The Dawn of Civilization
Metal Trade and the Urban Revolution

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June 20, 2023

Abstract

In the latter half of the fourth millennium BC, our ancestors experienced a remarkable transformation, progressing from simple agrarian villages to complex urban civilizations. In regions as far away as the Nile Valley, Mesopotamia, Central Asia, and the Indus Valley, the first states appeared together with writing, cities with populations exceeding 10,000, and unprecedented socio-economic inequalities. The cause of this 'Urban Revolution' remains unclear. We present new empirical evidence suggesting that the discovery of bronze and the ensuing long-distance trade played a crucial role. We find that trade corridors linking metal mines to fertile lands were more likely to experience the Urban Revolution. We propose that transit bottlenecks allowed the emergence of a new taxing elite. Using novel panel data and 2SLS techniques, we formally test this appropriability theory and provide several case studies in support.

Keywords: Urban Revolution, Cities, Trade, Bronze Age

JEL Codes: D02, F10, H10, N40, O43

We thank seminar audiences at Boston College, Bayreuth, Dartmouth, Drexel, George Mason University, Georgetown, Harvard, LUISS, Maastricht University, University of Michigan, New York University, University of Pennsylvania, Princeton, Stanford, University of Southern California, Toulouse, Yale, UCLA. We also thank participants in the following workshops: GDEC (2022), NBER Culture and Institutions workshop (2023), USC Trade Miniconference (2023), Princeton IES Summer Trade Workshop (2023). Finally, we would like to thank for helpful comments Ran Abramitzky, Jim Anderson, Costas Arkolakis, Gojko Barjamovic, Daniel Bernhofen, Leah Boustan, Thomas Chaney, Kerem Cosar, Mark Dincecco, Raquel Fernandez, James Fenske, Edward Glaeser, Leander Heldring, Noel Johnson, John McLaren, Ian Morris, Josh Ober, Teresa Fort, Stelios Michalopoulos, Mushfiq Mobarak, Lorenz Rhettstrom, Steve Redding, Jose-Antonio Espin-Sanchez, Robert Staiger, Jesus Fernandez-Villaverde, Joachim Voth, Yoto Yotov. Luigi Pascali acknowledges financial support from the Spanish Ministry of Economy and Competitiveness, through the Severo Ochoa Programme for Centres of Excellence in R&D (CEX2019-000915-S).

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1 Introduction

During the latter half of the fourth millennium BC, a remarkable transformation in human societal structures took place. Our ancestors evolved from simple agrarian villages into complex, urban civilizations. The seeds of this transformation can be traced back to around 9000 BC, when the advent of agriculture set off a demographic explosion and spurred the rise of the first large farming settlements. Yet, it wasn’t until the fourth millennium BC that state-level societies began to emerge, marked by the rise of monumental buildings, the appearance of writing, and the rise of bustling urban centers housing over 10,000 residents. This dramatic shift was eloquently encapsulated by Childe’s term, the “Urban Revolution.” Within less than a millennium, the defining elements of this revolution materialized in disparate regions, stretching from the Nile Valley and Mesopotamia to the distant landscape of Central Asia and the Indus Valley. Not long after, a comparable transition happened in Anatolia, China, Greece, and the broader Mediterranean basin. The emergence of the Urban Revolution raises intriguing, fundamental questions. What caused this transition? Why did it emerge in some regions but not in others? These are fundamental questions in comparative development as an early start in the civilization process has been posited as a crucial determinant in explaining the relative economic success of nations today¹. The objective of the article is to propose a theory aimed at addressing these research questions in the context of the Old World and to test this theory using novel data and a series of natural experiments of history.

We conjecture that the turning point is the invention of bronze in the fourth millennium BC. The discovery of bronze enabled our ancestors to create metal tools, which made farming and hunting more efficient, and metal weapons. Rapidly, bronze became a fundamental material for the survival of farming societies and elaborate arrangements had to be made to ensure a continuous supply of it for essentially two reasons. First, metals were generally scarce in densely populated areas. Second, bronze is an alloy made primarily with copper and tin, two metals that are naturally to be found in regions far away from each other. The result was an explosion of long-distance trade. Some of the trade routes connecting large populations with far-away mining regions were constrained by natural topography to pass by some regional bottlenecks. Traders could not avoid these bottlenecks unless they were willing to face disproportionate transportation costs. We posit that it is precisely in these choke points that a new elite, relying on taxing these transit traders, could emerge, leading

¹Recent research in the field of comparative development has highlighted an exceptional persistence in the levels of economic, technological, and political development around the world until 1500 AD (Comin, Easterly and Gong, 2010; Ashraf and Galor, 2011; Maloney and Valencia Caicedo, 2016; Davis and Weinstein, 2002; Olsson and Paik, 2020). Although the European colonization seems to have created a “reversal of fortune” among European colonies (Acemoglu, Johnson and Robinson, 2002), once accounting for migration between countries, ancient economic disparities are still explaining a large portion of current economic disparities (Putterman and Weil, 2010; Chanda, Cook and Putterman, 2014). See Galor (2011) and Galor (2022) for an exhaustive review of the main theories and narratives behind the long-term persistence of economic outcomes. Matranga and Pascali (2021) provide a review of the empirical work.
eventually to the city-states and the great civilizations of the antiquity.

To test this theory, we proceed in three steps: 1) identify the transit regions in the metal trade network, 2) estimate the causal impact of transit metal trade on the emergence of the Urban Revolution, and 3) elucidate the mechanism by which transit metal trade precipitated the rise of the Urban Revolution.

In Section 4, we identify the transit regions in the Bronze-Age metal trade network. We use a definition that goes back to Ramsay (1890), who proposed the concept of “road-knots”: the passages in which a series of routes, dictated by natural topography, intersect. To locate these areas, we start by constructing the Bronze-Age natural transportation network. Specifically, we combine data on natural topography and bilateral trade relationships (inferred from archaeological artifacts) to figure the least-cost paths between any two grid cells (1×1 degree) in the Old World. Long-distance trade during the Bronze Age is essentially an exchange of metals, mainly copper and tin, for cereal grains. We identify the “road-knots” in the resulting trade network by counting the least-cost paths that transit each grid cell, while connecting the cells with tin and copper mines with all the other reachable cells, weighted by their respective cropland areas.

In Section 5, we test the causal impact of transit metal trade on the rise of the Urban Revolution. Our research question doesn’t allow for one perfect randomized controlled trial that could prove and disprove our thesis. Plus, to our knowledge, there does not exist an ideal global database that coherently measures the different defining aspects of the Urban Revolution. We therefore perform multiple imperfect tests based on different datasets. We present our empirical analysis in four subsections, each using different data, that capture different aspects of the Urban Revolution, and different identification strategies, as dictated by the nature of the underlined data.

The first subsection focuses on the emergence of large cities. We use two readily available datasets to capture the evolution of urban settlements over time: Reba, Reitsma and Seto (2016) and Klein Goldewijk, Beusen and Janssen (2010) provide data on cities’ location and urban population from the fourth millennium BC. Figure 1 illustrates the grid cells we identified as road-knots in the metal trade network and all recorded settlements with 10,000+ inhabitants dating before the Bronze Age (1300 BC) collapse. Almost all cities in the sample arose in potential transit areas in the metal trade routes, a result confirmed by our cross-sectional OLS estimates. Still, several factors prevent a causal interpretation of this correlation. In particular, our measure of transit trade potential is likely to be affected by the rise of cities and the urban revolution itself as it depends on the distribution of mines and cropland areas around the globe, which are clearly endogenous to the location of cities and complex hierarchies. To get closer to a causal link between metal transit trade and the rise of cities, we use a 2SLS panel estimation framework. The instrumental variable is an alternative measure of transit trade potential, which does not rely on the endogenous distribution of
metal mines and cropland, is not affected by human intervention, and is purely driven by geography and climate. It is constructed by counting the number of least-cost paths that transit a certain cell, while connecting the cells with tin and copper natural deposits (not the Bronze-Age mines) to the other cells in the Old World, weighted by their approximate net primary production (NPP), a measure of the maximum potential biomass that can be produced in a certain region, given the local geo-climatic conditions\textsuperscript{2,3}. The 2SLS panel regressions confirm the results of the OLS panel regressions. Doubling the number of least-cost metal trade paths, transiting a certain cell, translates into an increased probability of a city being located in that cell by more than half of the average value of the dependent variable. Furthermore, we observe that while the transit regions in the copper trade played a crucial role from the fourth millennium BC, the significance of transit areas in the tin trade only became apparent from the latter half of the third millennium BC. This development mirrors the transition from arsenic bronze, an alloy of arsenic and copper, to tin bronze, an alloy of tin and copper, which occurred during the third millennium BC.

The results based on ancient cities are not conclusive. First, due to the cross-sectional nature of the data we cannot exclude potential omitted geographic factors that might be driving the 2SLS results (though we do control for a large set of potential confounders). Furthermore, an evaluation of pre-trends is challenging given that, barring a few exceptions, urban settlements prior to bronze usage are scarce. Secondly, the emergence of cities represents merely one facet of the Urban Revolution, failing to encapsulate other pivotal aspects such as the escalation in socioeconomic disparities and hierarchical complexity.

To overcome these limitations, in the second subsection, we employ two additional data sources, which report radio-carbon data on the location of archaeological sites in the Old World, which presumably indicate social and political hierarchy (e.g., pyramids, ancient temples, and palaces). The first is an historical atlas of the most relevant archaeological sites (Whitehouse and Whitehouse, 1975) and the second is a gazetteer for ancient history (the Pleiades Project, Bagnall, 2022). Using a difference-in-difference design, we show that road-knots are associated with a relative increase in settlements and archaeological sites during the Bronze Age (as compared to the Stone Age). This result is confirmed in both OLS and 2SLS estimates and is not explained by pre-trends. Our estimates suggest that metal trade accounts for approximately a third of the increase in sites indicative of complex social hierarchies. Admittedly, these back-of-the-envelope calculations are very crude estimates and should be taken with a grain of salt as they assume that the roll out of the metallurgical techniques was uniform across the globe. Still, overall, our estimates suggest that the invention of

\textsuperscript{2}To estimate the NPP, we used a paleoclimate simulator, which reconstructs past climate conditions in a high-resolution manner (Karger et al., 2021) in conjunction with a well-established model of habitat development in response to climate (Miami model, see Lieth, 1975)

\textsuperscript{3}Using the NPP to measure land productivity comes with important advantages: it is unaffected by human intervention and it captures land productivity for both hunter-gatherers and farmers, independently from the mixed of crops and animals (domesticated or not) used for subsistence.
bronzes were definitely not just a by-product of the Urban Revolution but an important driver. The two sources to capture the rise of social and political hierarchies in this subsection have some caveats: one is dated and the second one is skewed towards Europe, the Middle East and Mediterranean Africa. For this reason, in the following two empirical subsections, we move to high-quality regional data (at the cost of losing a global perspective).

In the third subsection, we use the Atlas of Chinese Relicss, a 47-volume atlas published by the Chinese National Heritage Administration with detailed information on 500,000+ archaeological sites dating from the Neolithic onwards. We digitize the atlas and use a Naive Bayesian text algorithm to identify sites indicative of the rise of the Urban Revolution. Specifically, the algorithm recognizes those sites that are indicative of some of the criteria that Gordon Childe uses to define the Urban Revolution: large settlements, monumental public works, specialized ruling class exempt from manual tasks, a system of recording used in the production process, written documents, and artistic expression. Once again, using both an OLS and 2SLS difference-in-difference design, we find that metal trade led to a statistically significant relative increase in all these six elements defining the Urban Revolution.

In the fourth subsection, we look at Bronze-Age Europe. We digitize the Prähistorische Bronzefunde, a series of monographs on metal artifacts dating from 3000 to 500 BC. Specifically, we focus on swords and axes found in graves, which have been argued to be a relevant indicator of relative social status. One of the advantages of focusing on Europe is that we can date the majority of copper and tin mines serving the continent depending on whether they were operating during the middle or late Bronze Age. We can thus study how changes in the road-knots, induced by new mineral discoveries, affected social hierarchy during the Bronze Age. We find that doubling the optimal paths transiting by a grid cell is associated with a three-fold increase in the probability of observing metal weapons in the Bronze Age graves located in that cell.

The results so far suggest that metal trade was an essential driver of the Urban Revolution: cities and unprecedented inequality were much more likely to emerge in the trade road-knots compared to other regions. But - why is it that road-knots were so crucial to the rise of cities and complex hierarchies? We propose a simple theory that emphasizes the appropriability of transit trade. When long-distance trade exploded following the invention of bronze, a new elite relying on taxing transit trade could emerge, leading eventually to the rise of cities and more complex hierarchies. We note that transit trade is appropriable not just by a would-be elite, but also by bandits – therefore, it also generated a demand for protection while, at the same time, facilitating the development of a tax system needed to finance the supply of such protection by an elite.

In Section 6, we test for this appropriability mechanism. Guided by theory, we construct a grid-cell measure of the potential revenues from taxing the local transit trade. For each grid cell in the Old World, we compute the increase in global transportation costs in the metal trade
network if that cell is removed from the network. The intuition is that fiscal revenues from taxing transit trade in a certain location cannot exceed the transportation costs traders would incur to bypass that location. Essentially, this variable identifies the bottlenecks in the metal trade network. We then study whether the Urban Revolution is predicted by our measure of potential transit trade (i.e., the road knots) or our measure of potential fiscal revenues (i.e., the bottlenecks). It turns out that, when both variables are included as regressors, only the latter one consistently seems to predict the rise of cities, settlements and archaeological sites produced during the Bronze Age. This result points towards our appropriability theory as the main candidate to explain the impact of transit trade on the rise of the Urban Revolution.

To provide further evidence in support of the appropriability theory, in Section 6, we present six case studies that illustrate the role of trade in spurring the rise of cities, socio-economic inequalities, and states in Mesopotamia, Anatolia, the Indus Valley, the Aegean Sea, and China.

The city-state of Assur, the capital of what would become the Assyrian Empire, provides an example of how trade in metals fostered the rise of cities and states in the Bronze Age. Originally, Assur was a small settlement lying on the least productive edge of Mesopotamia at an equal distance from Anatolia and Iran. Its fate changed when bronze metallurgy diffused in the Near East. Anatolia had a dense population supported by productive agriculture but lacked an indigenous tin source. The most feasible method for the Anatolians to import tin was engagement with Assyrians, who in turn probably obtained it from the mountains of southwest Iran. Assur became a nodal point on this route. The chiefs of Assur promoted this transit trade by guaranteeing a series of privileges and protection to the traders passing by the city (see Section 7.3 for further details). By the dawn of the second millennium, Assur became the capital of a trade civilization. Assyrian chiefs established a series of trading colonies along the trade routes connecting Assur with the small Anatolian city-states. These trade posts reproduced Assur’s legal and financial institutions and played a crucial role in fostering the economic, institutional, and demographic development of Anatolian city-states. In particular, they were instrumental to the rise of a local elite of Anatolian kings, which were both guaranteeing protection for passing merchant caravans and maintaining roads and bridges in exchange for tolls and taxes on transit trade.

Let us emphasize here that complex hierarchies and trade pre-date the invention of Bronze. The circulation of prestige goods in the Neolithic indicates both the presence of chiefs, who were able to control the surplus produced in areas with storable crops, and the existence of a system of exchange within a limited territory, with occasional short-lived long-distance connections. What is fundamentally different in the Bronze Age is the scale in both hierarchical complexity and long-distance exchanges. During the Neolithic, there were no states and no long-distance trade networks of the kind that provided all Bronze Age communities, on a regular basis, with metals coming from mines thousands of miles away. The shift from
local exchange to high-end international trade created, especially through rivers, seacoast and valleys, some clear bottlenecks. Controlling these bottlenecks allowed the rise of a new elite, which was based on the control (or ownership) of passage routes, rather than agricultural land for storable crops. An example of such a shift from the Neolithic to the Bronze Age is provided by the distribution of tells in Hungary. In the Neolithic, tells were concentrated in the highly fertile lowlands lands along the Tsiza. Archaeological findings of the prestige goods, dating from the period, are found with a typical fall-off curve from the tell indicating a regional economy with sporadic long-distance exchanges. During the Bronze Age, new tells formed in vacant areas, lined up along the Danube. These locations made little sense for agriculture: villages on the bank of a large river have access to only half of the circular catchment area of villages in the middle of productive land. They made sense, however, in the eyes of a new elite that could easily tax the resulting transit trade. This link between the elite and the metal trade is confirmed by the presence of metal hoards in the palaces and bronze objects in the elite burials. These objects also testify the development of regular interregional economic interactions and division of labor (see Kristiansen and Suchowska-Ducke, 2015).

The paper is organised as follows. Section 2 describes the previous literature. Section 3 provides a detailed description of the data used for the empirical analysis. Section 4 lays out the empirical strategy to identify the passage routes in the metal trade network. Section 5 identifies the impact of metal trade on the rise and diffusion of cities and inequality in the Old World. Section 6 describes and tests the appropriability mechanism. Section 7 presents six case studies that are consistent with a metal trade theory of the Urban Revolution. Some concluding remarks close the paper.

2 Previous Literature

Our work speaks essentially to two separate bodies of literature in the social sciences.

First, it contributes to a large empirical literature in economics that studies the role of international connections and market access for comparative development. To our knowledge, our work is a first attempt, within this literature, to go back to the very beginning of the civilization process, has a global scope and provides some empirical validation to the view that trade might have been the raison d’être of the Urban Revolution. The closest work is Barjamovic et al. (2019), which shows that natural transportation networks are critical in explaining the hierarchy of ancient city sizes in Central Turkey during the Middle Bronze Age (2000-1650 BC)\(^4\).

Second, our findings contribute to the body of literature that emphasizes the role of geography

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\(^4\)A recent literature has documented the role of trade in ancient development during the Iron Age. See Bakker et al. (2021) on Phoenician cities, Adamson (2021) on Greek city-states and Flückiger et al. (2022) on Roman cities.
in explaining the emergence of cities and complex hierarchies. Within this literature, three sets of theories have emerged. The first set of theories relates the emergence of the Urban Revolution to the increased productivity of labor that came with agriculture. An example of such a “productivity” theory is provided by Diamond (1998), who famously argued that the early comparative development of Eurasia lies in a series of environmental advantages, which resulted in a larger variety of domesticated crops and animals, and ultimately in both an earlier transition to farming and more productive agriculture\(^5\). The second set of theories suggests that the Urban Revolution is linked to an increased appropriability in the product of labor by an emerging elite: complex hierarchies and cities are more likely to emerge in regions in which the output of farmers could be easily taxed (or expropriated). An influential “appropriability” theory goes back to Carneiro (1970)’s circumscription theory, which contends that supranational polities emerge in areas with high agricultural productivity surrounded by geographic barriers that prevented farmers from escaping from an expropriating elite\(^6,7\). The third set of theories relates the emergence of complex hierarchies with a series of functions that a powerful elite can provide. Prominent “functionalist” theories focus on the demand for the construction and maintenance of hydraulic infrastructures\(^8\) or storage facilities\(^9\) and the demand for stability and security\(^10\) as means to increase the productivity of workers. These three sets of theories provide different mechanisms through which the alluvial lowlands of the Tigris and the Euphrates in Mesopotamia, the Nile in Egypt, the Indus and the Ghaggar-Hakra in India, and the Yellow River in China became the cradles of civilization. The productivity theories highlight the agricultural productivity of alluvial lands, the appropriability theories emphasize the circumscription of these areas or the relatively high productivity of cereal grains, and the functionalist theories point towards the higher scope for a series of infrastructures, like dams or irrigation systems. We propose a different mechanism, which speaks to both the appropriability and the functionalist approaches. Rivers were the highways of the Bronze Age: long-distance trade in metals and grains was forced to transit

\(^5\)The productivity theories on the rise of early complex hierarchies have a long pedigree in social sciences. Adam Smith argued that the Neolithic transition produced in some regions large farming surpluses. These surpluses made it possible to have a class of bureaucrats, as a result of labor specialization, and increased the demand for an extended role of government (Smith, 1978, p. 65). Friedrich Engels (1942) argued similarly that the surplus generated by the adoption of agriculture was a prerequisite for the transition to a class society. More recently, a growing empirical literature in comparative development has shown that a richer prehistoric availability of domesticates is an important predictor of the timing of the Neolithic transition (Ashraf and Galor, 2011), the early emergence of macro-level polities (Borcan, Olsson and Putterman, 2018; Petersen and Skaaning, 2010), independence from colonial powers post 1500 AD (Ertan, Fiszbein and Putterman, 2016) and higher per-capita GDP today (Bleaney and Dimico, 2011; Hibbs and Olsson, 2004).

