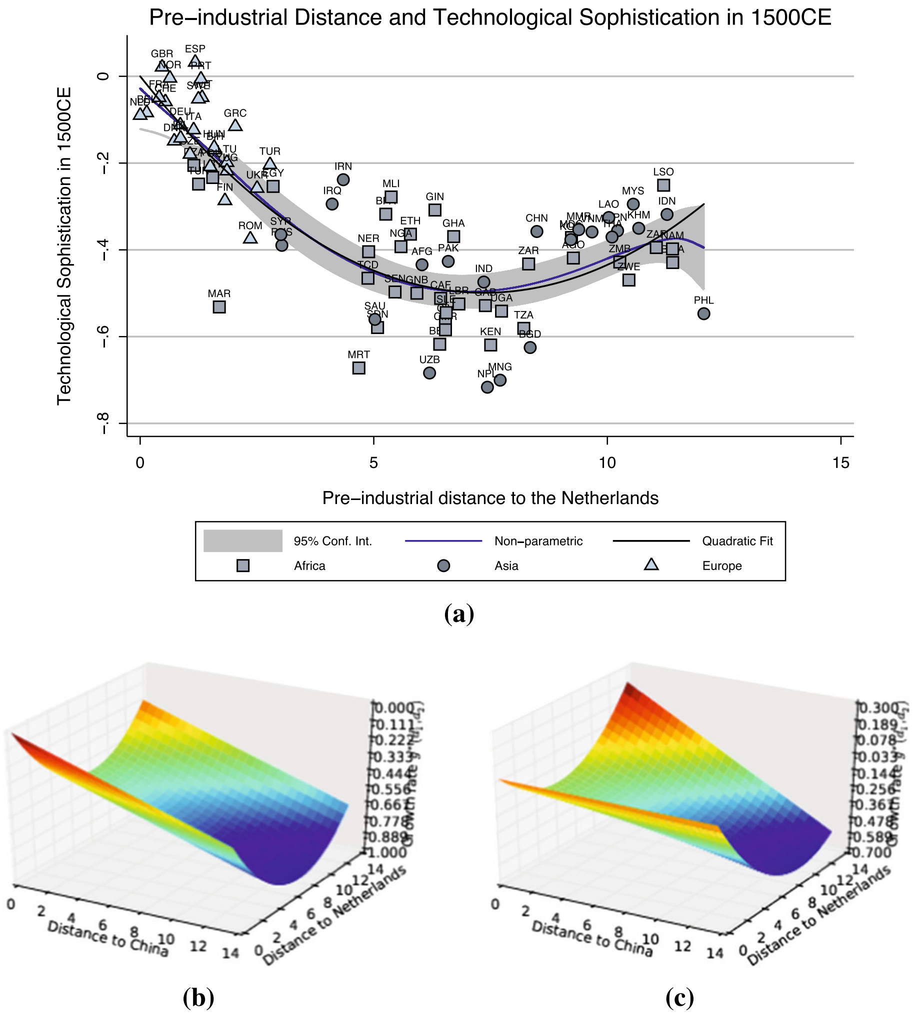


Fig. 6 Distance from the Pre-industrial Frontier and Technological Sophistication in 1500 CE. **a** Technological Sophistication (conditional association based on column 5 of Table 1), **b** growth valley based on column 5 of Table 1, **c** growth valley (interaction)

frontier correlates with other cultural, historical or institutional characteristics of a country, the estimated U-shaped relation may reflect alternative mechanisms or theories. Table 3 explores the confounding effects of lagged technological sophistication, European colonization, pre-industrial trade, local technological frontiers, and population diversity. For comparability, column (1) replicates the specification in column (5) of Table 1.

A potential concern with the previous findings is that the U-shape may reflect the effect of a country's lagged technology level. In particular, if conventional theory holds, then countries that are far from the frontier would be technologically backward and would benefit more from the advantages of backwardness (Gerschenkron 1962). Specifically, countries that were lagging technologically should be distant and have larger productivity and technological gains as they imitate from the technological frontier. Thus, according to this alternative theory,

Table 2 Distance from the pre-industrial frontier and technological sophistication in 1500 CE robustness to sector specific measures

	Technological sophistication in 1500CE						
	(Agr)	(Comm)	(Trans)	(Mil)	(Ind)	(Av.)	(Av.M.)
Pre-industrial distance to NLD	−0.14***	−0.06	−0.13***	−0.21***	−0.12*	−0.13***	−0.13***
	(0.05)	(0.05)	(0.04)	(0.07)	(0.06)	(0.03)	(0.03)
Sq. Pre-industrial distance to NLD	0.01**	0.00	0.01**	0.01**	0.01**	0.01***	0.01***
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)
Pre-industrial distance to CHN	−0.03	−0.02	−0.05***	−0.05**	−0.03**	−0.03***	−0.03***
	(0.02)	(0.02)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
LDD NLD	8.87***	8.83*	8.32***	7.60***	5.90***	7.66***	7.28***
	(2.21)	(4.82)	(1.90)	(1.82)	(1.02)	(1.26)	(1.13)
Continental FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.64	0.80	0.74	0.69	0.67	0.86	0.86
Observations	84	84	84	84	84	84	84

This table establishes the statistically and economically significant U-shaped relation between the distance to the frontier and sectorial technological sophistication in 1500CE across countries. Each column analyzes a specific sector: agriculture (Agr.), communications (Comm.), transportation (Trans.), military (Mil.), industry (Ind.), average (Av.) and migration adjusted average (Av.M.) across sectors. All columns include the same set of controls as column (5) in Table 1. Least desirable distance (LDD) is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests

Table 3 Distance from the pre-industrial frontier and technological sophistication in 1500 CE robustness to alternative theories

	Technological sophistication in 1500CE						
	Base (1)	Back (2)	Colony (3)	Trade (4)	Local (5)	OOA (6)	All (7)
Pre-industrial distance to NLD	−0.13***	−0.13***	−0.14***	−0.13***	−0.14***	−0.14***	−0.15***
	(0.03)	(0.04)	(0.03)	(0.04)	(0.03)	(0.03)	(0.04)
Sq. Pre-industrial distance to NLD	0.01***	0.01***	0.01***	0.01***	0.01***	0.01**	0.01**
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Pre-industrial distance to CHN	−0.04***	−0.03**	−0.04***	−0.04***	−0.04***	−0.05***	−0.06***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
Lagged technological sophistication		0.05					0.07
		(0.11)					(0.10)
European colony			−0.06				−0.08
			(0.06)				(0.07)
Pre-industrial distance to major trade routes				−0.00			0.02
				(0.03)			(0.04)
Pre-industrial distance to local frontier					0.01		0.01
					(0.02)		(0.02)
Pre-industrial distance to East Africa						0.01	0.02
						(0.01)	(0.01)
LDD NLD	7.77***	7.57***	7.83***	7.69***	7.84***	8.69***	9.83***
	(1.27)	(1.37)	(1.26)	(1.33)	(1.34)	(2.10)	(2.96)
Continental FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.87	0.86	0.87	0.86	0.86	0.86	0.86
Observations	82	82	82	82	82	82	82

This table establishes the robustness of the U-shaped relation between the distance to the frontier and technological sophistication in 1500CE across countries to accounting for lagged technology levels, European colonization, trade, local technological frontiers, and the Out-of-Africa hypothesis. Estimation by OLS. See Table 1 for list of additional controls. Least desirable distance (LDD) is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance to the Netherlands. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests

lagged levels of technology should be positively correlated with technological sophistication in 1500CE. Moreover, accounting for a country's past technology level should eliminate the non-monotonicity. Reassuringly, as established in column (2), accounting for the potential advantages of backwardness, as reflected by a country's lagged technological sophistication level, does not alter the results.

Another potential concern is that the results reflect the effect of the European expansion of the sixteenth century. In particular, if regions far from the technological frontier were colonized by (more developed) Europeans, who brought their technology, human capital, institutions, and culture, then regions far from the frontier would be more developed, but the cause would not be the one suggested by the theory. The analysis mitigates this potential concern in two ways. First, and importantly, technological sophistication in 1500CE is measured *before* the large technological transfers generated by European conquest (Comin et al. 2010). Thus, the positive effects of remoteness should not reflect the dispersion of Europeans, but conditions *preceding* it. Moreover, as established in column (3), accounting for countries' post-1500CE colonial history, by controlling for a dummy that is equal to 1 if post-1500CE a country will be colonized by an European power (including Turkey) and 0 otherwise, does not qualitatively alter the results. Thus, the results do not seem to be driven by unobservable time-invariant country characteristics that might jointly determine development around 1500CE and future colonization.

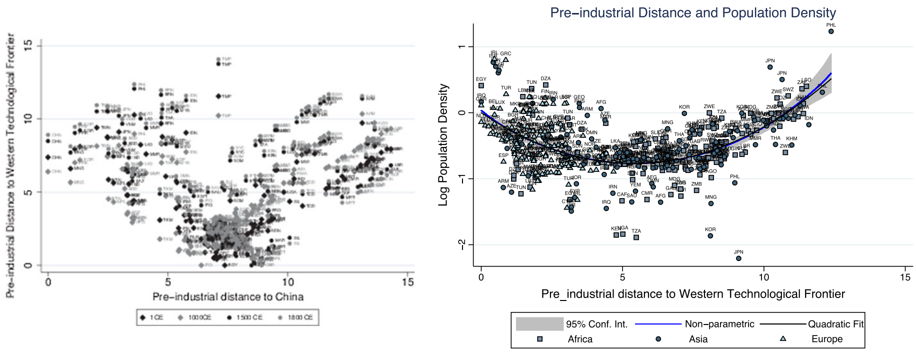
A further potential concern is that the results may reflect the potential beneficial effects of trade. In particular, if countries that are far from the frontier are close to major pre-industrial trade, pilgrimage, or other routes through which information and goods were transported, then the conventional positive effects of trade may be reflected in the U-shape. In particular, regions far from the frontier would be developed due to trade and information flows arriving through these routes, and not the channel suggested by the theory. In order to explore this issue, the analysis accounts for a country's pre-industrial distance to the location of pre-industrial trade, pilgrimage, banking and mail routes (Ciolek 2004). Reassuringly, as established in column (4) accounting for the pre-industrial distance to these networks does not alter the results.

Another potential concern is that the distance to the global technological frontiers is not as relevant for imitation and innovation as the distance to some local technological frontier. In particular, if the distance from the global technological frontier is negatively correlated with the distance to a local technological frontier, then countries far from the global frontier would be close to their local frontier. Thus, if conventional theory were true, they would be developed, but not through the channel suggested by the theory. The analysis mitigates this potential concern by accounting for a country's pre-industrial distance to the local technological frontiers identified by Ashraf and Galor (2013). Specifically, column (5) shows that accounting for a country's pre-industrial distance to its local technological frontiers does not affect the results.[19]

An additional concern is that the results may reflect the effect of the Out-of-Africa (OOA) hypothesis on economic development (Ashraf and Galor 2013). In particular, the OOA hypothesis suggests that economic development across countries in the Old World is positively associated with the pre-industrial distance to the Cradle of Humankind (East Africa). If the distance to the technological frontier is correlated with the distance to East Africa, then its omission may bias the results. Reassuringly, as established in column (6) accounting for the pre-industrial distance to East Africa does not alter the results.

Moreover, accounting jointly for all these other potential channels does not alter the results. This suggests that the U-shaped effect of the pre-industrial distance to the frontier on economic development does not capture the effect of these other theories. Finally, as established in Appendix F, including the New World, splitting the sample by regions, including the minimum distance to either frontier, or analyzing the alternative theories at the sectorial level does not alter the qualitative results either.

[19] This does not imply that local technological frontiers played no role. In particular, technology might have diffused from the global to the local technological frontiers and then to the countries. But this implies that the *relevant* distance from the source of innovation is still the global technological frontier, since imitation can only happen from the local frontier once enough time has passed for the innovation to diffuse or be created there.