\(^6\)Mayoral and Olsson (2020) and Schönholzer (2020) provide systematic evidence in support for the circumscription theory of state formation. See also Allen, Bertazzini and Heldring (2022).

\(^7\)More recently, Mayshar, Moav and Pascali (2022) show that the first urban civilizations emerged in regions in which farmers were constrained by geography to grow cereal grains, which are storable and easy to transport, making it relatively easy for an elite to confiscate them and transport them to distant centers of power.

\(^8\)See Wittfogel (1957) and Bentzen, Kaarsen and Wingender (2017).

\(^9\)See Testart et al. (1982).

these rivers, thus creating local demand for a state, able to guarantee the welfare gains from trade, and making it possible to have a state, as transit trade could be easily taxed. Cities in the Bronze Age, with few exceptions, were located on either alluvial valleys or, after 2000 BC, in coastal regions. One clear advantage of our proposed mechanism is that it can explain not only cities along the rivers but also cities along the coast, as coastal navigation provides an alternative to river navigation to move bulky materials. None of these first coastal cities was located in areas where agriculture was exceptionally productive, while all of them were located in strategic trade nodes. For instance, in the Mediterranean, the Aegean cities related with the Minoan (from 1900 BC) and the Mycenaean (from 1600 BC) civilizations emerged on a crucial passing point between Europe and the Near East, while the city of Troy (from 1400 BC), on the Bosporus Strait, could control all trade in and out of the Black Sea. Notice that the long-distance trade explanation of the origin of the Urban Revolution also provides some rationality for a fascinating hypothesis that relates the invention of ironworking with the collapse of the Bronze Age civilizations\textsuperscript{11}.

The idea that long-distance trade in metals was a fundamental driver of the civilization process is of course not new. Metal trade has been cited repeatedly as a factor in primary state development (Childe, 1930; Sanders, 1968; Polanyi, Pearson and Alrensburg, 1957). Our theory is particularly close to recent works of Timothy Earle and Kristian Kristiansen\textsuperscript{12}. These authors have emphasized the role of long-distance metal trade in fostering a regional economic division of labor. Specifically, they argue that bottlenecks in commodity flows created potential for social segments to control the production and flows of critical metal goods: this eventually led to more complex and ranked societies and the rise of networks of integrated polities\textsuperscript{13}.

Other authors have emphasized the role of long-distance trade in metals in fostering the development of specific civilizations. Famously, Gordon Childe suggested that the origins of the Egyptian states could be found in the copper long-distance trade between the Nile region

\textsuperscript{11}In the 13th century BC, ironworking starts spreading from present-day Bulgaria and Romania, while all major civilizations in Europe, West Asia and Africa collapsed. Within five decades, almost all cities were destroyed, trade relations were severed, writing systems vanished and populations living along the coast moved to the interior. Palmer (1962) suggested that spread of ironworking might be the reason behind the Bronze Age collapse. Iron is superior to bronze for weapons and agricultural tools and can be found almost anywhere in the Old World. The diffusion of the ironworking technology might have been detrimental for the Bronze Age main civilizations for two reasons. First, it undermined the role of Bronze-Age cities as it nullified their locational advantage on the trade routes towards copper and tin mines and it made obsolete a series of city-institutions constructed to protect interregional trade. Second, it undermined an elite based on the control of metal trade and it allowed newly formed peripheral armies with iron weapons to quickly destabilize entire states.

\textsuperscript{12}See Earle (2013); Earle and Spriggs (2015); Earle et al. (2015); Kristiansen and Suchowska-Ducke (2015); Kristiansen and Earle (2015)

\textsuperscript{13}According to Kristiansen and Earle (2015): “Participation in the metal trade and in other new forms of long-distance trade in wool/textiles and salt would have demanded the creation of political alliances linking polities together – sometimes in confederations – in order to protect traders and their products. Participation in such institutionalized networks (providing wealth finance) and the formation of institutionalized warrior groups enabled local chiefs and centrally located tells to mobilize local resources (stable finance) by controlling the distribution of metal for both subsistence and prestige goods.”
and the Red Sea\textsuperscript{14}. In section 7, we review the literature on the link between metal trade and the Urban Revolution with reference to a series of Bronze Age civilizations that rose in Mesopotamia, Anatolia, the Indus Valley, the Aegean Sea, and China. With respect to this literature, our approach has two advantages. First, we do not focus on a particular region or society: we test a general theory on the role of Bronze and trade in metals on the rise of the first urban civilizations using data covering the entirety of the Old World. Second, we use a natural experiment of history to infer causality.

3 Data

3.1 The Urban Revolution

The Urban Revolution is a multifaceted process and capturing it in the archaeological data in a consistent manner across space and time is difficult. Gordon Childe (1950) defined ten specific criteria, all deducible from archaeological data, to distinguish the earliest instances of the Urban Revolution from any older or contemporary Neolithic village: 1) population density higher than in any previous settlements, 2) a class of full-time specialists (craftsmen, merchants, officials, priests, etc.) that do not work directly to procure their food and live on-site, 3) a system of transfers (through taxes or donations) of the primary surplus from producers to the elite, 4) truly monumental buildings which symbolize the concentration of social surplus, 5) a ruling class exempt from all manual tasks, 6) systems of recording and exact sciences, 7) scripts and calendars, 8) artistic expressions, 9) regular long-distance trade relationships, 10) state organization based on residency rather than kinship. Unfortunately, to our knowledge, a dataset that perfectly captures the emergence of these ten criteria in archaeological sites across the Old World does not exist. We rely, instead, on imperfect datasets that capture only some of these criteria.

3.1.1 Urban settlements

We use two readily available datasets to capture the first of Childe’s criteria identifying the Urban Revolution: the increase in village size.

The first dataset captures the location of ancient cities and was assembled by Reba, Reitsma and Seto (2016) using two principal sources: Chandler (1987) and Modelski (2003). Both Chandler and Modelski define a city, as distinct from a village, based upon population estimates. Specifically, for the years before 1000 BC, a city is defined as a concentration of at least 10,000 inhabitants. The dataset is developed using archaeological records, historical works, census data, and applying rank-order principles, like Zipf’s law. Data are generally

\textsuperscript{14}In the words of Childe (1930): “Some favorably situated villages grew into real towns, and the chief of one of them, Abydos, that commanded one main caravan route to the Red Sea and the East, was eventually able to master the whole land to the Mediterranean coasts, founding what is termed the First Dynasty (about 3100 BC).
sparse over time. Some cities have several population data points before 1000 BC, while others only have one or two observations; some missing values in the time series are imputed using different methodologies. The sparse nature of the data does not allow us to measure the spread of urban settlements over time; we only use the information on whether there is any evidence of a certain city at any point in time before the Bronze Age collapse (1300 BC).\textsuperscript{15} The location of these cities is depicted by the grey-shaded dots in Figure 1. Based on this information, we then construct a dummy variable that identifies those 1\times1-grid cells in the Old World for which there is evidence of at least one ancient city. As an alternative outcome, we use the number of ancient cities located in each grid cell. The first two rows of Table A.1 report summary statistics for these two outcome variables. There are a total of 64 pre-1300 BC cities, which fall into 46 separate grid cells. There is evidence of ancient cities in only 0.5 percent of the sample, while the maximum number of ancient cities in a cell is 7 (at the delta of the Tigris and Euphrates).

A clear shortcoming of the Reba, Reitsma and Seto (2016)’s dataset is that is based on sources that date back to the early 2000s, thus omitting the most recent advances in urban archaeology. For this reason, we also run a series of robustness checks using a more recent dataset, HYDE 3.1 (Klein Goldewijk, Beusen and Janssen, 2010). This data source offers spatially explicit urban population estimates every millennium after 10000 BC. For our analysis, we use the estimates for 2000 BC, the latest available year before the Bronze Age Collapse.\textsuperscript{16} Admittedly, most of the information provided by HYDE 3.1 are the results of state-of-art imputation techniques based on relatively few data points.

\subsection{3.1.2 Archaeological sites}

In an attempt to capture the increase in large settlements, the rise of monumental buildings, and the increase in political and economic inequality -three essential elements of the Urban Revolution- we rely on two archaeological data sources. The first source is Whitehouse and Whitehouse (1975)’s Archaeological Atlas of the World, a collection of detailed maps and descriptions of the world’s most relevant archaeological sites. The Atlas covers 4,215 radiocarbon-dated sites. We geocode these sites and, using the information in the map titles and accompanying text, classify them according to whether they pre-date the invention of bronze. The result is a list of 1,487 sites that belong to the Stone Age and 1,373 sites that belong to the Bronze Age. Figure B.1 shows the location of these sites. For the empirical analysis, we create a 1\times1-degree grid cell level panel data set with the two time periods, Stone Age and Bronze Age, for which we record two variables: the number of sites and the number of sites classified as settlements. Table A.1 reports summary statistics for these two outcome variables. Only 8.5 (5.6) percent of grid cells have at least a

\textsuperscript{15}Results are not sensitive to the exact choice of the cutoff date. We obtain extremely similar results when we use any date between 1500 BC and 500 BC as a cutoff.

\textsuperscript{16}Using estimates for the year 1000 BC leaves our results unchanged.
site (a settlement), while the maximum number of sites (settlements) in a grid cell is 57 (19). The main drawback of the Atlas is that it is clearly outdated and does not reflect the archaeological findings in the last 40 years. For this reason, we also use a second source: the Pleiades Project, an open-source gazetteer of ancient sites (Bagnall, 2022).\textsuperscript{17} We limit our analysis to sites where the location is precisely known and categorize these sites into two groups: settlements and other archaeological sites.\textsuperscript{18} The first group is restricted to those places labeled as ‘settlement’ or ‘urban’ in the database. The second group includes all sites characterized by the presence of man-made structures. The spatial distribution of the sites used in our analysis is depicted in Figure B.2.

To assign these sites to a time period, we use two alternative approaches. First, we use the (textual) description in the Pleiades database to identify the Stone Age sites and the Bronze Age sites. (This leaves us with a total of 930 sites - 251 from the Stone Age and 679 from the Bronze Age). We then count the sites that fall into a grid cell in each of these two eras. The result is thus a two-period grid-cell level panel dataset. Alternatively, we exploit the (numeric) estimates of start and end date of a site, which are reported in the Pleiades database. On the basis of these dates we construct a panel dataset that covers the years 6000–1300 BC at a 1,000 year interval.\textsuperscript{19} For each millennium we then determine how many settlements and archaeological sites lie within a grid cell. This gives us a five-period grid-cell level panel dataset.

### 3.1.3 China

Data on the rise and spread of the Urban Revolution in China are drawn from the Chinese Cultural Heritage Atlas, the most comprehensive catalog of Chinese archaeological sites. This source is based on joint efforts between the Chinese central and provincial cultural heritage bureaus to compile a mapping of all excavated monuments and remains in China. The catalog is completed for 28 out of 34 provinces (data for the provinces of Taiwan, Macau, Hong Kong, Jiangxi, Guizhou and Hainan are still under construction). Each archaeological site is geocoded, dated and described in detail. We OCR the 31 volumes that compose the Atlas and focus on the 85,000+ sites dating Before the Common Era. The spatial distribution of these sites is illustrated in Appendix Figure B.3. Each site contains a long description (on average 58 words). For a tenth of the sample, we manually coded whether this description makes any reference to one of the following features: 1) urban settlements, 2) ruling class exempt from manual tasks, 3) monumental building, 4) a standardized system of measures and recordings used in exchange and production, 5) writing, 6) highly developed art forms. After developing this training sample, we use a naïve Bayesian classifier to classify all sites

\textsuperscript{17}See pleiades.stoa.org/docs for detailed documentation.

\textsuperscript{18}Bakker et al. (2021) refer to these two classes as ‘wide’ and ‘narrow’. See Bakker et al. (2021, p.658) for more details.

\textsuperscript{19}The time intervals are: [6000, 5000), [5000, 4000), [4000, 3000), [3000, 2000), [2000, 1300]
in the Atlas according to these six criteria. Appendix Figure B.4 reports a correspondence plot, which details the words that are overused to describe the sites classified according to each criterion. For instance, in the top right, we can see that words like “city”, “township”, “wall”, and “village” are associated with the criteria “Urban Settlements”, while words like “Han”, “Dynasty”, “State”, are associated with the criteria “Ruling Class”. Once each site has been classified, we then count the sites associated with criteria indicative of the Urban Revolution in each 1×1 grid cell in the Paleolithic, Neolithic and Bronze Age.

3.1.4 Europe

Europe is the most studied region in world archaeology. In this context, we attempt to measure the evolution of socio-economic stratification during Bronze Age, by studying the findings of high-value grave goods—particularly bronze weapons—which are indicative of the existence of local chiefdoms (Renfrew and Bahn, 2016, pp. 175, Earle et al., 2015).

We extract information on location and type of bronze weapons from the Prähistorische Bronzelfunde (PBF). This research project systematically gathers information on archaeological metal artifacts (predominantly bronze artifacts) excavated in Europe. Since 1966, the project has published 186 volumes which record details on individual metal finds dating from 3000 to 500 BC. PBF organizes these volumes into series of books—referred to as Abteilungen (divisions)—according to the type of artefact. For example, Abteilung IX covers axes and hatchets and includes 29 volumes. Each of these volumes, in turn, covers axes and hatchets excavated in one specific region. The PFB typically commissions an archaeologist specializing in this region to collate information on excavated artifacts from a variety of sources (e.g., museums).

Throughout, we focus on Bronze Age weapons. Specifically, we draw artifacts classified as ‘axes and hatchets’ and ‘swords’ (Abteilung IX and Abteilung IV). The former contains 29 volumes, the latter 10 volumes. We supplement these data with artifacts from the ‘Bronze- und urnenfelderzeitliche Schwert’ database (Hahnekamp, 2011). We provide further details on the sources and data construction processes in Appendix ??.

For each individual artifact in our database, we observe following three key pieces of information: (i) the geographical location of the excavation site, (ii) the nature of the excavation site (e.g., burial site), and (iii) the archaeological type or archaeological family of the artifact (e.g., Pădureni axe type). Based on (ii) we can identify the presence of elite burials, i.e., if a bronze weapon was a grave good or not. The detailed description of the artifact itself, (iii), allows us to assign the individual artifact to specific cultures which, in turn, enables us to map them to time periods (Early-, Middle- and Late Bronze Age).

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20 For example, the volumes on bronze axes and hatchets excavated in Romania (Abteilung IX: Äxte, Beile—Die Äxte und Beile in Rumänien I-II) were written by Alexandru Vulpe a Romanian archaeologist.

21 http://chc.sbg.ac.at/schwerter/map.php
For our empirical analysis we create a 1×1-degree grid-cell panel data set comprising two time periods: Early/Middle Bronze Age [3000 BC, 1300 BC) and Late Bronze Age [1300 BC, 500 BC]. Using aspects (i)–(iii) we define our measure of hierarchy as a dummy that takes the value one if a bronze weapon is discovered at a Bronze Age burial site in a given cell and period, and zero otherwise. Table A.1 reports summary statistics of the dataset.

### 3.2 Bilateral trade flows

We reconstruct trade flows for prehistoric periods using archaeological artifacts. For artifacts to be included in our analysis, two requirements have to be fulfilled. A first prerequisite is that an artifact’s find site and provenance can be identified. This allows us to reconstruct trade flows by defining the archaeological excavation site as the destination and the production site as the origin.\(^{22}\) The second prerequisite is that the period of production is known. In the main analysis, we will focus on goods produced and traded during the Bronze Age. For robustness checks, we will alternatively use goods produced during the Stone Age.

Combining existing databases, we identified approximately 7,500 artifacts that fulfill the two inclusion requirements. These artifacts vary in type and range from weapons, to jewelry, and utensils. For the Bronze Age, we estimate trade costs based on 3,744 metal-based artifacts. These data are taken from Flückiger et al. (2022). For the Stone Age, we can draw on around 3,700 artifacts. Data are taken from two existing databases (Pétrequin et al., 2012; Schauer et al., 2020). A more detailed description, including figures depicting the spatial extent of the trade data, is presented in Appendix C.

Based on the geocoded information on provenance and excavation site, we assign the artifacts to their respective 1×1-degree grid cell of origin and destination. We then aggregate this information to the grid-cell-pair level giving us the number of artifacts excavated in grid cell \(j\) and produced in grid cell \(i\) for the Stone Age and Bronze Age, respectively.

### 3.3 Cropland and productive land

We use data from Klein Goldewijk, Beusen and Janssen (2010) to determine the distribution of cropland over time. This dataset estimates land use at 1000-years intervals from 9,000 BC. It is worth noting that the distribution of farming populations may have been influenced by the great civilizations of the time. To isolate an exogenous component in this variable, we develop a specific measure of land productivity, the net primary production (NPP). This measure gauges the potential biomass that can be produced in a region based on local geo-climate conditions, and is therefore unaffected by human intervention. We utilize the Miami model (Lieth, 1975) to determine the NPP for given local climatic conditions, and the CHELSA-TraCE21k12 simulator (Karger et al., 2021) to reconstruct climatic conditions in a high-resolution manner every millennium from 9000 BC. This measure of land

\(^{22}\)See Flückiger et al. (2022) for a similar use of archaeological data.
productivity has several advantages for our analysis, compared to other measures previously used in the literature. Firstly, it captures land productivity for both hunter-gatherers and farmers. Secondly, it is independent of the mix of crops and animals used for subsistence, whether domesticated or not. Finally, it has a panel dimension with time variation generated by well-documented climatic changes.

In robustness checks, we also exploit two alternative measures of the productivity of the land, which have been widely used in the comparative development literature. The first is the Caloric Suitability Index developed in Galor and Özak (2016), which captures the highest attainable caloric yields from subsistence farming, given the set of crops available in Old World before the Columbian exchange. The second one is an index developed by Ramankutty et al. (2002), which captures the fraction of land that is suitable for agriculture.

3.4 Metal mines and deposits

We conducted a thorough review of the archaeological literature to compile a new dataset on Bronze-Age metal mining sites. The requirement for the inclusion of a mining site in the dataset is that both the location of the mine, as well as its activity during the Bronze Age, are identifiable. The final dataset comprises 44 tin mines and 121 copper mines, distributed across 30 and 79 separate grid cells, respectively. Appendix A provides a detailed description of the data-gathering process and the list of mines. For mines supplying Europe, we distinguish between those operating in the early and late Bronze Age. We exploit this variation in our case study on the rise of hierarchy in Europe in Section 5.4.

We face two significant challenges in using the mining data for our empirical analysis. Firstly, the location of mines is endogenous to the spatial distribution of cities and states. Secondly, the archaeological record of Bronze-Age mines may not accurately reflect the actual metal deposits exploited during that era. In particular, the sources of tin during the third millennium remain uncertain: Bronze Age miners did not have access to veins running through granite, and instead relied on cassiterite, which leaves no trace of its former contents. The resulting measurement error is not random, as archaeological findings on ancient metal sources are more likely to appear in regions that have been extensively excavated.

To address these endogeneity concerns, in the empirical analysis, we also use data on the actual location of tin and copper deposits as they are known today, regardless of whether they have ever been exploited or not, sourced from the U.S. Geological Survey (2011).

3.5 Other data

We construct a range of additional grid-cell level geographical characteristics for our empirical analysis. We extract information on coastlines and navigable rivers from naturalearthdata.\footnote{To account for the importance of rivers, we use the Strahler order of streams. This is an index that ranges from one to six. Navigable rivers are those that fall into categories 1–5 (Vörösmarty et al., 2000).}
com, while elevation data come from WorldClim (v. 2.1)\textsuperscript{24}. Additionally, we collect data on temperature and precipitation (Karger et al., 2021), length of growing season (FAO/IIASA, 2011), malaria suitability (Kiszewski et al., 2004), biomes (Olson et al., 2001) and natural harbors (NGA, 2019).