(a) **(b)**

Fig. 7 Changes in the location of the frontier and pre-industrial population density. **a** Countries' locations relative to China and the western technological frontier in 1CE, 1000CE, 1500CE, and 1800CE, **b** distance to the technological frontier and pre-industrial population density

5.3 Historical evidence II: population density (panel-data analysis)

This section further explores the existence of a non-monotonic relation between the pre-industrial distance to the technological frontier and economic development across countries. In particular, using data on countries' population density during the pre-industrial era, and exploiting changes in the location of the western pre-industrial technological frontier in the Old World, the analysis explores the effect of distance to the frontier on economic development across countries. Importantly, changes in countries' distances to the pre-industrial frontiers across time, permit the analysis to exploit within-country variations to explore the existence of a U-shaped relation, while mitigating potential concerns due to the confounding effects of time-invariant country-specific characteristics. As illustrated in Fig. 7a, which depicts the location of Old World countries in the two-dimensional space defined by their distance to China and the western technological frontier in the years 1CE, 1000CE, 1500CE, and 1800CE, there exist large variations in distances to these frontiers both between and within countries across time.

Table 4 explores the existence of a U-shaped relation between distance to the technological frontier and population density across countries during the pre-industrial era. In particular, column (1) uses Pooled OLS to establish that population density between 1CE and 1800CE had a U-shaped relation with the distance to the pre-industrial technological frontier across countries. The analysis in column (1) accounts for the distance to China as well as the geographical controls included in Table 1. The results suggest that the Least Desirable Distance, LDD, is economically and statistically significant, located at 5.9 weeks of travel from the pre-industrial frontier.

Additionally, as established in columns (2)–(4), accounting for the potential effects of time-invariant characteristics of regions that shared a common history, religion, or language (Findlay and O'Rourke 2007), as well as any period-specific unobserved heterogeneity, and any period-region-specific omitted factors does not qualitatively alter the results. Indeed, after accounting for historical region, period and period-region fixed effects, as well as countries' geographical characteristics, the estimated LDD remains statistically and economically significant, and is estimated to be located at 5.8 weeks of travel from the frontier.

Table 4 Distance from the pre-industrial frontier and pre-industrial population density

	Log population density in 1CE, 1000CE, 1500CE, and 1800CE							
	Pooled OLS					FE		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-industrial distance to frontier	−0.41***	−0.39***	−0.33***	−0.24**	−0.18**	−0.38***	−0.15***	−0.13**
	(0.10)	(0.08)	(0.07)	(0.10)	(0.08)	(0.07)	(0.05)	(0.05)
Sq. Pre-industrial distance to frontier	0.04***	0.04***	0.03***	0.02**	0.02***	0.05***	0.02***	0.02***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)	(0.00)
Pre-industrial distance to China	−0.06	−0.18***	−0.14**	−0.14**	−0.03			
	(0.04)	(0.07)	(0.07)	(0.07)	(0.09)			
Pre-industrial distance to major trade routes					−0.35*			
					(0.19)			
Pre-industrial distance to East Africa					−0.01			
					(0.06)			
Colonial status					0.32**			0.10
					(0.16)			(0.12)
Pre-industrial distance to local frontier					0.00			−0.13*
					(0.10)			(0.08)
Caloric suitability					−0.00			0.00
					(0.00)			(0.00)
LDD	5.90***	4.37***	6.12***	5.78***	4.59***	3.89***	4.16***	3.61***
	(0.53)	(0.44)	(0.68)	(1.24)	(0.98)	(0.40)	(0.69)	(0.81)
Country FE	No	No	No	No	No	Yes	Yes	Yes
Geographical controls	Yes	Yes	Yes	Yes	Yes	No	No	No

Table 4 continued

	Log population density in 1CE, 1000CE, 1500CE, and 1800CE							
	Pooled OLS					FE		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Region FE	No	Yes	Yes	Yes	Yes	No	Yes	Yes
Period FE	No	No	Yes	Yes	Yes	No	Yes	Yes
Region × period FE	No	No	No	Yes	Yes	No	Yes	Yes
Time since Neolithic Revolution	No	No	No	No	Yes	No	No	Yes
Adjusted-R^2	0.49	0.59	0.74	0.76	0.78	0.21	0.86	0.86
Observations	463	463	463	463	463	463	463	463

This table establishes the statistically and economically significant U-shaped relation between distance to the frontier and population density across countries in the pre-industrial era. Column names denote the estimator used: (POLS) pooled OLS estimator, (FE) fixed effects estimator. Additional controls as in Table 1. Least desirable distance (LDD) is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance to the technological frontier. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. Heteroskedasticity robust standard error estimates clustered at the country level are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests

Column (5) additionally accounts for the potential confounding effects of other sources of comparative development. In particular, it accounts for the potential confounding effect of (i) trade by controlling for a country's distance to a major trade route; (ii) population diversity as determined during the Out-of-Africa migration of modern humans by controlling for a country's pre-industrial distance to East Africa; (iii) the transition to agriculture by controlling for the number of years since a country experienced the Neolithic Revolution; (iv) European expansion by controlling for a country's colonial status in a period; (v) local technological spillovers by controlling a country's pre-industrial distance to a local technological frontier in a period; and (vi) agricultural productivity by controlling for the country's average caloric suitability in a period. Reassuringly, the U-shape and LDD remain statistically and economically significant.

Columns (6)–(8) further explore the potential effect of omitted time-invariant country-specific characteristics on the analysis. In particular, changes across time in the location of the western pre-industrial technological frontier in the Old World, permit the research to account for country fixed effects. Reassuringly, accounting for country fixed effects and thus for time-invariant country-specific characteristics does not alter the qualitative results. Moreover, additionally accounting for period and period-region fixed effects (column 7), as well as other time-varying pre-industrial characteristics of a country (column 8), does not affect the qualitative results either. Thus, these findings suggest that the U-shape is not reflecting omitted time-varying and time-invariant characteristics at the country and regional level. Figure 7b depicts the relation between a country's distance to the frontier and its population density in the pre-industrial era as estimated in column 8.