4 Bronze-Age transit regions

The aim of this section is to pinpoint the transit regions within the Bronze-Age metal trade network. To achieve this, we rely on Ramsay’s (1890) concept of 'road knots', the natural passage points where several trade routes intersect. In the first subsection, we employ established trade methodologies to analyze Bronze-Age trade data and reveal the underlying transportation network. In the second subsection, we utilize this network alongside information on the spatial distribution of cropland and metal sources to identify the road-knots in the metal trade network. To do this, we rely on the fact that long-distance Bronze-Age trade is driven by the necessity to exchange agricultural crops for tin and copper. Notably, the location of Bronze Age cropland and mines is likely influenced by the spatial development of the Urban Revolution. In the third subsection, we isolate an exogenous element of the road-knots by identifying the transit points that connect metal deposits and naturally productive land, which are not influenced by human intervention.

4.1 Period-specific transport costs

To our knowledge, estimates of the relative transportation costs during the Stone Age and the Bronze Age are unavailable. We infer them using a methodology in the spirit of Donaldson (2018). Based on data from naturalezaerthdata.com, we start by dividing the world into transport surface grids of 0.25\times0.25 degrees and assign each grid cell to one of the following shipping modes: sea, river, or land.\textsuperscript{25} Each mode is associated with a per-unit distance transport cost: $\alpha = (\alpha_{sea}, \alpha_{river}, \alpha_{land})$. We normalize $\alpha_{sea} = 1$, so that $\alpha$ captures how costly a given shipping mode is relative to maritime shipping. We impose three restrictions that reflect technological constraints during the Bronze Age: First, maritime transport is only possible along the coast (and below 60° latitude). Second, riverine transport is only feasible on navigable rivers. Third, transport is not possible across high mountain ranges (above 4,500 meters). The resulting topographical transport surface is depicted in Figure C.2.

The vector $\alpha$ is unknown, so we treat it as a vector of parameters to be estimated. Conditional on $\alpha$, we use the Dijkstra (1959)’s algorithm to identify the least-cost path between every

\textsuperscript{24}On the basis of these elevation data, we measure terrain ruggedness using the index devised in Riley, Degloria and Elliot (1999), ad in Nunn and Puga (2012).

\textsuperscript{25}The relatively coarse size of cells is chosen to account for the fact that coastlines as well as river courses can shift over time.
grid-cell pairs $ij$; $\text{LC}(\alpha)_{ij}$ denotes the associated transportation cost. We then estimate a standard gravity equation using the Poisson pseudo-maximum likelihood (PPML) estimator:

$$X_{ij}^p = \exp(\delta \ln \text{LC}(\alpha)_{ij} + \beta_i + \beta_j) + \varepsilon_{ij},$$

where $X_{ij}^p$ denotes the number artifacts dating from period $p$, excavated in grid cell $j$, and originating from grid cell $i$. $\beta_i$ and $\beta_j$ are a full set of origin and destination fixed effects.

We estimate equation (1) iteratively over all relative transport cost combinations $\alpha^{\text{river}} = [1, 100]$ and $\alpha^{\text{land}} = [1, 100]$ and we choose the vector $\alpha$ that minimizes the log-likelihood of the estimated gravity equation. For the Bronze Age, this fit-maximizing transport cost vector is given by $\alpha_{BA} = (1, 2, 6)$, while for the Stone Age is $\alpha_{SA} = (1, 1/14, 2/7)$.

Our estimates suggest that the relative costs of shipping goods changed dramatically across modes. Most strikingly, transport by sea evolved from being the most expensive way of moving goods during the Stone Age to being the cheapest in the Bronze Age. This implies that technological progress was heavily biased towards seafaring in the latter period. Reassuringly, this aligns well with archaeological evidence. During the Stone Age, waterborne transport depended entirely on dugout canoes. These canoes had shallow hulls and were propelled by men using oars or paddles. They were, therefore, neither suited for (or capable of) long-distance journeys nor large-scale cargo transport (Rahmstorf, 2010). As a result, long-distance trade took place overland. For example, goods exchanged between the Near East and Mediterranean Europe were most likely transported via the Anatolian land bridge (Rahmstorf, 2010). This pattern of overland-dominated transport changed with the development of deep-hulled boats alongside the invention of sails at the beginning of the Bronze Age. The plank boats with deep hulls could carry several tonnes of goods and were stable enough to be used for coastal shipping. The sailing technology further contributed to a reduction in seaborne transport by increasing the maneuverability and speed of boats (e.g., Nessel, Neumann and Bartelheim, 2018). These technological innovations facilitated large-scale transport of goods via sea routes, making seaborne transport the most cost-effective mode of shipping goods over long distances (e.g., Nessel, Neumann and Bartelheim, 2018). This resulted in the economic integration of the Mediterranean and Mesopotamia as well as flourishing long-distance trade between Mesopotamia and the Indus civilization via the Indian Ocean (e.g., Rahmstorf (2010), Cunliffe (2011, p.189) or Vogt (1996)).

Our estimates further suggest a moderate decline in overland transport costs relative to river transport between the Stone and the Bronze Age. Again, this finding aligns well with the archaeological evidence. During the Stone Age, goods were transported overland by humans or ox wagons, implying limited cargo carrying ability and slow progress across space. Several

26 Throughout, we assume that transshipment between different transport modes is costless.

27 However, it is important to note that river transport is relatively cheaper (compared to overland transport) during both the Stone Age and the Bronze Age.
important innovations increased both the speed and freight capacity during the Bronze Age. For example, the spoked wheel was invented along with chariots and other transport vehicles (Uckelmann, 2013). Furthermore, the Bronze Age saw the domestication of horses, which subsequently allowed harnessing them to vehicles. Similarly, the domestication of the camel made overland transport of bulk commodities in arid regions feasible. More details on the data and estimation procedure are provided in Appendix C.

4.2 Identifying the road-knots

We adopt a two-steps approach to identify the road knots within the metal trade natural transportation network.

In the first step, we utilize the estimated Bronze-Age specific transportation costs ($\alpha$) along with the topographic map of the world to infer the least-cost paths connecting each grid cell containing cropland in the year 3000 BC to the nearest tin mine and the nearest copper mine. To exclude impractically long routes, we disregard paths that are more costly than traveling a distance equivalent to 10,000 kilometers by sea. (It is important to note that this restriction does not significantly impact our empirical findings and results). In this way, we construct a comprehensive list of the optimal routes connecting cropland with metal mines.

In the second step, for each grid cell $g$, we calculate a 'transit index', $T_g$, as a weighted count of the optimal routes in this list that traverse through the cell. Specifically:

$$T_g = \sum_{m \in \text{copper, tin}} \sum_{\text{LCP}^m_{o} \cap g} \text{Crop}_o,$$

where $\text{LCP}^m_{o}$ denotes the optimal route connecting grid cell $o$ to the closest mine of metal $m$, and $\text{Crop}_o$ is the extent of cropland (measured in square kilometers) in grid cell $o$ in the year 3000 BC. In other words, $T_g$ is the number of least-cost paths transiting $g$ that connect one square kilometer of cropland to a metal mine. It is worth noting that $T_g$ is very similar to the concept of betweenness centrality in the network.\(^{28}\)

Figure 1 shows the spatial distribution of the transit index, with darker shading indicating the road-knots, and the location of Bronze-Age cities. We observe a clear correlation: most cities emerged in the metal trade road knots.

4.3 Transit trade: isolating an exogenous component

The finding above does not necessarily imply a causal link: the Bronze-Age distribution of both mines and cropland, which are used to infer $T_g$, was likely influenced by the spatial distribution of cities and advanced civilizations. To isolate exogenous variation in the transit index, we construct an alternative measure of centrality, $D_g$, which captures the transit regions

\(^{28}\)The betweenness centrality of a node in a network is defined as the number of least-cost paths, that pass through that node, connecting all node-pairs within the network
connecting metal deposits (rather than Bronze-Age mines) with productive land measured by net primary production (rather than Bronze-Age cropland), two components that are unaffected by human intervention.

We use the following formula:

$$D_g = \sum_{m \in \text{copper, tin}} \sum_{LCP^D_m \cap g} Prod_o,$$

where $LCP^D_o$ is the least-cost path that connects grid cell o with the nearest deposit of metal m that can be reached, paying the lowest transport costs; $Prod_o$ is the net primary production of cell o in the year 3000BC. Figure B.10 illustrates the distribution of tin and copper deposits and the net primary production measure (panel A) along with the resulting values of $D_g$ (panel B).

It is important to note that the estimation of $D_g$ relies on the relative transport costs estimated for the Bronze Age. The available technology during the time might have also been influenced by the Urban Revolution itself. To account for this, we also calculate an alternative value for $D_g$, which is based on the relative transport costs estimated for the Stone Age.
5 Metal trade and Urban Revolution

5.1 Cross-sectional evidence: Cities by 1300 BC

This subsection examines the link between metal trade and Bronze Age urban settlements. As we have seen, a visual inspection of Figure 1 provides a first clue of the positive correlation between the location of Bronze Age road knots and cities. We formally test for this relationship by estimating the following equation:

\[ y_g = \theta IHS(T_g) + X'_g \phi + \varepsilon_g, \]

(4)

\( y_g \) is a dummy indicating whether a city had emerged in grid cell \( g \) during the Bronze Age.\(^{29}\)

The main regressor of interest is \( T_g \), the transit trade index of grid cell \( g \), transformed using the inverse hyperbolic sine (IHS) transformation. The IHS transformation behaves like a log (thus filtering out scale effects), but it allows to retain the zero-value observations. The vector \( X_g \) represents a set of geographical controls.

To correct for the spatial autocorrelation of the error term, we estimate standard errors in two different ways: we allow either for clustering at the 5×5 grid cell level or for spatial autocorrelation, using Conley (1999) standard errors, with distance cutoffs of 1000 km. In Appendix Figures B.11a–B.11b, we show how results are affected by varying the size of the clustering grid (from 1×1 to 20×20) or the Conley cutoff (from 100km to 2,000km). The takeaway is that the size of standard errors is only slightly when relaxing the spatial correlation boundaries above those that we chose as benchmarks.

Table 1 reports the estimates. The data source for the location of Bronze-Age cities is Reba, Reitsma and Seto (2016). Column (1) reports the baseline OLS estimate, controlling solely for continent fixed effects.

The estimated coefficient on \( T_g \) is positive and statistically significant: doubling the number of least-cost paths, transiting a certain cell, translates into an increased probability of a Bronze Age city emerging in that cell by 0.0025. This is a significantly large figure, considering that cities are found in just 0.0049 percent of the grid cells by 1300 BC.

The OLS estimates reported in column (1) are far from having a causal interpretation. Variation in the transit index is influenced by various factors, including the spatial distribution of croplands and mines, which themselves may be affected by the spatial distribution of Bronze Age cities and civilizations. To get closer to a causal relationship between the metal transit trade and the emergence of cities, we employ a 2SLS estimation framework. The instrumental variable, described in detail in the previous section, is an alternative measure of potential transit trade, which captures the passage regions connecting mineral deposits and

\(^{29}\)For ease of interpretation, we multiply the dummy by 100.
Table 1: OLS and 2SLS-IV cross-sectional evidence: Reba, Reitsma and Seto (2016) city data

<table>
<thead>
<tr>
<th></th>
<th>Any City by 1300 BC (×100)</th>
<th>#Cities (×100)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OLS (1)</td>
<td>2SLS (2)</td>
</tr>
<tr>
<td><strong>OLS Panel A: Second stage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transit index</td>
<td>0.381 (0.106)***</td>
<td>0.431 (0.147)***</td>
</tr>
<tr>
<td></td>
<td>[0.142]***</td>
<td>[0.199]***</td>
</tr>
<tr>
<td>Proximity mines</td>
<td>0.014 (0.098)</td>
<td>-1.155 (0.484)**</td>
</tr>
<tr>
<td></td>
<td>[0.123]</td>
<td></td>
</tr>
<tr>
<td>Proximity croplands</td>
<td>0.225 (0.120)*</td>
<td>1.655 (0.610)**</td>
</tr>
<tr>
<td>Sea</td>
<td>0.274 (0.250)</td>
<td>0.353 (0.249)</td>
</tr>
<tr>
<td></td>
<td>[0.123]</td>
<td></td>
</tr>
<tr>
<td>River</td>
<td>0.439 (0.355)</td>
<td>0.620 (0.397)</td>
</tr>
<tr>
<td></td>
<td>[0.224]</td>
<td></td>
</tr>
<tr>
<td>Mountains</td>
<td>-0.433 (0.220)**</td>
<td>-0.088 (0.313)</td>
</tr>
<tr>
<td></td>
<td>[0.158]</td>
<td></td>
</tr>
<tr>
<td>Centrality</td>
<td>-0.019 (0.016)</td>
<td>-0.016 (0.015)</td>
</tr>
<tr>
<td></td>
<td>(0.016)</td>
<td></td>
</tr>
<tr>
<td><strong>Panel B: First stage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV Transit index</td>
<td>0.801 (0.050)***</td>
<td>0.689 (0.048)***</td>
</tr>
<tr>
<td></td>
<td>[0.071]***</td>
<td>[0.072]***</td>
</tr>
<tr>
<td>Continent fixed effects</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Area grid cell</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Mean dependent variable</td>
<td>0.488</td>
<td>0.488</td>
</tr>
<tr>
<td>First-stage F-stat (5×5 grids)</td>
<td>252.9</td>
<td>204.4</td>
</tr>
<tr>
<td>First-stage F-stat (Conley 1000km)</td>
<td>106.7</td>
<td>90.24</td>
</tr>
</tbody>
</table>

Notes: Panel A of this table reports the OLS and second-stage estimates of Equation (3) using 2SLS-IV. Panel B reports the corresponding first-stage estimates (Equation (4)). Standard errors clustered at the level of 5×5 degree grid cells reported in parentheses. Standard errors computed using the approach of Conley (1999) (cut-off 1000km) are reported in square brackets. ‘Any city by 1300 BC’ is a dummy equal to one if a city was present in a given 1×1 degree grid cell by 1300 BC. Variable is multiplied by hundred to facilitate interpretation. ‘#Cities’ is the total number of cities that had emerged in a grid cell by 1300 BC. Variable is multiplied by hundred to facilitate interpretation. ‘Transit index’ is the cropland and metal input weighted number of least-cost paths that intersect a grid cell, as defined in Equation (1). ‘IV Transit trade’ is the NPP and metal input weighted number of least-cost paths that intersect a grid cell, as defined in Equation (2). ‘Proximity mines’ is the inverse input weighted average transport costs to metal mines. ‘Proximity croplands’ represents the grid’s proximity to croplands, defined as the inverse transport cost weighted distance to croplands. ‘Sea’ is a dummy variable indicating whether a grid cell is intersected by the coastline. ‘River’ is a dummy variable indicating whether a grid cell is intersected by river. ‘Centrality’ is the cell’s transport surface eigenvector centrality. * p < 0.10, ** p < 0.05, *** p < 0.01.
productive land, two objects unaffected by human intervention (unlike mines and cropland). We remind the reader that the specific measure of land productivity used in constructing this variable reflects the potential biomass that can be produced in each region as dictated by climate factors: it is independent of the land’s exploitation strategy, encompassing both hunting-gathering and agriculture. The first stage is the following:

\[ IHS(T_g) = \delta IHS(D_g) + X_g^\prime \eta + \zeta_g, \]

where \( D_g \) is the instrumental variable.

The 2SLS estimates are reported in columns (2) to (8) of Table 1. Column (2) displays the most parsimonious specification, accounting solely for continent fixed effects. The first-stage results indicate that the instrument is positively correlated with the transit index and is powerful, with F-statistics ranging from 61 to 253. The second-stage results point towards an estimated \( \theta \) of similar magnitude to the OLS estimates. In the next six columns, we control for all those geographical features that are mechanically correlated with the transit index measure. Specifically, in column (3), we control for proximity to mines\(^{30}\), in column (4) for proximity to cropland\(^{31}\), in column (5) for topography\(^{32}\), and in column (6) for the centrality in the natural transportation network\(^{33}\). In column (7), we simultaneously add all the aforementioned controls. Including these controls, separately or together, has minimal effect on the estimates of \( \theta \). The final column of Table 1 focuses on the extensive margin, indicating that the transit index not only affects the emergence of cities during the Bronze Age but also the number of cities that arise within each cell.

Appendix Figure B.7 provides the estimates for the benchmark 2SLS regressions (controlling exclusively for continent fixed effects) but, instead of focusing on cities established before 1300 BC, it examines cities established every 500 years from 3300 BC to 1300 BC. The figure shows that while the estimated coefficient for the transit index is consistently positive, it rises between 3300 BC and 2300 BC, then remains stable thereafter. Notably, it only becomes statistically significant from 2300 BC onwards. In Appendix Figures B.8 and B.9, the analysis differentiates between transit routes leading to copper and tin mines. The estimated coefficients for both transit indexes are positive in each millennium and increasing from 3300 BC to 2300 BC. However, while the estimated coefficient on the copper transit index is

\(^{30}\)Formally proximity to mines \( M_g \) is defined as: \( M_g = \frac{1}{\sum_{m \in \text{copper, tin}} C^m_g} \), where \( C^m_g \) is the cost associated with shipping metal from the cost-minimising mine producing metal \( m \) to grid \( g \).

\(^{31}\)Formally, the proximity to cropland (PC) is given by \( PC_g = \sum_{c \neq g} \frac{1}{C_d^g} \times \text{crop}_c \), where \( C_d^g \) are the transport cost from grid cell \( c \) to cell \( g \) and \( \text{crop}_c \) is the croplands area of cell \( c \).

\(^{32}\)We include separate dummy variables for each of the topographical characteristics that influences the estimated transport cost to transit a cell. More specifically, making land the reference category, we include an indicator for the adjacency to the sea, the presence of a navigable river, and the presence of very high mountains.

\(^{33}\)Network centrality is measured as the eigenvector centrality in the natural transportation network.
statistically significant already in the fourth millennium, the estimated coefficient on the tin transit index is statistically significant only from the latter half of the third millennium. This finding might reflect the transition from arsenic bronze, a copper-arsenic alloy, to tin bronze, a copper-tin alloy during the third millennium BC.

In Appendix Table A.4 we repeat the benchmark 2SLS analysis but control for the various measures of land productivity that have been employed in the comparative development literature. As discussed in section 2, land productivity is commonly mentioned as a determinant of early urbanization and social hierarchy. However, when conditional on the transit trade index, land productivity is negatively associated with the presence of cities. This suggests that the data do not support the conventional productivity theories explaining the rise of the Urban Revolution. Furthermore, including land productivity as a control does not affect the point estimate of $\theta$.

A potential concern, related to the excluded instrument, comes from the mode-specific relative transportation costs used for its construction. As explained in Section 4.1, these costs are estimated from Bronze-Age trade relationships in Europe and the Middle East. This poses a significant threat to our identification strategy since Bronze Age transportation technologies might have been specifically tailored to the needs of civilizations in Europe and the Middle East: cities might be central in the metal trade network not because they initially emerged in natural passage regions between mines and cropland but because they acquired this centrality by developing specific transportation technologies to gain easy access to cropland and mines.

To address this concern, we conduct two robustness checks, which are reported in the first two columns of Appendix Table A.2. First, we document that our estimates remain stable if we restrict the spatial extent of our analysis to areas that are not used in the initial estimation of the relative transportation costs (column (1)). Second, we employ relative transportation costs estimated for the Stone Age, rather than the Bronze Age, in constructing our instrument (column (2)). In both cases, the results are virtually unchanged although, as expected, the instrument exhibits slightly less statistical power in the latter case.

In column (3) of Table A.2, we demonstrate that our estimates remain robust when accounting for a wide range of observable characteristics. To tie our hands, we extend the set of controls to include all natural characteristics employed in Henderson et al. (2018)’s article, which investigates the historical and current determinants of the spatial distribution of economic activity worldwide. Additionally, we demonstrate that our results remain stable when controlling for transit trade indices constructed for all the other metals discovered by the end of the Bronze Age: gold, lead and silver (Murr, 2015). This specifically speaks to the

---

34 Specifically, we control for average temperature, precipitation, (absolute) latitude, distance to coastline the length of growing period, ruggedness, Kiszewski et al. (2004)’s malaria index, 14 biome indicators, and dummy variables indicating a natural harbour lies within the grid cell.