Equation 7 suggests that changes across time in countries' economic development should be associated with changes in their distance to the frontier and its square. Importantly, by taking differences in Eq. 7, the analysis accounts for any time-invariant country-specific heterogeneity. Table 5 further explores the predictions of the theory using this strategy. Column (1) establishes that countries' population density has an economically and statistically significant U-shaped relation with their distance to the technological frontier. As established in columns (2) and (3), this result is robust to accounting for region, period, and region-period fixed effects, as well as changes in the number of years since a country experienced the Neolithic Transition, changes in a country's caloric suitability, changes in a country's colonial status, and changes in a country's distance to a local technological frontier.

A potential concern with these findings, is that they are driven by a specific period or frontier. Although period, region and period-region fixed effects ought to account for any unobserved heterogeneity at the region, period, or period-region levels, columns (4)–(6) further mitigate this concern. While the analysis in columns (1)–(3) employed the first-difference of Eq. 7 to explore the relation, the analysis in columns (4)–(6) uses long-differences for the 1–1800CE era. In particular, column (4) explores the change in population density between 1000CE and 1800CE, column (5) between 1CE and 1500CE, and column (6) between 1CE and 1800CE. Reassuringly, the analysis in all three columns suggests that there exists a statistically and economically significant U-shaped relation between population density and the distance to the frontier across countries.

5.4 Alternative tests of the theory

This section explores additional predictions of the theory. In particular, the theory predicts that countries located farther than the Least Desirable Distance (LDD) from the technological frontier should grow faster, and increasing their distance to the technological frontier should boost economic development during the pre-industrial era. Additionally, the theory predicts

Table 5 Distance from the pre-industrial frontier and pre-industrial population density

	Change in log population density					
	All periods			1000CE–1800CE	1CE–1500CE	1CE–1800CE
	(1)	(2)	(3)	(4)	(5)	(6)
ΔPre-industrial distance to frontier	− 0.18***	− 0.08*	− 0.07*	− 0.08	− 0.23***	− 0.32***
	(0.03)	(0.04)	(0.04)	(0.06)	(0.09)	(0.09)
ΔSq. Pre-industrial distance to frontier	0.01***	0.01***	0.01***	0.01**	0.03***	0.03***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)
ΔYears since transition to agriculture			− 0.72***			
			(0.13)			
ΔCaloric suitability			0.00			
			(0.00)			
ΔColonial status			0.03			
			(0.12)			
ΔPre-industrial distance local frontier			− 0.06			
			(0.06)			
LDD	5.92***	4.40***	4.04***	3.87***	3.67***	4.66***
	(0.45)	(0.99)	(1.21)	(1.46)	(0.75)	(0.64)
Region FE	No	Yes	Yes	Yes	Yes	Yes
Period FE	No	Yes	Yes	No	No	No
Region × period FE	No	Yes	Yes	No	No	No
Adjusted-R^2	0.08	0.43	0.43	0.49	0.56	0.60
Observations	343	343	343	116	107	106

This table establishes the statistically and economically significant U-shaped relation between distance to the frontier and population density across countries in the pre-industrial era. (i) Columns (1)–(3) use a panel of changes in countries' log population density and distances to the frontier (first differences). Columns (4)–(6) use long differences (two periods columns (4)–(5), column (6) three periods). (ii) Least desirable distance (LDD) is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance to the technological frontier. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. (iv) Heteroskedasticity robust standard error estimates clustered at the country level are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests

a cumulative positive effect of being distant from the technological frontier, reflecting its beneficial effect on the emergence of institutional and cultural characteristics conducive to innovation and entrepreneurship.

Table 6 explores the first prediction that countries that are distant from the pre-industrial technological frontier tend to grow faster, and that increases in their distance boosts their economic performance. Column (1) establishes that the pre-industrial distance to the technological frontier in a period is positively associated with future increases in population density during the following period. Additionally, column (2) establishes that distant countries that became even more distant from the frontier, benefited of a boost to population density growth. These results account for the potential confounding effects of region, period and region-period unobservable heterogeneity.

A potential concern with the results of columns (1) and (2) is that they reflect the confounding effects of other time-varying country characteristics. In order to mitigate this concern,

Table 6 Distance from the pre-industrial frontier and pre-industrial population density growth

	Change in log population density					
	Western frontier				Local frontier	Closest frontier
	(1)	(2)	(3)	(4)	(5)	(6)
Lagged pre-industrial distance to frontier	0.04**	0.04**	0.04**	0.04**	0.08***	0.03*
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
ΔPre-industrial distance to frontier		−0.03		−0.03	−0.27***	−0.04
		(0.04)		(0.04)	(0.08)	(0.04)
(Lag $\times\Delta$)Pre-industrial Distance to frontier		0.01**		0.01**	0.10***	0.01**
		(0.01)		(0.01)	(0.02)	(0.01)
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Period FE	Yes	Yes	Yes	Yes	Yes	Yes
Region × period FE	Yes	Yes	Yes	Yes	Yes	Yes
Other controls and interactions	No	No	Yes	Yes	Yes	Yes
Adjusted-R^2	0.43	0.44	0.43	0.43	0.47	0.43
Observations	343	343	343	343	343	343

This table establishes that during the pre-industrial era, countries located far from the technological frontier had higher economic growth as captured by growth in population density. Moreover, countries that became more distant from the frontier got an additional boost to their economic growth. Columns (1)–(4) use the distance to the western technological frontier. Column (5) and (6) show similar effects using a country's distance to a local or to the closest technological frontier. All columns account for region, time and region×time fixed effects. Additionally, columns (3)–(6) account for lagged values and changes in countries' caloric suitability and colonial status. Heteroskedasticity robust standard error estimates clustered at the country level are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests

columns (3) and (4) replicate the analysis, but account additionally for the lag, difference and interaction of the set of country's time-varying characteristics included in Table 4. Reassuringly, the results remain unchanged. Furthermore, the analysis uncovers qualitatively similar effects of the increases in the distance to the local or to the closest frontier (columns 5 and 6).