35 In analogy to our instrumental variable approach, we construct transit trade measures for gold, lead, and silver. That is, for each metal we combine the location of deposits with the climate-based net primary
concern that metal deposits could be spatially clustered, in which case the bronze trade index could capture the effects of trade in other metals (column (4)).

Finally, a concern related to our main results comes from the data sources on Bronze-Age cities. As discussed in the data section, the data in Reba, Reitsma and Seto (2016) are constructed from two rather old sources. For this reason, in Appendix Table A.3., we repeat the analysis using an alternative, more modern source: HYDE 3.1 (Klein Goldewijk, Bessen and Janssen, 2010). Rather than capturing the cities, this source reports the urban population in each grid-cell in each BC millennium since the Neolithic. The dependent variable is now an indicator of the presence of urban population in the cell in 2000 BC (the latest data point available before the Bronze Age collapse). Once again, all main results are confirmed.

Overall, the results presented in this subsection provide some evidence supporting the hypothesis that transiting long-distance metal trade played an important role in explaining the emergence of the Urban Revolution. Cities were much more likely to be established along trade corridors connecting cropland with tin and copper mines. The 2SLS estimates suggest a causal link but, due to the cross-sectional nature of the data, we cannot exclude that other potential omitted geographic factors might be driving the results (though we do control for a large number of confounders). To overcome this limitation, we next turn to panel data, which allows us to account for time-invariant geographic factors.

5.2 Difference-in-Differences evidence: Archaeological sites

In this subsection, we employ two additional data sources, which report radio-carbon data on the location of archaeological sites and ancient settlements in the Old World pre-dating the Bronze Age collapse. The first is a historical atlas of the most relevant archaeological sites (Whitehouse and Whitehouse, 1975), and the second is a gazetteer for ancient history (the Pleiades Project, Bagnall, 2022). We use a difference-in-difference design in which, essentially, we study whether, moving from the Stone Age to the Bronze Age, there was a shift in archaeological sites and settlements towards the passage regions in the Bronze Age metal trade. More specifically, we estimate the following equation:

\[
y_{g,p} = \beta IHS(T_g) \times I_{p}^{BA} + X_{g,p} \Phi + \mu_g + \mu_p + \psi_{g,p}. \tag{6}
\]

where \(y_{g,p}\) captures either archaeological sites or settlements dating from period \(p\) in grid cell \(g\); \(I_{p}^{BA}\) is an indicator for sites/settlements belonging to the Bronze Age; \(T_g\) is the transit index; \(X_{g,p}\) is a set of time-varying control variables. Cell fixed effects, \(\mu_g\), control for time-invariant factors, while period fixed effects, \(\mu_p\), control for any time pattern in the number of archaeological sites. We rely on a 2SLS framework to isolate an exogenous variation in the production to construct the transit trade measure according to equations (5) and (7).
difference-in-difference regressor. Specifically, the first stage is:

\[ IHS(T_g) \times I^{BA}_p = \sigma IHS(D_g) \times I^{BA}_p + X'_{g,p} \psi + \rho_g + \rho_p + \xi_{g,p}. \]  

(7)

Table 2 presents the difference-in-differences results. In Panel A we use the Whitehouse and Whitehouse (1975) data as outcomes, in Panel B the data from the Pleiades Gazetteer. The first five columns of Table 2 report the OLS results for different outcomes and different set of time-varying controls \(X'_{g,p}\). We start by focusing on the number of archaeological sites and using a parsimonious specification, in which we only control for regional trends by including continent \(\times\) period fixed effects \(\tau_p\). For both, the Whitehouse and Whitehouse (1975) and the Pleiades data, we find that road knots, as captured by our transit index, are associated with an increase in archaeological sites during the Bronze Age relative to the Stone Age. Specifically, doubling the number of least-cost paths passing by a grid cell is associated with an increase in the likelihood of observing an archaeological site in the cell from the Stone Age to the Bronze Age in the order of 0.8 in the Whitehouse and Whitehouse (1975)'s dataset and 0.46 in the Pleiades dataset. In column (2), we see that results are practically unchanged if we include a long list of geographical controls interacted with the period fixed effects. These controls include the full list of geographical features that are mechanically correlated with our transit index measure and that are already discussed in the previous subsection: proximity to mines, proximity to cropland, topography, and centrality in the transportation network. In columns (3)–(5), we replace the dependent variable with the number of archaeological sites, the presence of settlements, and the number of settlements, respectively. Our transit trade measure is associated with an increase in all these three alternative outcomes, thus confirming previous results.

In keeping with the structure of the previous analysis, we re-run all regressions using our 2SLS approach (columns (6)–(10)). The first-stage F-statistics range between 315 and 135, documenting the relevance of our instrument. Throughout, we find that bronze transit trade intensity increases the probability of discovering an archaeological site established during the Bronze Age, relative to a site established during the Stone Age (columns (6)–(8)). Similarly, we find a positive effect on the establishment of settlements in the following two columns in all but one regression model (column (9), Panel B). As in the cross-sectional analysis, the size of the IV estimates are very close to their OLS counterparts.

In Appendix Table A.5 we conduct robustness tests in analogy to those presented in the previous subsection. Specifically, we show that our estimates are robust if (i) we restrict our sample to cells not used in the estimation of the transport costs vector \(\alpha_{BA}\), (ii) use relative transportation costs estimated for the Stone Age (rather than the Bronze Age) in the construction of our instrumental variable, (iii) extent the set of control variables, (iv) account for transit trade in other metals, and (v) control for transit trade constructed using transport
Table 2: Difference-in-differences (Stone Age vs Bronze Age): Archaeological sites

<table>
<thead>
<tr>
<th></th>
<th>OLS</th>
<th>2SLS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Any Site (×100)</td>
<td>Any Settlement (×100)</td>
</tr>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td></td>
<td>#Sites (×100)</td>
<td>#Settlements (×100)</td>
</tr>
<tr>
<td></td>
<td>(5)</td>
<td>(6)</td>
</tr>
</tbody>
</table>

Panel A: Second stage Whitehouse and Whitehouse (1975) archaeological sites

<table>
<thead>
<tr>
<th>Transit Index×Bronze Age</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
<th>(7)</th>
<th>(8)</th>
<th>(9)</th>
<th>(10)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.238</td>
<td>1.186</td>
<td>6.932</td>
<td>1.044</td>
<td>3.559</td>
<td>1.382</td>
<td>1.785</td>
<td>8.661</td>
<td>1.818</td>
<td>5.367</td>
</tr>
<tr>
<td></td>
<td>(0.171)***</td>
<td>(0.186)***</td>
<td>(1.671)***</td>
<td>(0.190)***</td>
<td>(0.794)***</td>
<td>(0.219)***</td>
<td>(0.328)***</td>
<td>(2.344)***</td>
<td>(0.327)***</td>
<td>(1.096)***</td>
</tr>
<tr>
<td></td>
<td>[0.191]***</td>
<td>[0.202]***</td>
<td>[1.600]***</td>
<td>[0.201]***</td>
<td>[0.840]***</td>
<td>[0.207]***</td>
<td>[0.297]***</td>
<td>[2.394]***</td>
<td>[0.292]***</td>
<td>[1.013]***</td>
</tr>
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</table>

Panel B: Second stage Pleiades Gazetteer (Bagnall, 2022)

<table>
<thead>
<tr>
<th>Transit Index×Bronze Age</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
<th>(7)</th>
<th>(8)</th>
<th>(9)</th>
<th>(10)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>0.619</td>
<td>0.563</td>
<td>2.760</td>
<td>0.481</td>
<td>1.975</td>
<td>0.402</td>
<td>0.509</td>
<td>2.090</td>
<td>0.426</td>
<td>1.733</td>
</tr>
<tr>
<td></td>
<td>(0.122)***</td>
<td>(0.129)***</td>
<td>(1.089)**</td>
<td>(0.106)***</td>
<td>(0.584)***</td>
<td>(0.167)**</td>
<td>(0.271)*</td>
<td>(1.192)*</td>
<td>(0.219)*</td>
<td>(0.566)***</td>
</tr>
<tr>
<td></td>
<td>[0.126]***</td>
<td>[0.124]***</td>
<td>[1.047]***</td>
<td>[0.107]***</td>
<td>[0.637]***</td>
<td>[0.141]***</td>
<td>[0.201]**</td>
<td>[1.032]**</td>
<td>[0.169]**</td>
<td>[0.573]***</td>
</tr>
</tbody>
</table>

Panel C: First stage

<table>
<thead>
<tr>
<th>IV Transit index×Bronze Age</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
<th>(7)</th>
<th>(8)</th>
<th>(9)</th>
<th>(10)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.699</td>
<td>0.514***</td>
<td>0.514</td>
<td>0.514</td>
<td>0.514</td>
<td>0.699</td>
<td>0.514***</td>
<td>0.514</td>
<td>0.514</td>
<td>0.514</td>
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<tr>
<td></td>
<td>(0.039)***</td>
<td>(0.042)***</td>
<td>(0.042)***</td>
<td>(0.042)***</td>
<td>(0.042)***</td>
<td>[0.044]***</td>
<td>[0.044]***</td>
<td>[0.044]***</td>
<td>[0.044]***</td>
<td>[0.044]***</td>
</tr>
</tbody>
</table>

Notes: This table reports panel OLS estimates (Equation (6)) and panel 2SLS-IV estimates (Equation (7)). Panel A uses data from Whitehouse and Whitehouse (1975) as outcomes and Panel B data from (Bagnall, 2022). Panel C reports first-stage estimates. Standard errors clustered at the level of 5×5 degree grid cells reported in parentheses. Standard errors computed using the approach of Conley (1999) (cut-off 1000km) are reported in square brackets. ‘Any Site’ is a dummy equal to one if an archaeological site was present in a given 1×1 degree grid and period. ‘Any Settlement’ is a dummy equal to one if a settlement was present in a given 1×1 degree grid and period. ‘‘Any Site’’ is a dummy equal to one if an archaeological site was present in a given 1×1 degree grid and period. ‘Any Settlement’ is a dummy equal to one if a settlement was present in a given 1×1 degree grid and period. ‘Bronze Age’ is an indicator that takes that is equal to one during the Bronze Age and zero during the Stone Age. ‘Transit trade index’ is the cropland and metal input weighted number of least-cost paths that intersect a grid cell, as defined in Equation (2). ‘IV Transit trade’ is the NPP and metal input weighted number of least-cost paths that intersect a grid cell (defined in Equation (3)). ‘Geography controls’ include proximity to mines, proximity to croplands, sea dummy, river dummy, mountains dummy, and transport cost surface centrality. ‘Centrality’ is the cell’s transport surface eigenvector centrality. *p < 0.10, **p < 0.05, ***p < 0.01.
cost estimates not specific to the Bronze Age.

Finally, as in the previous subsection, in the appendix Figures B.12a–B.12d, we show the sensitivity of our estimates to different estimation methods for the standard errors.

**Pre-trends**

To trace out the impact of transit trade over time and test for pre-trends, we construct a panel dataset, which is based on the dated sites in the Pleiades Project and reports the number of archaeological sites in each grid cell, dated at 1,000 year intervals from 6000 BC to 1300 BC.

To investigate if our transit trade index exerts different effects over time, we interact the (time-invariant) index with time period fixed effects. In the subsequent analysis, we take the time period [4000,3000) as the reference category. The time-period interacted coefficients of the transit trade index thus capture the differential effect of the transit trade on the outcome in a given period relative to the base period. The inclusion of grid cell fixed effects and time period dummies implies that time-invariant cell-specific differences as well as general time-specific changes are washed out.

Formally, the second stage can be represented as:

$$y_{g,p} = \sum_{p=6000}^{1300} \psi_p T_g \times I_p + \tau_g + \tau_p + \varepsilon_{g,p}. \quad (8)$$

The dependent variable $y_{g,p}$ indicates the presence of any archaeological site in grid cell $g$ in millennium $t$. Grid-cell-level fixed effects are represented by $\tau_g$, time-period fixed effects by $\tau_t$, and the idiosyncratic error term by $\varepsilon_{g,p}$. The coefficients $\psi_p$ capture the additional effect of the transit trade index in each period relative to the reference millennium [4000,3000) BC.

Figure 2 visualizes the resulting 2SLS point estimates and the 90 percent confidence intervals. The figure documents that the transit trade only starts to exert a differential effect on the probability of finding an archaeological site after the onset of the Bronze Age (i.e., after 3000 BC). Point estimates for earlier time spans are not statistically significantly different compared to the reference millennium [4000, 3000). This absence of pre-trends provides further evidence that our estimates capture the Bronze Age-specific effects of transit trade in input metals.

Taken together, the estimates reported in this subsection corroborate the hypothesis that regions located along metal trade corridors were more likely to see the emergence of settlements and large built-up area during the Bronze Age. Still, an important note of caution relates to the quality of our outcome variables employed so far. As outlined in Section 3, these come with various caveats. Specifically, the Whitehouse and Whitehouse (1975) data are rather outdated, while the Pleiades data are skewed towards Europe, the Middle East, and Mediterranean Africa.

In the last part of this empirical section, we reproduce our main insights focusing on two
regions for which high-quality data are available: China and Europe.

5.3 China

Bronze metallurgy in China originated around 2000-1900 BC and it probably developed inside China separately from outside influence. The archaeological site of Erlitou is the largest among the sites dating from these years. As explained in detail in subsection 7.6, Erlitou is located at the center of an intricate network of rivers connecting metal-rich mountains to the fertile Chinese lowlands. Essentially, a recent archaeological literature argues that Erlitou took advantage of this strategic position to direct the metal trade in the region, eventually becoming the capital of a trade civilization (and probably the first state in Chinese history). In this subsection, we show that the link between trade and the Urban Revolution in China extends beyond the Erlitou civilization.

The advantage of focusing on China is that we can rely on a comprehensive and detailed catalog of Chinese archaeological sites, which we digitized to capture the rise and spread of the Urban Revolution in the Chinese context. As described in the data section, we use a text algorithm to identify sites indicative of (1) urban settlements, (2) ruling class exempt from manual tasks, (3) monumental building, (4) a standardized system of measures and recordings used in exchange and production, (5) writing, (6) highly developed art forms.

We aggregate these artifacts in 1×1 degree grid-cells for three periods: Paleolithic, Neolithic and Bronze Age. We assume that the Bronze Age starts in 2070 BC with the first Chinese dynasty (Xia) and ends in 771 BC with the Western Zhou dynasty. The result is a panel dataset that illustrates the rise of different aspects that have been associated with the Urban
Revolution in China.

**Empirical analysis**

To study how metal trade fostered the Urban Revolution in this context, we estimate the difference-in-differences regression model in equation (6). The main results are illustrated in Table 3. In this table we use three variables to capture the Urban Revolution. The first one is an indicator variable, which identifies the presence of archaeological sites that feature at least one of the six Childe’s criteria associated with the Urban Revolution; the second one is a variable that counts the number of criteria; the third is a principal component of the six criteria.

Both the OLS and 2SLS estimates point towards a large and statistically significant association between the transit index measure and the Chinese relics indicative of the Urban Revolution. The 2SLS estimates imply that an exogenous doubling of the number of transiting paths connecting metal mines with cropland implies an increase in the probability of featuring sites indicative of the Urban Revolution during the Bronze Age in the order of 600 log points. The magnitude of the estimated coefficient does not change if we run the parsimonious specifications, with only grid-cell and period fixed effects, or if we consider our benchmark specifications with the usual full set of controls.

The richness of the data further allows us to investigate if transit trade differentially fostered specific aspects of the Urban Revolution. To this end, we define six dummy variables, each capturing if a specific urban revolution criterion is present in a given grid cell and period. We then separately run our 2SLS difference-in-difference regressions with the full set of controls using these dummies as outcomes. Figure 3 visualizes the results: metal transit trade seems to affect almost every aspect of the Urban Revolution.

The results presented in this subsection corroborate the findings of our previous ‘global’ analysis for the case of China, where very detailed outcome variables are available. In a final step, we provide further evidence for the general validity of our results by testing for the existence of pre-trends. In analogy to the main part, we then analyze if metal transit trade had a differential impact during the Bronze Age by interacting the transit trade index with time period fixed effects (see Section 5.2 for more details). Figure 4 depicts the results. Reassuringly, we fail to detect any pre-trends. The transit index measure produces an increase in the sites indicative of the Urban Revolution only in the Bronze Age.

**5.4 Europe**

In this subsection, we focus on the European Bronze Age which represents the most extensively studied episode in world archaeology Radivojević et al. (2019). The rich archaeological record, combined with radiocarbon dating, enables us to track socio-economic development during this period at a detailed level of spatial and temporal aggregation. In the following, we will
Table 3: Difference-in-differences (Stone Age vs Bronze Age): Atlas of Chinese Relics

<table>
<thead>
<tr>
<th>OLS</th>
<th>Any Criteria (×100)</th>
<th>IHS #Criteria</th>
<th>Principal Component (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit Index × Bronze Age</td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
</tr>
<tr>
<td>4.611</td>
<td>3.688</td>
<td>0.118</td>
<td>0.131</td>
</tr>
<tr>
<td>(0.624)**</td>
<td>(0.615)**</td>
<td>(0.024)**</td>
<td>(0.028)**</td>
</tr>
<tr>
<td>[0.421]**</td>
<td>[0.421]**</td>
<td>[0.019]**</td>
<td>[0.024]**</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2SLS</th>
<th>Any Criteria (×100)</th>
<th>IHS #Criteria</th>
<th>Principal Component (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit Index × Bronze Age</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
</tr>
<tr>
<td>6.233</td>
<td>7.863</td>
<td>0.179</td>
<td>0.225</td>
</tr>
<tr>
<td>(1.297)**</td>
<td>(3.275)**</td>
<td>(0.080)**</td>
<td>(0.102)**</td>
</tr>
<tr>
<td>[0.863]**</td>
<td>[2.396]**</td>
<td>[0.069]**</td>
<td>[0.074]**</td>
</tr>
</tbody>
</table>

Panel B: First stage

<table>
<thead>
<tr>
<th>IV Transit index × Bronze Age</th>
<th>(7)</th>
<th>(8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.991</td>
<td>0.482</td>
<td>0.482</td>
</tr>
<tr>
<td>(0.124)**</td>
<td>(0.143)**</td>
<td>(0.143)**</td>
</tr>
<tr>
<td>[0.123]**</td>
<td>[0.118]**</td>
<td>[0.118]**</td>
</tr>
</tbody>
</table>

Geography controls: No, Yes
Grid cell fixed effects: Yes, Yes
Period fixed effects: Yes, Yes
Mean dependent variable: 15.48, 15.48, 0.348, 0
First-stage F-stat (5×5 grids): 64.54, 16.46, 16.46, 16.46

Notes: This table reports panel OLS estimates (columns (1)–(3)) and panel 2SLS-IV estimates (columns (4)–(6)). Panel A reports the main and second-stage estimates (Equation (6)), while panel B reports the first-stage estimates (Equation (7)). Standard errors clustered at the level of 5×5 degree grid cells reported in parentheses. Standard errors computed using the approach of Conley (1999) (cut-off 1000km) are reported in square brackets. 'Any Criteria' is a dummy equal to one if at least one of Childe (1950)'s criterion of urban revolution was present in a given 1×1 degree grid and period. Variable is multiplied by hundred to facilitate interpretation. 'IHS #Criteria' represents the IHS of number of sites that fulfill at least one of Childe's criteria located in a within grid cell and period (transformed using the inverse hyperbolic sine function). 'Principal Component (SD)' is the first principal component obtained from the individual Childe's criteria. Variable standardised to a mean of zero and standard deviation of one. 'Bronze Age' is an indicator that takes that is equal to one during the Bronze Age and zero during the Stone Age. 'Transit trade index' is the cropland and metal input weighted number of least-cost paths that intersect a grid cell, as defined in Equation (2). 'IV Transit trade' is the NPP and metal input weighted number of least-cost paths that intersect a grid cell (defined in equation (3)). 'Geography controls' include proximity to mines, proximity to croplands, sea dummy, river dummy, mountains dummy, and transport cost surface centrality. 'Centrality' is the cell's transport surface eigenvector centrality. * p < 0.10, ** p < 0.05, *** p < 0.01.
Figure 3: Effect of transit trade index on Childe’s criteria of Urban Revolution
Figure depicts 2SLS-IV point estimates and 90% confidence intervals of the effect of transit trade on individual Urban Revolution criteria relative to the Stone Age. Dependent variables are dummies equal to one if a given criterion was present in a given 1×1 degree grid and period. Variable is multiplied by hundred to facilitate interpretation. See Section 3 for details on definition and construction of variables.