Table 7 further explores the predicted benefits of being far from the frontier. In particular, it analyzes the association between the time (measured in centuries) that a country spent more than one standard deviation farther away than the average country from pre-industrial technological frontiers, i.e., at the More Desirable Distances (MDD). The theory predicts that the more time a country was located at the MDD the higher its economic development. Column (1) establishes that after accounting for country, period, and region-period fixed effects, the time spent at the MDD is positively associated with population density. The results suggest that for each century a country was located at the MDD, its population density increased by 3%. Additionally, accounting for a country's colonial status, its distance to a local technological frontier, its caloric suitability, and the time since the Neolithic Revolution does not affect the results (column 2).

A potential concern with these results is that countries located at the MDD in one period, may be located close to another frontier in a different period. Thus, the positive effect of being located at the MDD may be reflecting the confounding positive effect of being close to the frontier in different periods. In order to mitigate this concern, columns (3)–(7) constrain

Table 7 Persistent effect of distance from the pre-industrial technological frontier on pre-industrial population density

	Log population density in period						
	Full sample		Distance from frontier always ≥				
			1 Std	2 Std			
					Distance to China always ≥		
					1 Std	2 Std	3 Std
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Time at MDD	0.03**	0.03**	0.03**	0.04**	0.03**	0.03**	0.03**
	(0.02)	(0.02)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
Colonial status		0.06	0.20**	0.23*	0.24	0.16	0.16
		(0.12)	(0.09)	(0.12)	(0.16)	(0.13)	(0.13)
Pre-industrial distance local frontier		−0.09	0.28***	0.39***	0.39***	0.42***	0.42***
		(0.08)	(0.09)	(0.08)	(0.07)	(0.07)	(0.07)
Caloric suitability		−0.00	−0.00	−0.00	−0.00	−0.00	−0.00
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region × time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time since Neolithic Revolution	No	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.85	0.85	0.90	0.91	0.94	0.95	0.95
Observations	463	463	298	178	161	110	106

This table establishes the positive cumulative effect of being relatively far from the technological frontier during the pre-industrial era. In particular, years at MDD measures the number of centuries a country had been located at more than 9 weeks of travel (more than one standard deviation further away than the average country) from pre-industrial technological frontiers. Columns (3)–(7) additionally impose that the country is never too close to a western frontier, nor is located close to the eastern frontier (China). All columns account for country, time and region×time fixed effects. Heteroskedasticity robust standard error estimates clustered at the country level are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests

the sample to countries that are always more than 1 or 2 standard deviations away from the technological frontiers.[20] As established in columns (3) and (4), constraining the sample to countries located always more than 1 or 2 standard deviations away from the technological frontier does not affect the results. Moreover, focusing on countries that are additionally far away from China, thus accounting for the potential confounding effect of diffusion from the Eastern technological frontier does not alter the results either.

Finally, Table 8 establishes the robustness of the results to the measure of the time a country was located at the MDD. In particular, instead of using the time spent at the MDD, which might potentially be subject to measurement error, it employs the MDD Index that counts the number of pre-industrial technological frontiers for which the country was located at the MDD. Reassuringly, the results remain qualitatively similar and imply that for each

[20] Constraining the sample to include only countries that are always more than 3 standard deviations (i.e., 9 weeks) away from the technological frontier in every period results in a much smaller sample size. Reassuringly, the results remain qualitatively similar.

Table 8 Persistent effect of distance from the pre-industrial technological frontier on pre-industrial population density

	Log population density in period						
	Full sample		Distance from frontier always ≥				
			1 Std	2 Std			
					Distance to China always ≥		
					1 Std	2 Std	3 Std
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
MDD Index	0.21***	0.22***	0.20***	0.22***	0.18**	0.18**	0.18**
	(0.07)	(0.07)	(0.07)	(0.07)	(0.07)	(0.07)	(0.07)
Colonial status		0.06	0.19**	0.23*	0.24	0.09	0.09
		(0.12)	(0.09)	(0.12)	(0.16)	(0.12)	(0.12)
Pre-industrial distance local frontier		− 0.10	0.26***	0.35***	0.35***	0.39***	0.39***
		(0.08)	(0.08)	(0.07)	(0.06)	(0.06)	(0.06)
Caloric suitability		− 0.00	0.00	− 0.00	− 0.00	− 0.00	− 0.00
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Period FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region × period FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time since Neolithic Revolution	No	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.85	0.85	0.90	0.92	0.94	0.96	0.96
Observations	463	463	298	178	161	110	106

This table establishes the positive cumulative effect of being far from the technological frontier during the pre-industrial era. In particular, MDD measures the number of technological frontiers for which a country had been located at more than 9 weeks of travel (more than one standard deviation further away than the average country). Columns (3)–(7) additionally impose that the country is never too close to a western frontier, nor is located close to the eastern frontier (China). All columns account for country, time and region×time fixed effects. Heteroskedasticity robust standard error estimates clustered at the country level are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests

pre-industrial technological frontier for which a country was at the MDD, its population density increased by 18%.

6 Distance to the pre-industrial technological frontier and contemporary economic development

This section explores the persistent effects of the distance to the pre-industrial technological frontier on contemporary economic development. In particular, it establishes the existence of a U-shaped relation between countries' contemporary GDP per capita and their distance to the UK, which was the technological frontier around 1800. Moreover, the analysis demonstrates a cumulative positive effect of being far from the technological frontiers during the pre-industrial era on contemporary economic development across countries. In particular, the analysis demonstrates the persistent effect of distance from the pre-industrial frontier on contemporary GDP per capita, innovation and entrepreneurial activity across countries. Thus, the results suggest that distance from the frontier may have beneficial effects on innovation and entrepreneurship as proposed by the theory.