Figure 4: Effect of transit trade index over time
Figure depicts 2SLS-IV point estimates and 90% confidence intervals of time-period interacted effect of transit trade relative to the Neolithic Age. Standard errors are clustered at the level of 5×5 degree grid cells. Grey: Dependent variable is a dummy equal to one if at least one of Childe’s Urban Revolution criteria was present in a given 1×1 degree grid and period. Variable is multiplied by hundred to facilitate interpretation. Black: Dependent variable is the first principal component obtained from the individual Childe’s criteria. Variable standardised to a mean of zero and standard deviation of one. See Section 3 for details on definition and construction of variables.

focus on Central and Western Europe. Importantly, this excludes the Aegean and the Eastern Mediterranean. There the Bronze Age started around 2700 BC and is characterized by the emergence of the first European civilizations and cities.36 In our study region—depicted in Figure B.5—the Bronze Age started around 2200 BC. Similar to other regions of the world, the

36See Section 1 for more details.
diffusion of the new technology—bronze—was pervasive and happened within a few centuries (Hänsel, 2014, pp.114, Kristiansen and Larson, 2005, pp.112). The ensuing demand for bronze led to the establishment of interregional trade networks in order to secure tin and copper in large quantities from mines, which were primarily located in Europe. However, demand for metals from these mines extended beyond Central and Western Europe to regions such as Anatolia or the Eastern Mediterranean (O’Brien, 2013). For example, large-scale mining of copper during the Bronze Age is well-documented in Mittenberg, where a total of 18,000 tons is estimated to have been mined during the Bronze Age. Important tin mines were located in Cornwall and Western Iberia (O’Brien, 2013, Earle et al., 2015). Noteworthy for the subsequent empirical analysis, for Europe we have detailed information on location of mines along with the approximate period during which they were operational (e.g. O’Brien, 2015).

In contrast to the Aegean and the Eastern Mediterranean, civilizations or cities did not emerge during the Bronze Age. However, Central and Western Europe witnessed the start of the precursory process of socio-economic stratification—the formation of local elites—during this period (Earle et al., 2015, Harding, 2000, pp.388). Previously typically organized as classless bands and tribes, the Bronze Age saw the emergence of hierarchically organized societies, i.e., chiefdoms, with local leaders having some centralized decision-making power (Earle et al., 2015). The archaeological literature directly links this development to long-distance trade in copper and tin (Cunliffe, 2011, pp.221, Earle et al., 2015). Control over inter-regional commodity flows led to the emergence of chiefdoms and a warrior class that was able to defend territories and hence secure trade corridors and associated revenues (Earle et al., 2015). Archaeological evidence for the presence of chiefdoms is found in graves. Valuable grave goods, and bronze artifacts in particular, are indicative of an elite status of the deceased (Harding, 2000, p.389, Hänsel, 2014, pp.113). Weapons (partly) made out of bronze, e.g., battle axes and swords, represent the strongest evidence for the existence of local chiefdoms (Earle et al., 2015, Hänsel, 2014, pp.118, Harding, 2015).

In addition to the establishment of long-distance trade networks and chiefdoms, the European Bronze Age was also characterized by increased regional and supra-regional cultural integration. That is, the formation and evolution of regional cultural groups or ethnicities. The presence of these groups, such as the Bell Beaker culture, can be identified in archaeological records by the recurrence of specific artifact types (e.g., particularly shaped drinking vessels), housing types or burial traditions in a given region (Harding, 2000, ch.1). Importantly, the relative chronology of different cultural groups across Europe is well-established in the literature (Harding, 2000, p.10). For our empirical analysis, this implies that we can map artefacts to different time periods within the European Bronze Age.

In sum, the defining features of the European Bronze Age are the large-scale use of bronze across all of Europe, interconnected regional economies as well as the emergence of socio-
economic stratification (Cunliffe, 2011, pp.179). The presence of local elites can be identified and periodized using bronze grave goods. Subsequently, we refer to these graves as ‘elite burials’.

**Empirical analysis**

As described in Section 3.1.4, we construct a two-period panel data set that spans the Early/Middle Bronze Age [3000 BC, 1300 BC) and Late Bronze Age [1300 BC, 500 BC]. For each period, we have information on the presence of hierarchy, as measured by the presence of elite burials. Hence our dataset represents a within-Bronze Age panel. As an important improvement over the previous analysis, the high-quality information on the start and end periods of the European mines allows us to exploit the temporal dimension in mining activity within the Bronze Age. More specifically, we can construct a transit trade index that varies within the Bronze Age by taking into account which mines are active during the Early/Middle and the Late Bronze Age. For each grid cell we thus have two values of the transit trade index: one for the Early/Middle Bronze Age and one for the Late Bronze Age.

For our empirical analysis, we restrict the sample to grid cells in which artifacts were ever excavated. This addresses potential issues regarding the selective coverage of the PBF publications (i.e. the various volumes only cover specific regions). Restricting our sample to the ‘intensive’ margin further mitigates concerns related excavation biases (e.g., more excavation near known metal mines). The cells included in our analysis are shaded grey in Figure B.5. Using this sample, we run the following panel data model to test if social stratification is more likely to emerge when transit trade intensifies:

\[
y_{g,p} = \beta IHS(T_{g,p}) + X_{g,p} \chi + \mu_g + \tau_p + \psi_{g,p},
\]

where \( y_{g,p} \) is the presence of an elite burial. The main explanatory variable \( IHS(T_{g,p}) \) is the IHS of the transit trade index for cell \( g \) in period \( p \). As outlined above, \( T_{g,p} \) now exhibits within-Bronze Age variation. The vector \( X_{g,p} \) represents control variables. Grid cell fixed effects and period fixed effects are symbolized by \( \mu_g \) and \( \tau_p \). Finally, \( \psi_{g,p} \) is the error term.

Table 4 reports the results of regression model (9). The point estimate in column (1) implies that the it becomes 2.7 percentage points more likely to find evidence of an elite when transit trade increases by one percent. This translates into a 24 percent increase when moving from a cell without transit trade to one cell intersected by a path that connects a mine to a

---

37 That is, we construct the transit trade index as described in Section 4.3 separately for the Early/Middle and the Late Bronze Age. Thereby, we only use the subset of mines that were active in the respective period in the construction process.

38 A drawback of focusing on within-Bronze Age variation is that we cannot employ our instrumental variable strategy due to the fact that we do not have temporal variation in the location of metal deposits (within the Bronze Age).

39 Our results, however, do not depend on this restriction. Including all grid cells within Europe produces very similar estimates.
cell that devotes all of its area to crop cultivation. The size of the point estimate drops only slightly to 2.2 when we control for proximity to mines—the other variable that exhibits within-Bronze Age variation—in column (2). The statistical significance of our results, however, is unaffected.

In columns (3)–(4) we use the IHS number of elite burials as a measure of hierarchy whereas. Again, we find that increased transit volumes raise the probability of hierarchy emerging.

Table 4: OLS panel evidence: Elite Burials

<table>
<thead>
<tr>
<th></th>
<th>Any Elite Burial (×100)</th>
<th></th>
<th>IHS Number of Elite Burials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
</tr>
<tr>
<td>Transit index</td>
<td>2.677</td>
<td>2.202</td>
<td>0.050</td>
</tr>
<tr>
<td></td>
<td>(1.129)**</td>
<td>(1.080)**</td>
<td>(0.021)**</td>
</tr>
<tr>
<td></td>
<td>[1.040]***</td>
<td>[0.903]***</td>
<td>[0.027]***</td>
</tr>
<tr>
<td>Geography controls</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Grid cell fixed effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Period fixed effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Observations</td>
<td>850</td>
<td>850</td>
<td>850</td>
</tr>
<tr>
<td>Mean dependent variable</td>
<td>38.35</td>
<td>38.35</td>
<td>0.801</td>
</tr>
<tr>
<td>Within R²</td>
<td>0.107</td>
<td>0.125</td>
<td>0.208</td>
</tr>
</tbody>
</table>

Notes: This table reports estimates of Equation (9) using OLS. Standard errors clustered at the level of 1×1 degree grid cells reported in parentheses. Standard errors computed using the approach of Conley (1999) (cut-off 1000km) are reported in square brackets. ‘Any Elite Burial’ is a dummy equal to one if a weapon was present in a grave in a given 1×1 degree grid and period. Variable is multiplied by hundred to facilitate interpretation. ‘IHS Number of Elite Burials’ is the IHS of the total number of weapons found in graves in a given 1×1 degree grid and period. ‘Transit trade index’ is the cropland and metal input weighted number of least-cost paths that intersect a grid cell, as defined in Equation (2). ‘Geography controls’ include the time-varying proximity to mines. * p < 0.10, ** p < 0.05, *** p < 0.01.

6 Appropriability mechanism

The results so far indicate that trade in bronze inputs was an important driver of the Urban Revolution. Social stratification, complex hierarchies, states, and cities were more likely to emerge in regions central in the metal trade network. In this section, we study the mechanism underlying this result. The first subsection spells down a theoretical framework which emphasizes the appropriability nature of transit metal trade. While some optimal routes connecting populations with mining regions could be easily circumvented, some others could not be avoided unless traders were willing to face disproportionate transportation costs. We argue that it is exactly in these latter regions that a new elite, relying on taxing transit traders, could rise. Sufficient fiscal revenues allowed this elite to pay the fixed cost needed to establish the monopoly of power and commit to a revenue-maximizing tax rate. In turn, this arrangement was beneficial to metal traders, who avoided higher expropriation rates by unorganized roving bandits. The main insight from the model is that a trade-taxing elite, and associated civilization, is more likely to emerge in the bottlenecks to the metal trade network - regions that (a) have high transit trade volumes and (b) are costly to circumvent. In the
second subsection, we bring the theory to the data. We construct a measure of the potential tax revenues that could be extracted by a would be elite in a grid-cell, by calculating the additional trade costs to metal traders to avoid that cell. We then run a horse race between this measure, which identifies the bottlenecks in the metal trade network, and the transit trade index, which identifies the road-knots. It turns out that the bottlenecks were indeed the ultimate cradle of civilization.

6.1 Theory

In Appendix D, we present a simple model inspired by Mayshar, Moav, and Pascali (2022). Our model features a spatial dimension since geography and location determine the transport costs between metal mines and bronze producers. Transport costs drive the key results in our model. Space in our model is organized—like in the empirical setup—in grid cells. There are three types of relevant agents: farmers, traders, and foragers. Farmers are located in grid cells and produce crops using metal and cropland. Traders transport metal from the mines to farmers. The revenues for traders are given by the metal sold to farmers, while the costs are given by the mill price for metal and the costs to ship metal from mines to farmers. Traders travel along transport routes that connect mines and farmers. Routes traverse across grid cells. We assume perfect competition among traders for each mine-to-farmer supply connection. This implies that farmers source metal from only one mine, i.e., the mine that provides metal at lowest costs. Since mill prices for metal are identical in our model, total trade costs determine which particular mine supplies a specific grid cell with metal.

Total costs to ship metal depend on the per unit transport costs and the quantity shipped. Additionally, kings or bandits may tax (i.e., expropriate) the traders when passing their territory (i.e., grid cells with either a king or bandits). Traders may have to pay multiple taxes, depending on the number of grid cells that they pass. Traders chose the least-cost route given transport costs and tax rates.

Foragers earn a fixed exogenous income. In each cell, the expropriation of transit trade can be organized in two ways: hierarchy (with a king that employs tax collectors) and anarchy (with unorganized bandits).

Case one: Anarchy. Under anarchy, some foragers may turn into bandits. The expropriation rates (i.e., tax rates) are the ones that make bandits indifferent between entering banditry or staying foragers.

Case two: Hierarchy. Political entrepreneurs can establish themselves as kings and establish the monopoly of violence in a grid cell by paying a fixed cost. The monopoly of violence allows states to deter bandits and to tax transit metal trade. The king hires tax collectors among foragers and pays wages that are set by the outside option of foraging. In our model kings set transport route-specific optimal tax rates to maximize net tax revenue for each least cost...
route traversing their territory. At the intensive margin, total tax revenue is determined by the costs of taxation and the total number of transit routes crossing the grid cell. But kings are further constrained at the extensive margin. If a king sets tax rates too high, they may induce traders to switch towards another transport route to evade her grid cell. In this case, tax revenue from a specific least-cost route is zero. This extensive margin of adjustment by traders determines the maximum tax rate a king can set on a specific path (i.e., the least-cost route from a metal mine to a destination cell). At the maximum tax rate, the traders are indifferent between staying on the path going through the king’s cell and switching to the second-best alternative path evading her cell.

Our model provides three key insights about total tax revenue and the establishment of states in a given grid cell. First, the total maximum tax revenue a king can collect across all least-cost routes traversing through her grid cell is what we call “blockage costs”. In our model, the blockage costs—and hence the maximum tax revenue a king can generate in a specific grid cell—are equivalent to the increase in total transport costs for the network when we remove this cell from the network. Everything else equal, the blockage costs will be higher if a grid cell represents a bottleneck, i.e., detours to evade this specific grid cell come with high transport costs. Second, if the total maximum tax revenue is lower than the fixed costs kings need to pay for the monopoly of violence, no hierarchy will emerge. Third, increasing the number of metal trade routes traversing a given grid cell leads to higher tax revenue and hence to a deeper state, i.e., a state with more bureaucracy (tax collectors).

6.2 Empirical evidence

To gauge the extent to which the rise of a tax-levying elite drives our results, we construct a transit trade centrality measure that incorporates the scope for taxation. We build on the intuition, developed in our theoretical framework, that revenues from taxing transit trade in a certain region depends not only on the optimal routes passing by the region, but also on the absence of valid alternatives to these routes. In order to translate this insight to the data we construct a measure of the trade costs that metal traders would have to incur to avoid a certain region. To this end, we compute the Modified Efficiency Centrality (Wang, Wang and Deng, 2019) in the metal trade network. This centrality index captures how much the total transport costs in the global metal trade increases if a given cell is blocked for transit (i.e., if we do not allow paths to intersect the cell). That is, it represents the difference in global transport costs between the unrestricted case—which is equal to the total transport costs associated with our main transit trade index—and the situation in which a given cell is blocked for transit trade (see Appendix L for more details). Subsequently, we refer to this increase in transport cost as ‘blockage cost’. The higher the blockage cost, the more costly it is to circumvent a cell, and—consequently—the greater is the potential tax revenue. Figure 5 visualizes the geographic variation in these costs.
Figure 5: Blockage cost.
Figure depicts the global cost of blocking a cell for transit trade in 3000 BC (see Appendix L for more details). Darker shadings imply greater costs.

We test if the rise of a trade-taxing elite is a plausible mechanism by running a horse race between our main transit trade index and the blockage cost. If taxation plays a role, we would expect the blockage cost coefficient to be statistically significant, positive and sizable. Table 5 presents the findings of the horse race regressions. In analogy to the structure of Section 5 we first look at cross-sectional city data from Reba, Reitsma and Seto (2016). Column (1) reports the results of the OLS regression with full controls. This produces a point estimate of 0.393. The size of the transit trade index drops by almost a third (column (2)), when we account for the blockage cost. More importantly, the latter is statistically significant, positive and of considerable economic magnitude. This suggests the rise of a trade-taxing elite is one important reason why civilization emerged in regions central to the metal trade.

In columns (3)–(4) we run the same type of horse race using the Pleiades Gazetteer panel, whereas we use data from the Atlas of Chinese Relics in columns (5)–(6). The pattern of results does not change compared to the cross-sectional setup. In both cases, the difference-in-differences regressions document that blockage cost exert a statistically significant and economically sizable effect. That is, the likelihood that a site emerges during the Bronze Age increases considerably in a cell that is costly to circumvent in the metal trade. The coefficient

40 Subsequently, we restrict our analysis to OLS regressions. With IV regressions, we are not able to disentangle the relative importance of the trade versus taxation channel because both instruments (the one for our main transit index and the one for the blockage cost) have predictive power for both potentially endogenous variables. See Appendix L for more details.
Table 5: Controlling for blockage costs

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Any City 1300 BC (×100)</td>
<td>Any Site (×100)</td>
<td>Principal Component (SD)</td>
<td>Any Elite Burial (×100)</td>
</tr>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
</tr>
<tr>
<td>Transit index</td>
<td>0.393</td>
<td>0.280</td>
<td>2.202</td>
<td>1.336</td>
</tr>
<tr>
<td></td>
<td>(0.104)***</td>
<td>(0.071)***</td>
<td>(1.080)**</td>
<td>(0.631)*</td>
</tr>
<tr>
<td></td>
<td>[0.137]***</td>
<td>[0.087]***</td>
<td>[0.903]**</td>
<td>[0.357]**</td>
</tr>
<tr>
<td>Blockage cost</td>
<td>0.374</td>
<td>1.144</td>
<td>1.144</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.141)**</td>
<td>(0.631)**</td>
<td>(0.631)**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[0.194]**</td>
<td>[0.357]***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transit index×Bronze Age</td>
<td>0.563</td>
<td>0.353</td>
<td>0.131</td>
<td>0.107</td>
</tr>
<tr>
<td></td>
<td>(0.129)***</td>
<td>(0.142)**</td>
<td>(0.028)***</td>
<td>(0.027)***</td>
</tr>
<tr>
<td></td>
<td>[0.124]***</td>
<td>[0.106]***</td>
<td>[0.024]***</td>
<td>[0.021]***</td>
</tr>
<tr>
<td>Blockage cost×Bronze Age</td>
<td>0.711</td>
<td>0.079</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.275)**</td>
<td>(0.059)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[0.228]***</td>
<td>[0.034]**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geography controls</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Grid cell fixed effects</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Continent×period fixed</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Observations</td>
<td>9,426</td>
<td>9,426</td>
<td>18,852</td>
<td>18,852</td>
</tr>
<tr>
<td>Mean dependent variable</td>
<td>0.488</td>
<td>0.488</td>
<td>3.962</td>
<td>3.962</td>
</tr>
</tbody>
</table>

Notes: Standard errors clustered at the level of 5×5 degree grid cells (columns 1–6) and 1×1 degree grid cells (columns 7–8) reported in parentheses. Standard errors computed using the approach of Conley (1999) (cut-off 1000km) are reported in square brackets. ‘Any city by 1300 BC’ is a dummy equal to one if a city was present in a given 1×1 degree grid cell by 1300 BC. ‘Any Site’ is a dummy equal to one if an archaeological site was present in a given 1×1 degree grid and period. Variable is multiplied by hundred to facilitate interpretation. ‘Any Elite Burial’ is a dummy equal to one if a weapon was present in a grave in a given 1×1 degree grid and period. Variable is multiplied by hundred to facilitate interpretation. ‘Principal Component (SD)’ is the first principal component obtained from the individual Childe (1950)’s criteria. Variable standardised to a mean of zero and standard deviation of one. ‘Any Elite Burial’ is a dummy equal to one if a weapon was present in a grave in a given 1×1 degree grid and period. Variable is multiplied by hundred to facilitate interpretation. ‘Bronze Age’ is an indicator that takes that is equal to one during the Bronze Age and zero during the Stone Age. ‘Transit trade index’ is the cropland and metal input weighted number of least-cost paths that intersect a grid cell, as defined in Equation (2). ‘Blockage cost’ are the globally incurred additional transport costs to the closest copper and tin mines resulting from blocking a given grid cell. ‘Geography controls’ as defined in Tables 1–4. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. 
of transit trade drops between 18% to 37% when we control for variation in blockage costs. In the last two columns of Table 5, we focus on Europe and run the statistical horse race exploiting only within-Bronze Age variation. The results continue to exhibit a consistent picture. When including the blockage cost as a regressor our main transit index drops by nearly 40%, now even losing statistical significance at conventional confidence levels. The blockage cost coefficient, on the other hand, is statistically significant and substantial in size. Taken together, the results presented in 5 provide strong evidence that the emergence of a metal trade-taxing elite is an important driver of the Urban Revolution.