Table 9 explores the persistence of the non-monotonic effect of distance from the (last) pre-industrial technological frontier on contemporary economic development across countries. In particular, it analyzes whether countries' pre-industrial distance to the UK has a U-shaped association with contemporary technological sophistication (2000CE) and income per capita (average 2000–2015CE). Columns (1) and (5) establish that there exist unconditional U-shaped associations between the distance to the pre-industrial frontier and both measures of contemporary development across countries. Even though the estimates are based on two different measures and samples, the estimated Least Desirable Distance (LDD), at 7.3 weeks of travel from the UK, is similar in both columns. Figure 8a depicts the quadratic relation as well as the results of a non-parametric regression between income per capita and distance to the pre-industrial frontier. The figure suggests that the quadratic specification is a good approximation to the underlying association.

Clearly, these U-shaped relations may be biased due to omitted variables. In order to mitigate this potential concern, columns (2)–(4) and (6)–(8) explore their robustness to accounting for the effect of various potential confounders. Reassuringly, the U-shaped relation and the existence of the LDD are robust to accounting for a country's geographical characteristics; the number of years since a country experienced the Neolithic Revolution; continental fixed effects; the pre-industrial distance to China; the effect of European colonization; and the pre-industrial distance to East Africa and its square. Figure 8b depicts the U-shaped relation and semi-parametric regression associated with the specification in column (8). The results suggest that the LDD is located at 6 weeks of travel from the pre-industrial technological frontier. Moreover, additionally accounting for geographical characteristics associated with the emergence of pre-modern states, risk attitudes, and cooperation; religious composition of the population; institutional quality; a country's share of population with European ancestry; legal origins; and the distance to the contemporary technological frontier does not alter the qualitative nature of the results.[21]

Table 10 further explores the potential persistent effects of distance from the pre-industrial technological frontier on contemporary economic development across countries. It exploits variations in the location of the western pre-industrial frontier in the Old World to analyze the effect of the time a country spent far from the pre-industrial technological frontier. In particular, column (1) establishes the positive association between the time (measured in centuries) that a country spend more than one standard deviation farther away than the average country from pre-industrial technological frontiers, i.e., at the More Desirable Distances (MDD). The results suggest that after accounting for regional fixed effects, each additional century at the MDD is associated with a 7% increase in contemporary income per capita. Moreover, accounting for other geographical characteristics of a country, the number of years since it experienced the Neolithic revolution and its colonial experience does not qualitatively alter the results (columns 2–3).

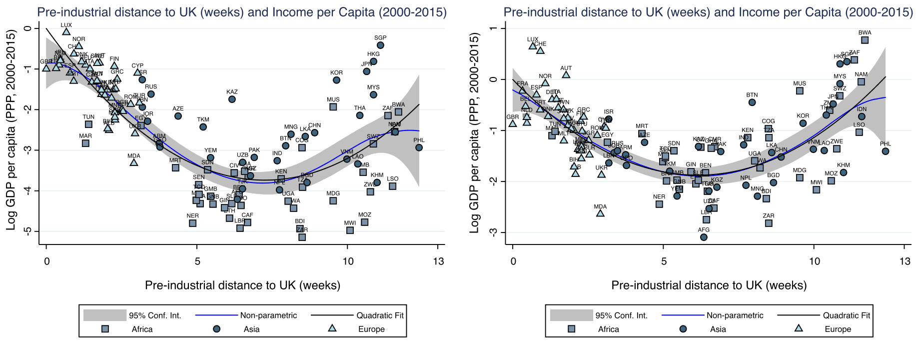
A potential concern with these results is that they may be capturing the potential confounding effects of other sources of economic development. In particular, the time spent at the MDD may be correlated with geographical characteristics associated with risk attitudes, trust, cooperation and pre-modern states (Durante 2009; Depetris-Chauvin and Özak 2015b; Bentzen et al. 2017), which may have independently affected development. Similarly, changes in the distance to the pre-industrial technological frontier may be correlated with the religious composition of a country, which in turn may independently affect its development.

[21] These results can be obtained from the author upon request.

Table 9 Distance from the pre-industrial technological frontier and contemporary development

	Contemporary development							
	Technological sophistication				Log[GDP per capita (2000–2015CE)]			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-industrial distance to frontier	−0.16***	−0.14***	−0.14***	−0.14***	−1.03***	−0.65***	−0.64***	−0.61***
	(0.01)	(0.03)	(0.03)	(0.03)	(0.09)	(0.14)	(0.16)	(0.17)
Sq. Pre-industrial distance to frontier	0.01***	0.01***	0.01***	0.01***	0.07***	0.05***	0.05***	0.05***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)
Pre-industrial distance CHN			0.00	0.01			0.01	0.04
			(0.01)	(0.01)			(0.05)	(0.07)
Pre-industrial distance to Addis Ababa				0.01				0.13
				(0.03)				(0.14)
Sq. Pre-industrial distance to Addis Ababa				−0.00				−0.01
				(0.00)				(0.01)
European colony (includes Turkey)				−0.07				−0.45
				(0.05)				(0.37)
LDD	7.32***	7.06***	7.02***	6.97***	7.25***	6.25***	6.21***	6.15***
	(0.28)	(0.37)	(0.39)	(0.42)	(0.27)	(0.40)	(0.50)	(0.54)
Geographical controls	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Time since Neolithic Revolution	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Continental FE	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Adjusted-R^2	0.60	0.71	0.71	0.70	0.57	0.77	0.77	0.77
Observations	97	97	97	97	112	112	112	112

This table establishes the U-shaped association between the distance to the pre-industrial technological frontier and contemporary development as measured by technological sophistication in 2000CE and income per capita (average 2000–2015CE) across countries. The analysis accounts for country's geographical characteristics, the time since the country experienced the Neolithic Revolution, continental fixed effects, colony fixed effects, and pre-industrial distances to China and East Africa (and their squares). Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests



(a) **(b)**

Fig. 8 Distance to pre-industrial technological frontier (UK) and income per capita (2000–2015CE). **a** Unconditional relation, **b** conditional relation

Moreover, the results may be biased if a country's distance to the pre-industrial technological frontier is associated with the quality of its institutions, the share of its population that descends from Europeans, its legal origins, or its distance to the contemporary technological frontier. Reassuringly, as columns (4)–(9) establish, accounting for these characteristics does not alter the estimated positive association between the time spent at the MDD and contemporary economic development.

Additionally, the analysis explores the potential persistent effects of distance from the pre-industrial technological frontier on contemporary innovation across countries. In particular, the theory predicts that periods of remoteness from the technological frontier during the pre-industrial era promoted the emergence of a culture and institutions that were conducive to innovation and entrepreneurship, and thus to economic development. Table 11 explores this prediction by analyzing the association between a country's time spent at the MDD and its contemporary propensity to innovative, as measured by its average patenting activity per capita in the 2000–2015CE period. Column (1) establishes that after accounting for unobserved regional heterogeneity, an additional century of remoteness from the technological frontier during the pre-industrial era is associated with a 15% increase in the number of patents per capita. Additionally accounting for geographical characteristics, the time since the Neolithic Revolution, the effects of colonization, and the geographical characteristics associated with risk attitudes, trust, cooperation and pre-modern states increases the statistical and economic significance of the effect. Specifically, after accounting for all these confounders, the results suggest that an additional century of remoteness from the technological frontier during the pre-industrial era is associated with an increase of 17% in contemporary patenting activity (columns 2–5).

A potential concern with these results is that they capture foreign patenting activity. In order to mitigate this concern, columns (6) replicates the analysis for the domestic patenting activity of residents only. In particular, it establishes that there is a statistically and economically significant positive association between the time spent at the MDD and domestic patenting activity by residents of a country. After accounting for the same set of controls as in column (5), the analysis suggests that an additional century of remoteness from the technological frontier during the pre-industrial era is associated with an increase of 20% in contemporary domestic patenting activity by residents. This result supports the proposed theory that distance from the frontier during the pre-industrial era was conducive to the emergence of a culture and institutions that promote innovation and entrepreneurship.

Table 10 Persistent effect of distance from the pre-industrial technological frontier on contemporary development

	Log[GDP per capita (2000–2015CE)]								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Time at MDD	0.07***	0.07***	0.08***	0.07**	0.07**	0.08***	0.08***	0.05*	0.07**
	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical controls	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time since Neolithic Revolution	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Colony FE	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Volatility controls	No	No	No	Yes	No	No	No	No	No
Religious shares	No	No	No	No	Yes	No	No	No	No
Constraints on executive	No	No	No	No	No	Yes	No	No	No
Population share with European ancestry	No	No	No	No	No	No	Yes	No	No
Legal origin FE	No	No	No	No	No	No	No	Yes	No
Distance to USA	No	No	No	No	No	No	No	No	Yes
Adjusted-R^2	0.70	0.76	0.76	0.77	0.76	0.76	0.76	0.79	0.76
Observations	105	105	105	105	105	105	105	105	105

This table establishes the positive cumulative effect of being far from the technological frontier during the pre-industrial era on contemporary income per capita (average 2000–2015CE). The analysis accounts for regional fixed effects, country's geographical characteristics, the time since the country experienced the Neolithic Revolution, colony fixed effects, geographical determinants of statehood, cooperation and risk preferences, religious composition of the population, constraints on the executive, European ancestry, legal origins, and distance to the contemporary technological frontier. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests

Table 11 Persistent effect of distance from the pre-industrial technological frontier on contemporary patenting activity

	Log[Patents per Capita (2000–2015CE)]					
	All					Residents
	(1)	(2)	(3)	(4)	(5)	(6)
Time at MDD	0.15**	0.14**	0.14**	0.17***	0.17***	0.20***
	(0.07)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes
Geographical controls	No	Yes	Yes	Yes	Yes	Yes
Time since Neolithic Revolution	No	No	No	Yes	Yes	Yes
Colony FE	No	No	No	Yes	Yes	Yes
Volatility controls	No	No	No	No	Yes	Yes
Adjusted-R^2	0.60	0.70	0.70	0.74	0.78	0.80
Observations	84	84	84	84	84	84

This table establishes the positive cumulative effect of being far from the technological frontier during the pre-industrial era on domestic patenting activity (average patents per capita 2000–2015CE). The analysis accounts for regional fixed effects, country's geographical characteristics, the time since the country experienced the Neolithic Revolution, colony fixed effects, and geographical determinants of statehood, cooperation and risk preferences. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests

A major potential concern with this result is that it may capture the confounding effect of omitted cultural or institutional characteristics of the country. In particular, the time spent at the MDD may be correlated with the religious composition of a country, and thus with a major cultural determinant of economic behavior (Andersen et al. 2017). Similarly, given the European expansion in the post-1500 era, the time spent at the MDD may be correlated with the culture or institutions brought by European migrants. Moreover, the results may be biased if the time spent at the MDD is correlated with a country's distance to the contemporary technological frontier.

In order to mitigate these concerns, Table 12 explores the robustness of the positive association between the time spent at the MDD and domestic patenting activity by residents to accounting for the potential effects of these confounders. Column (1) replicates the analysis of column (6) in Table 11 for the sample of countries for which all additional controls are available. The result remains statistically and economically significant and suggests that an additional century of remoteness from the technological frontier during the pre-industrial era is associated with an increase of 18% in contemporary domestic patenting activity by residents. Reassuringly, accounting for a country's religious composition, and thus for any cultural effects of religion (column 2); its level of constraints on the executive (column 3); fixed effects for the identity of its main colonizer, and thus for any unobserved cultural, institutional or ancestral characteristics associated with its main colonizer (column 4); the share of its population that descends from European ancestors, and thus for the extent of European influence in the country's culture, institutions and human capital (column 5); fixed effects for the origin of its legal system, and thus for any unobserved heterogeneity due to its legal tradition (column 6); or its distance to the contemporary technological frontier does not qualitatively affect the results. Moreover, accounting simultaneously for all these potential confounders has no effect on the estimated relation.