7 Case studies

In this section, we focus on Mesopotamia, the Indus Valley, Greece and Egypt and discuss the rise of some of the very first urbanized societies. We establish three facts that support our appropriability theory behind the rise of the Urban Revolution. First, Bronze-Age urban centers are strategically located in the trade network. In fact, most cities can be found at the confluence between different rivers (e.g., Erlitou), at the delta of large rivers (e.g., Ur) or on waterways connecting different seas (e.g., Troy). Land productivity does not seem relevant: in several cases (e.g., Assur), cities are surrounded by rather infertile land. Second, a large archaeological literature has related the rise of the first urbanized core of these civilizations to the transit metal trade and has documented that the first urban elites were directly involved in the trade of metals. Third, recent work in archaeology and history has emphasized that the expansion of the core and the rise of the first empires is motivated by the need to secure trade connections and directly access metal mines.

7.1 Ancient Sumer in the Early Dynastic Period (2900-2334 BC)

The Urban Revolution started with the Sumerian Civilization. After a long transition during the Uruk period, full urban life flowered during the Early Dynastic Period. At this point, all the 10 formal criteria that Childe use to define Urban Revolution can be traced in South Mesopotamia. A thesis with a long-standing tradition in anthropology and archaeology is that long-distance trade was the main driving factor of this “Revolution.” The first Sumerian cities emerged along the coast of the Persian Gulf, in the alluvial delta of the Tigris and Euphrates. These cities were located in a nodal point connecting Anatolia, Mesopotamia, and Iran with the Persian Gulf, through an enormous dendritic transportation system created by the north-to-south flowing rivers. In the words of Guillermo Algaze:

“That emergence of early cities in the southern Mesopotamian alluvium must be understood in terms of the unique ecological conditions that existed across the region during the fourth millennium, and the enduring geographical framework of the area, which allowed for the efficient movement of commodities via water
transport and facilitated interaction between diverse social units alongside natural and artificial river channels. These conditions promoted evolving long-term trade patterns that, inadvertently, differentially favored the development of polities in the southern Mesopotamian alluvium over contemporary societies in neighboring regions.”

The principal commodities referred to in commercial documents during the Early Dynastic Period are copper, tin, and tin-bronze, which were usually purchased in exchange for silver, barley and wool (Lambert, 1953; Leemans, 1975; Foster, 1997; Dercksen, 1999; Prentice, 2010). Ancient Sumerian cities were the first to show evidence of copper alloys utilization. Sumer was the birthplace of arsenic copper, which became prevalent in the second half of the 6th millennium BC, and bronze technology. The rise of bronze production coincides with the rise of the Urban Revolution among the Sumerians: tin bronze is thought to have been introduced in Mesopotamia at the very end of the 4th millennium BC, with the first known bronze object dating from around 3000 BC.

Notice, however, that South Mesopotamia has no local sources of metals. The focus of much documented commercial activity of Sumerian cities is the acquisition of copper and tin, through both land routes connected to the rivers or sea routes.41

Regarding copper, two well-documented routes were used to bring this metal to Mesopotamia. The first was a land route, which connected the mines in the Zagros (Iran) and the Taurus (Turkey) mountains with Southern Mesopotamia, and was facilitated by the rivers and canals in the water system formed by the Tigris and the Euphrates (Muhly, 1973; Morr and Cattin, 2013). The second route was a sea route, which connected Ur and the other Sumerian ports in Southern Mesopotamia, through the Persian Gulf, to three exporters of copper: Magan, Dilmun and Meluhha. Magan was a polity located in present-day Oman and a major source of copper ores. Recent estimates report that approximately half of the Sumerian copper was coming from there (Giardino, 2019)42. Dilmun is already cited in archaic texts dealing with the copper trade in Uruk from the late fourth millennium BC. The importance of this trading post is confirmed by the fact that copper trade in the Persian Gulf was carried out by the “Dilmun boats” and transactions in Ur were conducted using the “Dilmun weight standard.” Dilmun probably served only as a trading post and it was never the ultimate

Curiously, a famous tablet, excavated in Ur, contains the oldest known customer complaint. The complaint refers to the quality of the copper sold from a merchant coming from Dilmun, a polity almost certainly corresponding to present-day Bahrein: “When you came, you said to me as follows: I will give Gimil-Sin (when he comes) fine quality copper ingots. You left then but you did not do what you promised me. You put ingots which were not good before my messenger (Sit-Sin) and said: If you want to take them, take them; if you do not want to take them, go away! [...] Is there anyone among the merchants who trade with Dilmun who has treated me in this way? You alone treat my messenger with contempt!”

Moreover, excavations from the 1970s have yielded clear evidence of large-scale production of copper throughout the mountainous region of eastern Oman that can be traced back at least to the middle of the third millennium BC (Weisgerber, 1981, 1983).
origin of the traded products. Based on epigraphic and archaeological evidence, it seems that the ultimate source of copper trade through Dilmun was Meluhha (Begemann et al., 2010), which is generally believed to be located in the present-day Indus Valley (Muhly, 1973), where the Harappan Civilization flourished starting from the mid-third millennium BC. In particular, lead isotope studies have suggested that the ultimate source of copper traveling through Dilmun in Mesopotamia might be the Aravalli Hills in southern Rajasthan (Begemann and Schmitt-Strecker, 2008).

As opposed to copper, the sources of tin for Mesopotamia during the Bronze Age are not as well defined. The cuneiform texts seem to indicate that all the major tin sources used in the region in the early bronze age were located east of Mesopotamia. Tin imported in Mesopotamia is believed to mainly originate from western Afghanistan and the Zagros mountains in current-day Iran. Tin from Afghanistan was probably transported through a sea route passing by Magan (Cleuziou, 1982), while a land route from the Zagros mountains was probably opened later. Limited evidence of tin mining during the Bronze Age is also present in Goltepe, in Anatolia, which led to the hypothesis that some of the tin used in Mesopotamia might have also come from Anatolia (Yener and Vandiver, 1993; Yener, 2021).

The trade vocation of Sumerian cities is evidence in the Epic of Gilgamesh, the first known piece of literature in history. The story opens with a description of Uruk (probably the first city in human history), emphasizing the beauty of its walls and its markets. The city itself, is referred to as “the great market”. The cuneiform texts indicate that ancient Sumerian cities were not only a trading hub for tin and copper, but also important manufacturing centers with stratified classes of metal workers.

7.2 The Harappan civilization in the Indus Valley (2600-1900 BC)

The second half of the third millennium BC marked the birth of the first urban civilization in southern Asia, in the Indus Valley. Rather than emerging from a slow period of gradual growth and modification, as in the Sumerian case, the Harappan civilization seems to have resulted from a very short period of transformation (Possehl, 1990). During the Urban Phase (or Mature Harappan), within 100-150 years, both writing and a widely used system of weights and measures appeared, towns started displaying monumental buildings, signs of centralized urban planning (e.g., massive brick platforms, well-digging, drainage systems, grid plans) and unprecedented levels of social differentiation emerged (e.g., big/tiny houses, brick/mud houses, growth in the use of precious metals for personal adornments etc.). Several scholars have suggested that external trade was a major factor in the rise and maintenance of the urban centers (Possehl, 1990; Ratnagar, 1981). Trade was facilitated by two major river systems, the Indus and the Ghaggar-Hakra (now dry), which were connecting regions rich in tin and copper in Baluchistan and Afghanistan, through the Gulf of Oman, to the Persian Gulf and Mesopotamia. In the words of Gregory Possehl (1996):
"The Indus-Mesopotamia trade developed in part because ships had many advantages over caravans for the long-distance transport of products that were also theoretically available from alternative sources, and in part because, for some desirable products, there was no readily available alternative source."

Archaeological traces of the pivotal role of the Harappan civilization in moving raw materials from the center of Asia to Mesopotamia through the Persian Gulf can be found throughout the route. Several Harappan-related sites have been found in Southern Baluchistan and in Afghanistan: these were apparently trading colonies near major lapis lazuli, copper, and tin sources. Moreover, a series of archaeological findings point towards the presence of Harappan colonies or trade posts throughout the Persian Gulf. In Oman, archaeologists found a series of metal tools of clear Indus origin, several Indus trade tools used to normalize exchanges (e.g., the Indus-type stamp seals and cubical weights) and several Indus-type artifacts made in Oman by Indus or Indus-trained craftspeople using local raw materials. Moreover, more and more Indus pottery is steadily being recognized at sites in Oman and the Persian Gulf and Indus products were imitated in the Arabian coast (Edens, 1993, p.354).

As discussed in the previous subsection, although the tin sources in Mesopotamia are still not fully understood, several scholars have suggested that the Harappan civilization provided a major source. The supply of tin by this sea route is suggested, for instance, in a passage in one of the texts of Gudea, a priest-king reigning in Southern Mesopotamia, who describes the trove of objects reserved for the god and placed in the temple:

"Along with copper, tin, slabs of lapis lazuli, shining metal (and) spotless Meluhha cornelian".

People of Meluhha are described as traders in the Sumerian texts and there are frequent references to their ships. Harappan-style artifacts, including seals, beads, and shell objects, have been recovered from sites in Mesopotamia dating from 2550 BC. Conversely, there is no archaeological evidence of Mesopotamian goods in Indus cities. This has been interpreted as a sign that either import from Mesopotamia were perishable goods, or that the Indus-Mesopotamia trade was mainly indirect, via Dilmun and Magan.

7.3 Assur in the Old Assyrian period (1950-1750 BC)

The Old Assyrian commercial network (1950-1750 BC) stands out as a remarkable example of the emergence of a state that promoted long-distance commerce as its primary political and economic objective and relied on taxing transit traders within a thriving long-distance trade ecosystem. Our understanding of the Assyrian trade primarily comes from a unique collection of some 23,500 merchant records inscribed on clay tablets, excavated in the city of Kanesh. These records stand virtually alone as evidence for the organization of overland
trade in the Bronze Age: they are therefore critical for a comprehensive understanding of the
relationship between geography, trade, and the rise and organization of a Bronze-Age state.
The epicenter of this vast trade network was Assur, a city erected on a sandstone cliff by
the Tigris River. The city was surrounded by relatively unproductive farmland. However, its
position at the confluence of the Tigris and its two largest tributaries - the Great Zab and the
Little Zab, provided a natural bridge linking Anatolia to Sumer and Iran. One of the very
first rulers of Assur, Ilushuma, left behind this inscription:

“Ilushuma, vice-regent of Ashur, built the temple for the goddess Ishtar, his mis-
tress, for his life. A new wall [...] I constructed and subdivided for my city
house-plots. The god Ashur opened for me two springs in Mount Ebih and I made
bricks for the wall by the two springs. [...] The freedom of the Akkadians and
their children I established. I purified their copper. I established their freedom
from the border of the marshes and Ur and Nippur, Awal and Kismar, Der of the
god Ishtar, as far as the City (i.e., Assur)."

This early inscription links the rise of the city with trade in metals. Specifically, the first part
of the inscription alludes to the city’s foundation, while the final sentence delineates what
seems to be three trade routes leading to Assur from the south: one from Ur, the copper
entry point from the Gulf, via Nippur; one through the Tigris from Awal and Kismar in the
Hamrin region; and one from Elam, via Der, east of the Tigris, passing by Susa (Larsen,
1976). The inscription explicitly mentions copper and omits tin, possibly due to the text’s
early date (Barjamovic, 2008). The central role of the metal trade in the city’s rise is echoed
in the only inscription referring to Ilhusuma’s successor, Erishum I, which states that Erishum
made tax-exempt trade in copper, tin, and barley, transiting the city.

In 1950-1750 BC, Assur controlled the trade corridor between Assur and Anatolia, and a
commercial circuit within central Anatolia. These trade routes likely formed part of a chain
of interlocking commercial networks that most likely was ultimately connecting the Chinese
frontier with the Balkans (Barjamovic, 2008). Assur and Kanesh functioned as the main
markets for Assyrian traders. Assur was the endpoint of "the caravan of the Lower Coun-
try," which transported the tin, mined in Central Asia, from the city of Susa in Southern
Mesopotamia. Assyrian traders would then purchase this tin (along with textiles) in Assur,
transport it to Kanesh - the city where all imports coming to Anatolia were cleared - and
then transport it to other Anatolian settlements. Kanesh also served as a central node in the
Anatolian copper trade, with Assyrian traders connecting Northern Anatolia’s copper-rich
areas with the West’s urban centers.

The scale of the metal trade was immense. Recent estimates (Stratford, 2010; Barjamovic,
2018) suggest that roughly 1500 donkeys, carrying around 15 tons of tin and 32,000 textiles
annually, traveled from Assur to Kanesh. To provide a sense of the scale, 15 tons of tin could
be exchanged in Kanesh for an average of 2 tons of silver (although prices would fluctuate considerably), which was enough to cover the annual cost of living for two to four thousand individuals in Kanesh (Dercksen, 2014). Detailed accounts also point towards significant volumes of copper and textile traded by Assyrian merchants across Anatolian settlements. In one instance, a single transaction involved 23 tons of copper and 15 tons of wool. In general, references to the transport of copper by the ton are not rare (Barjamovic, 2011).

The Assyrian texts depict a flourishing market economy based on free enterprise and private initiative, with profit-oriented and risk-taking merchants supported by sophisticated financial contracts and a well-functioning judicial system. Assyrian merchants established trade outposts or "ports" among the small city-states of Anatolia. These trading posts had their own legal and financial institutions, mirroring those of Assur.

Trade activities were regulated by taxes levied at various stages within the metal trade network. For instance, consider the tin trade (which was the most significant in terms of value). Upon arrival in Assur, the tin destined for sale in Anatolia was wrapped in textiles, and the package was put under sealing, hence the name "sealed tin". The “sealed tin” was distinguished from the “hand-tin”, brought to pay the taxes along the route. The “sealed tin” was then subject to an export tax when leaving Assur (wasitum: 1/120 over the value of all merchandise and donkeys), a transit tax on the route between Assur and Kanesh (datum: 6-10 percent), an entry tax (nishatum: 3 percent) in Kanesh, an export tax from Kanesh (sadduatum: 6 percent) and finally was subject to a series of toll taxes to local rulers when transiting through the Anatolian city-states.

Traders often attempted to evade these taxes by using a series of smuggling routes. Despite the risk of punitive measures such as imprisonment and fines, when tin prices fell in Kanesh, merchants were willing to take the chance. Assyrian texts reveal candid discussions among traders regarding smuggling routes, their potential profits, and associated risks.

Guards and guard posts located at bridges or along roads traveled by the Assyrians are also a recurring theme in the records (Barjamovic, 2011). Their number and distribution imply that barracks or forts must have been a common sight in the Anatolian landscape. These posts were likely both patrolling the countryside, discouraging smugglers and protecting traders, and maintaining roads or mountain passes clear and in good conditions.

7.4 The city of Mari in the Mari Age (1810-1760 BC)

Mari was an ancient Semitic city-state in modern-day Syria. It was an important political power already starting from 2600 BC. Our primary understanding of this society is derived from nearly 25,000 cuneiform tablets excavated in Mari starting from the 1930s and spanning the years between 1810-1760 BC (the Mari Age). Nevertheless, glimpses into the city’s political and economic landscape also emerge from select inscriptions in the city dating from 2500-2350 BC (Charpin, 1987), as well as the Ebla archives (dating approximately 2500-2200
Mari was strategically located on the Euphrates, just downstream from the confluence with the Khabur River. One of the factors in Mari's prominence was that, because of its unique position along a series of crucial trade passages, it played a major role as an entrepot in international trade (Kuhrt (1995, p.101) and Kristiansen and Larson (2005, p.93)). The archives suggest that the most relevant commodity that was traded was tin. In particular, a series of tablets deciphered by Dossin (1970) suggests that tin was transported east to west, using Mari as a nodal point. Tin came from unspecified sources in the east, transiting through Babylon and Susa. Once arrived in Mari, it would then be transshipped to various sites in Syria and Palestine and, through the port of Ugarit, even across the Mediterranean Sea to Crete (Morris, 1992, p.102)\(^{43}\). Over time, Mari emerged as the primary source of tin for the Western regions (Muhly, 1995, p.1509). The value put on the tin, and Mari's central role in its distribution, is illustrated in a letter (part of Mari's archive) from the king of Qatna, a city located 400 km west of Mari, addressed to the King of Ekallate, a city located to the east of Mari:

“This matter is unspeakable, yet I must speak and relieve my feelings: you are a great king; you asked me for two horses, and I had them sent to you. And now you sent me (only) 20 minas (c. 10 kilos) of tin. Is it not the case that, without any quibbling and in full, you got (what you wanted) from me? And you dare to send me this paltry amount of tin! If you had sent nothing at all, by the god of my fathers, I could not have been so angry!”

Given Mari's control of crucial commercial routes, royal income derived from trading ventures must have been considerable. The Mari texts show that royal journeys, as well as being an occasion to visit other kings, were accompanied by trade caravans (Durand, 1983, p.314). While the palace was actively involved in long-distance commerce, often exerting a dominant influence, it was not the sole player. A thriving network of private traders also existed, representing a substantial portion of Mari’s economy. For example, the archives highlight the critical role of one Elamite trader, Kuyaya, in the tin trade industry. A local Mari merchant named Ishkhi-Dagan, who made purchases of tin ingots, is similarly mentioned. More generally, there is evidence for private commercial ventures and an extensive private commercial network.

How taxation worked is not completely certain. However, in the words of Amelie Kuhrt (1995):

\(^{43}\)An interesting tablet, which dates back from the eighteenth century BC is set up as a balanced account, listing the tin received and shipped in Mari. It describes the tin received from the kings of Babylon (Hammurabi) and Susa (Shephard), stocked in Mari, and then shipped to individuals residing in Ugarit and Caphtorite, a town presumably located in Crete.
“state income was certainly derived from revenues levied on the transit trade, crossing-dues, tolls, boat taxes, and dues demanded in return for land grants”.

Tax returns must have been substantial, as indicated by the monumental Royal Palace of Mari, one of the wonders of the 18th century BC, and the monumental irrigation works that were undertaken during the Mari Age.

7.5 The Bronze Age Aegean

The Bronze Age Aegean in the eastern Mediterranean encompassed several powerful entities: the Minoans in Crete; the Mycenaecans in mainland Greece, and the Cypriots in Cyprus.

During the third millennium BC, the Minoans were already at the center of the Aegean trade network, with close contact with the Cyclades. This is testified by imports from these islands, trade in raw materials (e.g., obsidian, copper, lead, silver), the local production of material culture in Cycladic styles or technologies, and a relocation of Cycladic groups along the northern coast of Crete (Renfrew, 1964; Warren, 1984; Karantzali, 1996; Day, Wilson and Kiriatzi, 1998; Dimopoulou-Rethemniotaki, Wilson and Day, 2007). It is during the Middle Minoan period (1900-1800 BC), however, that the trade network of the Minoans starts expanding above the Cyclades: Minoan products and cultural influences starts to be found in mainland Greece, Asia Minor, the entire Mediterranean coast of the Middle East, and even as far as Egypt. At the same time, the Minoans are becoming the most powerful European civilization. Several hallmarks testify social development and economic growth. A state emerged together with writing, monumental burials, roads, and other public infrastructures. Towns such as Knossos, Malia, Gournia, and Plaikastro are often described as the first urban settlements of Bronze Age Europe. These towns were centers of craft production (textile, pottery, and metalworking) and long-distance trade. They developed around royal “palaces’, monumental buildings that, in some cases, had true Cyclopean size. These buildings were at the center of an economic system, which has often been referred to as “palace economy”, in which a substantial share of wealth was flowing under the control of a centralized administration, centered in the palace. The palaces gathered up, manufactured, traded, and redistributed product and services needed in Crete. They were at the heart of an extensive network of intra-regional and interregional maritime trade of agricultural products in exchange for obsidian and metals (copper and tin). A long-standing fascinating hypothesis in the historical and archaeological literature is that the centrality of Crete in the metal trade network in the Mediterranean might go a long way in explaining the rise of the palaces and the Minoan civilization. The Minoan civilization has often been referred to as the first example in history of a thalassocracy44, a polity that derives its power from its naval/commercial supremacy on the seas. Already in the fifth century BC, the Greek historian Thucydides wrote:

44Thalassokrateo means “to be master of the sea”
“Minos is the first to whom tradition ascribes the possession of a navy. He made himself master of a great part of what is now termed the Hellenic Sea; he conquered the Cyclades, and was the first colonizer of most of them, expelling the Carians and appointing his own sons to govern in them. Lastly, it was he who, from a natural desire to protect his growing revenues, sought, as far as he was able, to clear the sea of pirates.”