Table 12 Persistent effect of distance from the pre-industrial technological frontier on contemporary domestic patenting activity (robustness)

	Log[Patents per capita by Residents (2000–2015CE)]							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Time at MDD	0.18***	0.17***	0.17***	0.17**	0.18***	0.12**	0.26***	0.18**
	(0.05)	(0.06)	(0.06)	(0.07)	(0.05)	(0.06)	(0.05)	(0.07)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Colony FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Volatility controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Religious shares	No	Yes	No	No	No	No	No	Yes
Constraints on executive	No	No	Yes	No	No	No	No	Yes
Main Colonizer FE	No	No	No	Yes	No	No	No	Yes
Population share with European ancestry	No	No	No	No	Yes	No	No	Yes
Legal origin FE	No	No	No	No	No	Yes	No	Yes
Distance to USA	No	No	No	No	No	No	Yes	Yes
Adjusted-R^2	0.80	0.79	0.80	0.77	0.80	0.84	0.81	0.82
Observations	81	81	81	81	81	81	81	81

This table establishes the robustness of the positive cumulative effect of being far from the technological frontier during the pre-industrial era on domestic patenting activity (average patents per capita 2000–2015CE) by residents. In particular, it establishes the robustness of the result to accounting for religious composition, institutional quality, colonizer's identity, European ancestry, legal origins, and distance to contemporary frontier. All columns account for the full set of controls in Table 11. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests

Another concern with these results is that not all innovative activity results in new patents. Thus, the results may underestimate the potential positive effect of the time spent at the MDD on innovation. On the other hand, patents may not translate directly into economic activity and thus development. In order to mitigate this concern, Table 13 analyzes the effect of the time spent at the MDD on entrepreneurship. In particular, innovative activity that results in the creation of new business opportunities should potentially be accompanied by the arrival of new firms in the economy. Reassuringly, the results in Table 13 suggest that there exists an economically and statistically significant positive association between the time spent at the MDD and the density of new firms. Moreover, this association is robust to accounting for regional fixed effects and countries' characteristics like geography, the time since the Neolithic Revolution, colonial fixed effects, religious composition, institutional quality, colonizer fixed effects, European ancestry, legal origin fixed effects, and the distance to the contemporary technological frontier. In particular, after accounting for the potential effect of all these confounders, the analysis suggests that an additional century of remoteness from the technological frontier during the pre-industrial era is associated with an increase of 19% in the number of new firms per 1000 people.[22]

7 Conclusions

This research explores the effects of distance to the pre-industrial technological frontiers on comparative economic development in the course of human history. It proposes that during the pre-industrial era, while a country's remoteness from the frontier diminished imitation, it fostered the emergence of a culture conducive to innovation, knowledge creation and entrepreneurship, which may have persisted into the modern era. The emergence of these cultural values generated a positive force that counteracted the conventional negative effects of distance. Thus, the theory proposes that the interaction of these opposing forces resulted in a U-shaped relation between economic development and the distance to the frontier in the pre-industrial era. In line with this prediction, the analysis establishes both theoretically and empirically that distance to the frontier had a persistent non-monotonic effect on a country's pre-industrial level of economic development. In particular, advancing a novel measure of the travel time to the technological frontiers, the analysis establishes a robust persistent U-shaped relation between distance to the frontier and pre-industrial economic development across countries. Moreover, it demonstrates that countries, which throughout the last two millennia were relatively more distant from these frontiers, have higher contemporary levels of innovation and entrepreneurial activity, suggesting that distance from the frontier may have fostered the emergence of a culture conducive to innovation, knowledge creation, and entrepreneurship.

Although technological progress may have diminished the role of geographical distance in the contemporary period, the theory suggests that cultural and institutional differences from the contemporary technological frontier may be similarly conducive to innovation and entrepreneurship in the modern era. Thus, these forces may be driving the innovative and entrepreneurial activities in locations where cultural and institutional differences may prevent technological diffusion from the contemporary technological frontier. In particular, health care innovations that could substantially lower costs and increase access are being generated

22 Tables F.10, F.11 and F.12 provide additional support to the proposed thesis. They establish that there exists a U-shaped association between patenting and entrepreneurial activity and the distance to the last pre-industrial technological frontier.

Table 13 Persistent effect of distance from the pre-industrial technological frontier on contemporary entrepreneurial activity

	Log[New firms per 1000 people (2000–2015CE)]						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Time at MDD	0.16***	0.19**	0.18**	0.19**	0.18**	0.17**	0.19**
	(0.06)	(0.08)	(0.08)	(0.08)	(0.08)	(0.08)	(0.09)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical controls	No	Yes	Yes	Yes	Yes	Yes	Yes
Time since Neolithic Revolution	No	No	Yes	Yes	Yes	Yes	Yes
Colony FE	No	No	No	Yes	Yes	Yes	Yes
Volatility controls	No	No	No	No	Yes	Yes	Yes
Religious shares	No	No	No	No	No	Yes	Yes
Constraints on executive	No	No	No	No	No	Yes	Yes
Main colonizer FE	No	No	No	No	No	No	Yes
Population share with European ancestry	No	No	No	No	No	No	Yes
Legal origin FE	No	No	No	No	No	No	Yes
Distance to USA	No	No	No	No	No	No	Yes
Adjusted-R^2	0.41	0.56	0.55	0.55	0.54	0.54	0.65
Observations	85	85	85	85	85	85	85

This table establishes the positive cumulative effect of being far from the technological frontier during the pre-industrial era on the number of new firms registered per 1000 people of ages 15–64 (average 2000–2015CE). In particular, it establishes the robustness of the result to accounting for regional fixed effects, all geographical controls in Table 11, time since the country experienced the Neolithic Revolution, colony fixed effects, geographical determinants of statehood, risk attitudes and cooperation, religious composition, institutional quality, colonizer's identity, European ancestry, legal origins, and distance to contemporary frontier. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests in countries that are culturally and institutionally different from the West. For example, the development and simplification of cataract surgery with lens implantation at the community level, small incision cataract surgery, intraocular lenses, and sutureless surgical procedures has been pioneered by a group of doctors in the Tilganga Eye Center in Nepal. Similarly, General Electric's strategy of reverse innovation, in which products are developed in markets dissimilar to the frontier and then distributed globally, have generated innovations like the portable ultrasound and ECG (Immelt et al. 2009).

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