More recently, Gordon Childe has emphasized the absolute centrality of the Minoans in the Mediterranean trade:

“In the Early Bronze Age peninsula Italy, central Europe, and the west Baltic coastlands, and the British Isles were united by a single system for the distribution of metalware, rooted in the Aegean market.”

Minoan vessels were the primary means of transportation of copper ingots in the Mediterranean (Muhly, 1985) (Kropp (1990)). In a shipwreck near present-day Israel, numerous tin ingots, with Minoan seals, have been found: trace-element analysis points towards Cornwall, present-day England, as the most likely provenance of the tin (Berger et al., 2019). This finding puts the Minoans at the center of a tin trade route connecting western and northern Europe with the Syrian civilizations.

The Mycenaean civilization appeared later in history, in the middle Bronze Age, from approximately 1750 to 1050 BC. As for the Minoans, the center of the Mycenaean economy was the palace. The production of manufactures, the internal circulation, and the long-distance trade were conducted mainly under their control. Several tables found in the palace in Pylos demonstrate a very tight palatial control of the metal industry. Bronze smiths were distributed throughout the kingdom. Each smith was allocated raw ore and other materials from the palace and assigned a task, and then was expected to deliver the final product to the palace. (Chadwick, 1994, p.141) argues that the total number of smiths in the Pylian kingdom was nearly 400 and he estimates that the production would likely exceed the local demand. This fact, together with the absence of local copper and especially tin deposits, made Pylos a major center of exchange. It has been argued that long-distance trade became increasingly important in the region as the quality of the soil for growing cereals (which was already poor) progressively declined as a result of continuous intensive cultivation (Ascherson, 2011). Starting from 1550 BC, the Mycenaens established a wide network of colonies in coastal Anatolia, in southern Italy, and western Sicily, as well as in the Black Sea, Spain, and Southern France. These colonies helped to facilitate international trade with the Mycenaean states, by providing military protection and a uniform set of institutions and customs along the main Mediterranean trade routes. Long-distance trade promoted the rise of a political and administrative palatial elite that directly participated in trade voyages and would often
engage in wars to crush their trade rivals. In the Odyssey Book, Menelaus, the legendary Spartan wanax (king), describes the source of his wealth and power in the following way:

“But when it comes to men, I feel that few or none can rival me in wealth, for it took me seven years and great hardship to amass this fortune and bring it home in my ships. My travels took me to Cyprus, to Phoenicia, and to Egypt. Ethiopians, Sidonians, Erembians, I visited them all; and I saw Libya too...” (The Odyssey, Book 4, 75-85).

While there is little doubt that interregional trade in the Mediterranean was driven by bronze-making metals, it is also clear that it enabled the exchange of luxury, or less utilitarian, goods, items that were enabling powerful statements. This is particularly evident for Mycenaeans, where eastern regions made the strongest contribution, as the sophisticated states of Egypt, the Levant, Mesopotamia, and Anatolia provided a wealth of precious items that functioned as technological and artistic models for the development of local arts and society (Burns, 2010).

Another influential Aegean civilization rose in Cyprus. Starting from 1650 BC, the island experienced a rapid change from a somewhat isolated, village-oriented culture to an international urban-centered and highly complex society. It is generally agreed that the first urban developments and the gradual movement of population from rural hinterland to coastal towns were not merely an internal socioeconomic process, but rather the outcome of overseas demand for Cypriot copper (Knapp, 2013; Negbi, 2005). The development of metallurgy on Cyprus was driven by the local copper mines and the need to meet the increasing demand for copper in the Mediterranean basin. Eventually, the intensified production and trade of copper catapulted Cyprus into the role of the most important purveyor of this metal in the Mediterranean region, which lasted until the Roman Empire (the name Cyprus is directly related to the Latin word for copper, cuprum). A large number of documents of the second millennium Egyptian, Syrian, Babylonian, Anatolian, and Mycenaean mention exchanges with Cyprus (Alashiya) and gifts of coppers.

7.6 The Bronze Age in China and the Erlitou period (1900-1500 BC)

Bronze metallurgy in China originated in what is referred to as the Erlitou period and it probably developed inside China separately from outside influence (Liu, 2005). The site of Erlitou is the largest among all its contemporary sites in China. Several researchers have argued that Erlitou was the capital of the first state in China (Liu, Chen et al., 2003; Liu and Chen, 2012; Liu et al., 2004).

Erlitou was nestled in an alluvial basin, positioned on the boundary between the Chinese lowlands and highlands, encircled by mountain ranges. Despite these natural barriers, the

45 Some scholars believe Erlitou to be the capital of the mythical Xia Dynasty, China’s first, although this is controversial (Wu et al., 2016).
basin maintained effective connections to regions in all directions through an intricate network of rivers. Specifically, Erlitou was situated at the point in which two major rivers, the Yi and Luo, converged in a short canal, the Yiluo. The Yiluo, within a span of less than 30 kilometers, intersected with several smaller rivers, eventually discharging into the Yellow River. This interconnected river system, combined with its prime location, sandwiched between mountains and plains, made of Erlitou an important road knot connecting the mineral-rich mountains with the fertile lowlands.

In the last four decades, more than 200 sites containing Erlitou material assemblages have been found over a very broad region from the middle Yellow River to the middle Yangzy River regions. The sites are distributed along several river systems and the pattern of settlement distribution is indicative of the emergence of a highly integrated and centralized socio-political system (Liu, 2005, p.226). The line expansion of this first state suggests a series of attempts to achieve political domination of metal-rich peripheries. One notable example is Panlongcheng, a site located at the intersection between the Han and the Yangzi River, and in close proximity to both copper and tin deposits. There is evidence that copper was melted at the mining sites, while the elite in Panlongcheng was likely playing a major role in forwarding copper ingots to the primary center at Erlitou (Liu, Chen et al., 2003). There is also evidence of limited bronze-making dating from the Erlitou period. Another example of an outpost to control metal resources, set up by the Erlitou state, is the site of Donglongshan. Donglongshan is located on the north bank of the Dan River with close proximity to copper resources in Mt. Hongyan. Few pieces of metal slag were found at the site, suggesting that bronze metallurgy was carried out there (Yang, 2000).

The formation of the Erlitou state involved rapid territorial expansion by colonizing the surrounding regions, with the quest for bronze alloys as the main territorial driver. In the words of Li Liu (2005):

“The Erlitou state formed an inter-regional network focused on the production and distribution of prestige goods, especially bronze vessels. This network incorporated two interdependent sectors, core and periphery. The dominant core controlled the production of prestige items (bronze products, etc.), and the subordinate periphery provided raw material resources (e.g., metal ingots) [...] The Erlitou elite in the core achieved domination through military force by establishing outposts in the periphery to ensure the flow of material and information.”

8 Conclusion

The prevailing literature attributes the emergence of the Urban Revolution to farming and sedentism. Although we do not deny that both might represent necessary conditions, we
contend they are sufficient. The regions where the Urban Revolution started were not necessarily the most productive. Moreover, the invention of farming preceded by more than five thousand years the explosion of cities, states, and inequality that can be observed from the forth millennium BC.

We provide first empirical evidence that the discovery of bronze and the ensuing long-distance metal trade played an important role in explaining this phenomenon. Consistent with the qualitative archaeological literature, we document that regions located along trade corridors connecting copper and tin mines to fertile lands were more likely to experience the Urban Revolution. We conjecture that transit bottlenecks allowed a tax-levying elite to emerge and to be sustained. We formally test this appropriability theory and provide several case studies in support.
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Appendices

A  Additional Tables
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<td>2138</td>
</tr>
<tr>
<td>Principal component</td>
<td>0</td>
<td>1.991</td>
<td>-0.729</td>
<td>8.431</td>
<td>2138</td>
</tr>
<tr>
<td>Transit Index</td>
<td>184.998</td>
<td>1056.815</td>
<td>0</td>
<td>16984.861</td>
<td>2138</td>
</tr>
<tr>
<td>IV Transit trade</td>
<td>184.998</td>
<td>1056.815</td>
<td>0</td>
<td>16984.861</td>
<td>2138</td>
</tr>
<tr>
<td>Blockage cost</td>
<td>7.609</td>
<td>66.821</td>
<td>0</td>
<td>1487.478</td>
<td>2138</td>
</tr>
<tr>
<td><strong>Europe (Section 5.4)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any elite burial (×100)</td>
<td>36.471</td>
<td>48.163</td>
<td>0</td>
<td>100</td>
<td>850</td>
</tr>
<tr>
<td>Number of elite burials</td>
<td>2.956</td>
<td>8.851</td>
<td>0</td>
<td>95</td>
<td>850</td>
</tr>
<tr>
<td>Transit Index</td>
<td>2070.372</td>
<td>6032.984</td>
<td>0</td>
<td>68723.164</td>
<td>850</td>
</tr>
<tr>
<td>Blockage cost</td>
<td>8833.989</td>
<td>9978.144</td>
<td>0</td>
<td>26347.975</td>
<td>850</td>
</tr>
</tbody>
</table>

Notes: a data from Whitehouse and Whitehouse (1975); b data from Pleiades.
Table A.2: Threats to identification: Reba, Reitsma and Seto (2016) city data

<table>
<thead>
<tr>
<th>Any City by 1000 BC (×100)</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit Index</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panel A: Second stage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transit Index</td>
<td>0.443</td>
<td>0.446</td>
<td>0.348</td>
<td>0.442</td>
</tr>
<tr>
<td></td>
<td>(0.144)**</td>
<td>(0.198)**</td>
<td>(0.172)**</td>
<td>(0.228)*</td>
</tr>
<tr>
<td></td>
<td>[0.177]**</td>
<td>[0.236]***</td>
<td>[0.175]**</td>
<td>[0.261]***</td>
</tr>
<tr>
<td>Panel C: First stage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV Transit Index</td>
<td>0.574</td>
<td>0.395</td>
<td>0.462</td>
<td>0.464</td>
</tr>
<tr>
<td></td>
<td>(0.056)**</td>
<td>(0.043)***</td>
<td>(0.047)***</td>
<td>(0.060)***</td>
</tr>
<tr>
<td></td>
<td>[0.081]**</td>
<td>[0.062]***</td>
<td>[0.066]**</td>
<td>[0.075]***</td>
</tr>
</tbody>
</table>

| Geography controls       | Yes | Yes | Yes | Yes |
| Continent fixed effects  | Yes | Yes | Yes | Yes |
| Observations             | 8,496 | 9,426 | 9,426 | 9,426 |
| Mean dependent variable  | 0.341 | 0.488 | 0.488 | 0.488 |
| First-stage F-statistic (5×5 grids) | 104.5 | 84.01 | 95.61 | 59.28 |
| First-stage F-statistic (Conley 1000km) | 49.85 | 39.61 | 47.69 | 37.89 |
| Check                    | Drop IV Controls Metal | Henderson et al. (2018) transit |

Notes: Panel A reports second-stage estimates of the cross-sectional 2SLS-IV model (5), while panel B reports the corresponding first-stage estimates. Standard errors clustered at the level of 5×5 degree grid cells reported in parentheses. Standard errors computed using the approach of Conley (1999) (cut-off 1000km) are reported in square brackets. ‘Any city by 1000 BC’ is a dummy equal to one if a city was present in a given 1×1 degree grid cell by 1000 BC. Variable is multiplied by hundred to facilitate interpretation. All regressions account for the full set of controls (see Section 3 and notes in Table ??). Column (1) restricts the spatial extent of the analysis to grid cells not used in the estimation of $\alpha_{BA}$. In column (2) we construct the instrument using the transport cost estimates of the Stone Age ($\alpha_{SA}$). Column (3) extends the set of controls by the characteristics used in Henderson et al. (2018). Column (4) controls for the transit trade index in gold, lead, and silver. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. 
Table A.3: OLS and 2SLS-IV cross-sectional evidence: Hyde 3.1 urban population data

<table>
<thead>
<tr>
<th></th>
<th>Any urban population by 2000 BC (×100)</th>
<th>Panel A: Second stage</th>
<th>Panel B: First stage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
</tr>
<tr>
<td></td>
<td>OLS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transit index</td>
<td>0.121</td>
<td>0.097</td>
<td>0.066</td>
</tr>
<tr>
<td></td>
<td>(0.016)***</td>
<td>(0.022)***</td>
<td>(0.026)**</td>
</tr>
<tr>
<td></td>
<td>[0.025]***</td>
<td>[0.033]***</td>
<td>[0.038]*</td>
</tr>
<tr>
<td>Proximity mines</td>
<td>0.120</td>
<td>0.216</td>
<td>0.125</td>
</tr>
<tr>
<td></td>
<td>(0.025)***</td>
<td>(0.097)***</td>
<td>[0.051]***</td>
</tr>
<tr>
<td>Proximity croplands</td>
<td>0.125</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.032)***</td>
<td>[0.051]***</td>
<td>[0.051]***</td>
</tr>
<tr>
<td>Sea</td>
<td>0.436</td>
<td>0.412</td>
<td>0.436</td>
</tr>
<tr>
<td></td>
<td>(0.075)***</td>
<td>(0.075)***</td>
<td>[0.122]***</td>
</tr>
<tr>
<td>River</td>
<td>0.041</td>
<td>0.083</td>
<td>0.041</td>
</tr>
<tr>
<td></td>
<td>(0.078)</td>
<td>(0.083)</td>
<td>(0.078)</td>
</tr>
<tr>
<td>Mountains</td>
<td>-0.085</td>
<td>0.164</td>
<td>-0.085</td>
</tr>
<tr>
<td></td>
<td>(0.054)</td>
<td>(0.064)*</td>
<td>(0.054)</td>
</tr>
<tr>
<td></td>
<td>[0.067]</td>
<td></td>
<td>[0.067]</td>
</tr>
<tr>
<td>Centrality</td>
<td>-0.003</td>
<td>-0.011</td>
<td>-0.003</td>
</tr>
<tr>
<td></td>
<td>(0.005)</td>
<td>(0.006)*</td>
<td>(0.005)</td>
</tr>
<tr>
<td></td>
<td>[0.007]</td>
<td></td>
<td>[0.007]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: Panel A of this table reports the OLS and second-stage estimates of Equation (3) using 2SLS-IV. Panel B reports the corresponding first-stage estimates (Equation (4)). Standard errors clustered at the level of 5×5 degree grid cells reported in parentheses. Standard errors computed using the approach of Conley (1999) (cut-off 1000km) are reported in square brackets. ‘Any city by 1300 BC’ is a dummy equal to one if any urban population was present by 2000 BC. Variable is multiplied by hundred to facilitate interpretation. Variable is multiplied by hundred to facilitate interpretation. ‘Transit trade index’ is the cropland and metal input weighted number of least-cost paths that intersect a grid cell, as defined in Equation (1). ‘IV Transit trade’ is the NPP and metal input weighted number of least-cost paths that intersect a grid cell, as defined in Equation (2). ‘Proximity mines’ is the inverse input weighted average transport costs to metal mines. ‘Proximity croplands’ represents the grid’s proximity to croplands, defined as the inverse transport cost weighted distance to croplands. ‘Sea’ is a dummy variable indicating whether a grid cell is intersected by the coastline. ‘River’ is a dummy variable indicating whether a grid cell is intersected by river. ‘Centrality’ is the cell’s transport surface eigenvector centrality. * p < 0.10, ** p < 0.05, *** p < 0.01.
Table A.4: Accounting for land fertility

<table>
<thead>
<tr>
<th>Any City by 1300 BC (×100)</th>
<th>2SLS (1)</th>
<th>2SLS (2)</th>
<th>2SLS (3)</th>
<th>2SLS (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel A: Second stage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transit index</td>
<td>0.307</td>
<td>0.512</td>
<td>0.511</td>
<td>0.590</td>
</tr>
<tr>
<td></td>
<td>(0.168)*</td>
<td>(0.169)***</td>
<td>(0.179)***</td>
<td>(0.197)***</td>
</tr>
<tr>
<td></td>
<td>[0.220]</td>
<td>[0.227]**</td>
<td>[0.239]**</td>
<td>[0.270]**</td>
</tr>
<tr>
<td>Farming land</td>
<td>0.134</td>
<td>-0.279</td>
<td>-0.037</td>
<td>-0.261</td>
</tr>
<tr>
<td></td>
<td>(0.072)*</td>
<td>(0.128)**</td>
<td>(0.020)*</td>
<td>(0.101)***</td>
</tr>
<tr>
<td></td>
<td>[0.089]</td>
<td>[0.156]**</td>
<td>[0.025]</td>
<td>[0.140]**</td>
</tr>
<tr>
<td>Panel B: First stage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV Transit index</td>
<td>0.496</td>
<td>0.770</td>
<td>0.663</td>
<td>0.637</td>
</tr>
<tr>
<td></td>
<td>(0.038)***</td>
<td>(0.051)***</td>
<td>(0.056)***</td>
<td>(0.053)***</td>
</tr>
<tr>
<td></td>
<td>[0.058]***</td>
<td>[0.076]***</td>
<td>[0.076]***</td>
<td>[0.081]***</td>
</tr>
<tr>
<td>Continent fixed effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Observations</td>
<td>9,426</td>
<td>9,426</td>
<td>9,426</td>
<td>9,426</td>
</tr>
<tr>
<td>Mean</td>
<td>0.488</td>
<td>0.488</td>
<td>0.488</td>
<td>0.488</td>
</tr>
<tr>
<td>First-stage F-stat (5×5 grids)</td>
<td>174.4</td>
<td>225.2</td>
<td>174.8</td>
<td>144.8</td>
</tr>
<tr>
<td>First-stage F-stat (Conley 1000km)</td>
<td>71.52</td>
<td>100.3</td>
<td>75.25</td>
<td>61.29</td>
</tr>
</tbody>
</table>

Notes: Panel A of this table reports the OLS and second-stage estimates of Equation (3) using 2SLS-IV. Panel B reports the corresponding first-stage estimates (Equation (4)). Standard errors clustered at the level of 5×5 degree grid cells reported in parentheses. Standard errors computed using the approach of Conley (1999) (cut-off 1000km) are reported in square brackets. ‘Any city by 1300 BC’ is a dummy equal to one if a city was present in a given 1×1 degree grid cell by 1300 BC. Variable is multiplied by hundred to facilitate interpretation. ‘Any Cities’ is the total number of cities that had emerged in a grid grid cell by 1300 BC. Variable is multiplied by hundred to facilitate interpretation. ‘Transit trade index’ is the cropland and metal input weighted number of least-cost paths that intersect a grid cell, as defined in Equation (1). ‘IV Transit trade’ is the NPP and metal input weighted number of least-cost paths that intersect a grid cell, as defined in Equation (2). ‘Proximity mines’ is the inverse input weighted average transport costs to metal mines.* p < 0.10, ** p < 0.05, *** p < 0.01.
Table A.5: Threats to identification: Difference-in-differences (Stone Age vs Bronze Age): Archaeological sites

<table>
<thead>
<tr>
<th>Any Site (×100)</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Panel A: Second stage Whitehouse and Whitehouse (1975) archaeological sites</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transit Index×Bronze Age</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td></td>
</tr>
<tr>
<td>1.885</td>
<td>2.480</td>
<td>1.279</td>
<td>1.322</td>
<td></td>
</tr>
<tr>
<td>(0.339)***</td>
<td>(0.432)***</td>
<td>(0.381)***</td>
<td>(0.455)***</td>
<td></td>
</tr>
<tr>
<td>[0.326]***</td>
<td>[0.392]***</td>
<td>[0.311]***</td>
<td>[0.363]***</td>
<td></td>
</tr>
<tr>
<td><strong>Panel B: Second stage Pleiades Gazetteer (Bagnall, 2022)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transit Index×Bronze Age</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td></td>
</tr>
<tr>
<td>0.709</td>
<td>0.913</td>
<td>0.681</td>
<td>0.929</td>
<td></td>
</tr>
<tr>
<td>(0.255)***</td>
<td>(0.290)***</td>
<td>(0.417)</td>
<td>(0.469)***</td>
<td></td>
</tr>
<tr>
<td>[0.186]***</td>
<td>[0.220]***</td>
<td>[0.330]***</td>
<td>[0.349]***</td>
<td></td>
</tr>
<tr>
<td><strong>Panel C: First stage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transit Index×Bronze Age</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV Transit Index×Bronze Age</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td></td>
</tr>
<tr>
<td>0.487</td>
<td>0.325</td>
<td>0.377</td>
<td>0.452</td>
<td></td>
</tr>
<tr>
<td>(0.045)***</td>
<td>(0.032)***</td>
<td>(0.045)***</td>
<td>(0.059)***</td>
<td></td>
</tr>
<tr>
<td>[0.048]***</td>
<td>[0.034]***</td>
<td>[0.042]***</td>
<td>[0.052]***</td>
<td></td>
</tr>
<tr>
<td>Geography controls</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Grid cell fixed effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Continent×period fixed effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Observations</td>
<td>16,992</td>
<td>18,852</td>
<td>18,852</td>
<td>18,852</td>
</tr>
<tr>
<td>Mean dependent variable Panel A</td>
<td>4.620</td>
<td>8.498</td>
<td>8.498</td>
<td>8.498</td>
</tr>
<tr>
<td>Mean dependent variable Panel B</td>
<td>1.236</td>
<td>2.376</td>
<td>2.376</td>
<td>2.376</td>
</tr>
<tr>
<td>First-stage F-statistic (5×5 grids)</td>
<td>115.4</td>
<td>100.2</td>
<td>71.13</td>
<td>58.37</td>
</tr>
<tr>
<td>First-stage F-statistic (Conley 1000km)</td>
<td>103</td>
<td>87.70</td>
<td>79.00</td>
<td>74.15</td>
</tr>
<tr>
<td>Check</td>
<td>Drop</td>
<td>IV</td>
<td>Controls</td>
<td>Metal</td>
</tr>
<tr>
<td>extent $\alpha_{BA}$</td>
<td>using $\alpha_{SA}$</td>
<td>Henderson et al. (2018)</td>
<td>transit</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Panel A reports second-stage estimates of the panel 2SLS-IV model (7), while panel B reports the corresponding first-stage estimates. Standard errors clustered at the level of 5×5 degree grid cells reported in parentheses. Standard errors computed using the approach of Conley (1999) (cut-off 1000km) are reported in square brackets. Any Site’ is a dummy equal to one if an archaeological site was present in a given 1×1 degree grid and period. Variable is multiplied by hundred to facilitate interpretation. All regressions account for the full set of controls (see Section 3 and notes in Table 2). Column (1) restricts the spatial extent of the analysis to grid cells not used in the estimation of $\alpha_{BA}$. In column (2) we construct the instrument using the transport cost estimates of the Stone Age ($\alpha_{SA}$). Column (3) extends the set of controls by the characteristics used in Henderson et al. (2018). Column (4) controls for the transit trade index in gold, lead, and silver. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. |
B Additional Figures

Figure B.1: Sites Whitehouse and Whitehouse (1975)
Figure depicts the location of archaeological sites from Whitehouse and Whitehouse (1975)’s Archaeological Atlas of the World used in our analysis.
Figure B.2: Sites Pleiades Gazetteer
Figure depicts the location of archaeological sites from the Pleiades Gazetteer Bagnall (2022) used in our analysis.
Figure B.3: Sites Atlas of Chinese relics
Figure depicts the location of archaeological sites of the Atlas of Chinese relics. Data is unavailable for provinces shaded in grey.
Figure B.4: Correspondence plot

Figure depicts the correspondence plot of the most frequent 100 words according to the seven criteria indicative of the rise of the Urban Revolution in China.
Figure B.5: Elite burials  
Figure depicts the location of bronze weapon finds as recorded by Prähistorische Bronzefunde (Abteilung IX and Abteilung IV). Grid cells in which at least one bronze weapon was excavated are shaded in gray. Our regression analysis is restricted to these cells (see Section 5.4 for more details.)
Figure B.6: Distribution Croplands
Figure depicts spatial distribution of croplands for the year 3000 BC (source: Klein Goldewijk, Beusen and Janssen (2010). Darker shadings imply larger areas of croplands.

Figure B.7: Cities and transit index over time
Figure depicts 2SLS-cross-sectional IV point estimates and 90% confidence intervals of transit trade. Standard errors are clustered at the level of 5×5 degree grid cells. Dependent variable is a dummy equal to one if a city site was present in a given 1×1 degree grid and period. Variable is multiplied by hundred to facilitate interpretation.
Figure B.8: Cities and copper transit index over time
Figure depicts 2SLS-cross-sectional IV point estimates and 90% confidence intervals of transit trade. Standard errors are clustered at the level of $5 \times 5$ degree grid cells. Dependent variable is a dummy equal to one if a city site was present in a given $1 \times 1$ degree grid and period. Variable is multiplied by hundred to facilitate interpretation.

Figure B.9: Cities and tin transit index over time
Figure depicts 2SLS-cross-sectional IV point estimates and 90% confidence intervals of transit trade. Standard errors are clustered at the level of $5 \times 5$ degree grid cells. Dependent variable is a dummy equal to one if a city site was present in a given $1 \times 1$ degree grid and period. Variable is multiplied by hundred to facilitate interpretation.
Figure B.10: Deposits, NPP and IV
Panel (a) depicts the spatial distribution copper deposits (brown dots), tin deposits (blue dots), and NPP (green shadings, where darker shadings imply higher values of NPP). Panel (b) visualises the instrumental variable (where continent fixed effects are partialled out). Klein Goldewijk, Beusen and Janssen (2010).
(a) Figure shows the point estimate of Table 1 (column (1)) along with alternative standard error clustering approaches. Standard errors depicted in black are clustered at grid cells of various sizes, while Conley (1999) standard errors are shown in grey using different cutoff levels.

(b) Figure shows the point estimate of Table 1 (column (2)) along with alternative standard error clustering approaches. Standard errors depicted in black are clustered at grid cells of various sizes, while Conley (1999) standard errors are shown in grey using different cutoff levels.
(a) Figure shows the point estimate of Table 2 (Panel A column (1)) along with alternative standard error clustering approaches. Standard errors depicted in black are clustered at grid cells of various sizes, while Conley (1999) standard errors are shown in grey using different cutoff levels.

(b) Figure shows the point estimate of Table 2 (Panel A column (6)) along with alternative standard error clustering approaches. Standard errors depicted in black are clustered at grid cells of various sizes, while Conley (1999) standard errors are shown in grey using different cutoff levels.
(c) Figure shows the point estimate of Table 2 (Panel B column (1)) along with alternative standard error clustering approaches. Standard errors depicted in black are clustered at grid cells of various sizes, while Conley (1999) standard errors are shown in grey using different cutoff levels.

(d) Figure shows the point estimate of Table 2 (Panel B column (6)) along with alternative standard error clustering approaches. Standard errors depicted in black are clustered at grid cells of various sizes, while Conley (1999) standard errors are shown in grey using different cutoff levels.

Figure B.13: Effect of transit trade index separate by type of archaeological site reported in Whitehouse and Whitehouse (1975)

Figure depicts 2SLS-IV point estimates and 90% confidence intervals of the effect of transit trade on individual types of archaeological sites relative to the Stone Age. Dependent variables are dummies equal to one if a given type of site was present in a given $1\times1$ degree grid and period. Variable is multiplied by hundred to facilitate interpretation. See Section 3 for details on definition and construction of variables.
C Period-specific per-unit transport costs

To estimate period-specific transport cost we require two main inputs: bilateral trade data and a suitable estimation framework. We describe these two components below.

C.1 Bilateral trade data

Following Flückiger et al. (2022), we reconstruct trade flows by defining the archaeological excavation site of an artefact as the destination and the production site as the origin. A first prerequisite for artefacts to be included in our analysis therefore is that their find site as well as provenance can be identified. A second prerequisite is that the time period can be assigned to the artefacts (i.e., Stone or Bronze Age). To identify suitable data, we systematically scoured the archaeological literature. We identified two existing large-scale databases on trade during the Stone Age that report precise origin and destination of artefacts. Trade data for the Bronze Age are drawn from the database created by Flückiger et al. (2022). Below, we describe the characteristics of the databases as well as the aggregation process from artefact-level to regional-level trade flows. The origins and destinations of artefacts are depicted in Figure C.1. In the context of our analysis, it is important to note that the overwhelming majority of artefacts contained in our datasets were traded within Europe.

C.1.1 Stone Age trade data

Alpine jade—Neolithic period

The Alpine jade database was compiled by more than 50 researchers from several European countries as part of the project “JADE: Social inequalities in Neolithic Europe: the circulation of long axeheads of Alpine jades” (Pétrequin et al., 2012). The data was compiled between 2008 and 2018 and focuses on long axeheads made from jade (mainly extracted in the Alps). In total, the database contains precise information on the find site of 2,173 jade axeheads which can be downloaded at http://jade.univ-fcomte.fr. These axes mainly circulated within Europe during the 5th and 4th millennia BC, but some of the objects moved over long distances from the Alpes to the Atlantic coast and the Black Sea via extensive exchange networks. To identify the provenance of the axeheads, the researchers used visual analysis and spectroradiometry. For 1,355 axeheads, the database includes information on the origin of the artefacts with sufficient precision for the purpose of our analysis. The jade included in our analysis primarily originates from high-altitude quarries at Monte Viso near Turin (973 pieces) and Monte Beigua near Genoa (151 pieces) in the Italian Alps. Some of the finds can also be reliably traced back to the Vosges in France or the Pennine Alps in Switzerland.

British axeheads—Early Neolithic period

Schauer et al. (2020) provide an extensive database on British axeheads that combines information collected in projects overseen by the Imple-

46 Description of the Stone Age trade data is taken from Flückiger et al. (2022) in large parts.
ment Petrology Group (IPG), the Neolithic Axehead Archive, and the Irish Stone Axe Project. The database contains precise information on the find site of 5,809 axeheads from the Early Neolithic (4100–3400 BC) discovered across England, Wales and southern Scotland. Provenance of the axeheads is identified via petrological analysis. For our analysis, we exclude axeheads made from flint (1,512 pieces) due to fact that origins could not be unambiguously determined. We further exclude axeheads for which the source was specified as ‘other’ (1,766 pieces) which includes jade pieces originating from continental Europe. These restrictions leave us 2,345 artefacts for which the provenance is pinpointed within a radius of less than 50 km in Schauer et al. (2020).

C.1.2 Bronze Age trade data
We draw information on goods traded during the Bronze Age from the database compiled by Flückiger et al. (2022). A large share of the objects contained in their database are weapons, tools, and jewellery. In total, this database encompasses 3,744 artefacts for which find site and provenance can be determined with sufficient precision. In most cases, the artefacts’ provenance was identified based on metal parts, such as copper, silver, tin, or lead, using lead isotope analysis and trace element pattern analysis. In few cases it was determined by typology of similar instruments. For more details on the data construction process and a list of sources, see Online Appendix E in Flückiger et al. (2022).

C.1.3 Aggregation
For the inference of trade costs, we aggregate the information of the individual artefacts to the grid-cell-pair level. In keeping with the spatial unit of analysis of our main analysis, we first identify into which of the 1×1 degree grid cell its origin and destination fall. We then aggregate this information to the grid-cell-pair level giving us the number of finds within cell \(j\) that originate from cell \(i\). The resulting trade volume represents the dependent variable used in the regression framework. This framework is described next.

C.2 Estimation framework
To infer period-and mode-specific per-unit distance transport costs we proceed in three steps. First, we divide the world into grid cells of 0.25×0.25 degrees and classify each grid as being either a sea, river, or land grid. The classification of grids—and equivalently transport modes—is based on spatial data from Natural Earth. As mentioned in the main part, we impose three restrictions: (i) maritime transport is only possible along the coast (below 60° latitude); (ii) riverine transport is only feasible on navigable rivers; and (iii) transport is not possible across high mountain ranges (above 4,500 meters). The resulting transport surface is depicted in Figure C.2.

\(^{47}\)The relative coarse size of cells is chosen to account for the fact that coastlines as well as river courses can shift over time.
Figure C.1: Origins and Destinations of Artefacts
Panel (a) depicts origins (blue triangles) and destinations (red dots) of artefacts traded during the Stone Age. Panel (b) depicts origins (blue triangles) and destinations (red dots) of artefacts traded during the Bronze Age.

Second, we assign (relative) per-unit-distance transport cost to each shipping mode: $\alpha_{sea}$, $\alpha_{river}$, and $\alpha_{land}$. For the transport cost vector $\boldsymbol{\alpha} \equiv \left(1, \alpha_{river}, \alpha_{land}\right)$ we then use Dijkstra (1959)'s algorithm to identify the least-cost path and associated transport cost between any two 1×1 degree grid cells.\footnote{The geographical centres (centroids) of grid cells are set as origins and destinations.} Throughout, we assume that transshipment between different transport modes is costless.

In the third step, we use the (logarithmized) costs associated with transporting goods along the least-cost path as the explanatory variable in a standard gravity equation using the Poisson pseudo-maximum likelihood (PPML) estimator:

\[
X_{ij}^p = \exp (\delta \ln LC(\boldsymbol{\alpha})_{ij} + \beta_i + \beta_j) + \varepsilon_{ij}, \tag{C.1}
\]
where \( X^p_{ij} \) denotes the number of period-specific artefacts excavated in grid cell \( j \) that originate from grid cell \( i \), as described above. The main explanatory variable—\( LC(\alpha)_{ij} \)—is the cost associated with transport along the least-cost path given the transport cost vector \( \alpha \). We account for the full set of origin and destination fixed effects (represented by \( \beta_i \) and \( \beta_j \), respectively).

Separately for each period (i.e. Stone and Bronze Age), we repeat the three-step procedure described above iterating over all cost combinations \( \alpha^{\text{sea}} = [1, 50], \alpha^{\text{river}} = [1, 50], \) and \( \alpha^{\text{land}} = [1, 100] \). This implies that we run regression model (C.1) 250,000 times for a given period. Each time we measure model fit using the log-likelihood. Akin to Donaldson (2018) we then define the cost vector that minimises the log-likelihood as our period-specific transport costs (\( \alpha^P \)). For the Bronze Age, this fit-maximising transport cost vector is given by \( \alpha_{\text{BA}} = (1, 2, 6) \), where we normalise \( \alpha^{\text{sea}} = 1 \) for ease of interpretation. For the Stone Age, the transport costs are \( \alpha_{\text{SA}} = (1, \frac{1}{14}, \frac{2}{7}) \).


D Theoretical Model

E Prelude

We develop a theoretical model that takes Mayshar, Moav and Pascali (2022) as starting point but incorporates interregional metal trade, a prerequisite for the emergence of the Bronze Age. Kings tax metal trade. The optimal tax turns out to be a function of their position in the trade network, which motivates our concept of blockage costs (\(=\) the maximum tax revenue a king can collect) below. The model has three types of important agents: i) farmers, which use cropland and metals to produce crops; ii) traders, which bring metals from the mines to the farmers and are subject to taxes and the probability of getting raided by bandits; and iii) Foragers, which serve as outside option for bandits and tax collectors. Furthermore, we analyze two types of possible states: anarchy or hierarchy. Under anarchy a cell is ruled by bandits. Under hierarchy, kings use their monopoly of violence to deter bandits and to tax traders in order to finance their state.

We describe each agent and state in turn next.

F Farmers

We assume that farmers in region/cell \( i \) use their cropland, \( L_i \), and metals, \( M_i \), as perfect complements for production of crops:

\[
Y_i = \min \{M_i, L_i\}.
\]

Demand for metals in cell \( i \) is therefore given by \( Y_i \). We assume that crops are sufficiently valuable so that it is always optimal to produce, independent from the price of metals. Furthermore, we assume that if in cell \( i \) there is cropland, \( L_i = 1 \), and if there is not, \( L_i = 0 \). Hence, demand for metals in \( i \) is given by:

\[
M_i = M = \begin{cases} 
1 & \text{in cells with cropland} \\
0 & \text{in cells without cropland} 
\end{cases}
\]

G Traders

Traders bring metals from the mines to cells and sell it to farmers. The revenues for traders are determined by the quantity of metals sold, while the costs are a function of the effort to ship metals to farmers. We assume perfect competition among traders for each route, i.e, metals from each mine to each destination cell will be served under perfect competition. As
a consequence each destination will source metal from only one mine, i.e., the mine which can supply metal at lowest costs. Since we assume identical production costs across mines, metal prices at the different mines are homogenous and trade costs fully determine prices at the destination cell.

Traders travel along transport routes between mines and cells. Since space is organized in grid cells, the length of the transport route is measured in number of grid cells, i.e., the number of grid cells a transport route traverses. In addition, each transport route is associated with route-specific total trade costs. The magnitude of these costs depend on the sum of the transport mode-specific transport costs per cell, $t$, along the transport route and the quantity shipped. Additionally, kings may tax traders when passing their cells. If they pass a cell without a king, traders may be raided by bandits.

Traders chose the least-cost route given transport costs and taxes. Least cost routes are transport routes with the lowest total trade costs that connect supply (mines) and demand (grid cells with crop). Traders may have to pay multiple taxes on route, depending on the cells $k \in K$ that they pass. We denote the total amount of taxes payed for a trader bringing metals from a mine in cell $a$ to a farmer in cell $b$ as $T_{ab}$. The least costs are denoted by $LC(t, M, T)$.

We assume that traders optimize each route separately, i.e., there are no economies of scale from serving different routes and also no capacity constraints in terms of number of routes served. Given the exogenous costs of metals at the mine, $c_a = c$, the profit function of traders for sales of metals from mines in cell $a$ to farmers in cell $b$ is given by:

$$\pi_{ab}^T = p_b M - c M - LC_{ab} (t_{ab,k}, M, T_{ab,k}).$$  \hfill (G.1)

The first-order conditions for traders are given by:

$$p_b - c - \frac{\partial LC_{ab} (t_{ab,k}, M, T_{ab,k})}{\partial M} = 0,$$  \hfill (G.2)

To get more concrete results, we assume the following specific functional form for the least costs:

$$LC_{ab} (t_{ab}, M, T_{ab}) = \min_{P_{ab}} \sum_{k \in K} \left( t_k^p + T_{ab,k}^T + T_{ab,k}^B \right) I_{P_{ab}} [k] ,$$

where $I_{P_{ab}} [k]$ is an indicator function\footnote{Formally, the indicator function is defined as:}

$$I_{P_{ab}} [k] = \begin{cases} 
1 & \text{if } k \in P_{ab}, \\
0 & \text{if } k \notin P_{ab}.
\end{cases}$$  \hfill (G.3)

\[82]
transport costs occurring in cell \( k \) (\( \rho \) denoting the elasticity with respect to trade costs).\(^{50}\) \( T_{ab,k}^T \) denotes the taxes levied by the king ruling in cell \( k \) on the traders serving the route \( a \) to \( b \) (\( T_{ab,k}^T = 0 \) if no king rules in cell \( k \)). Alternatively, traders pay taxes, \( T_{ab,k}^B \), to bandits if cell \( k \) is not ruled by a king (with \( T_{ab,k}^B = 0 \) if a cell is ruled by a king). The least-cost path, \( LC_{ab}(t_{ab,k}, M, T_{ab,k}) \),\(^{51}\) denotes the path with the lowest costs (including transport costs and all taxes) for transporting metals to destination cell \( b \), where \( a \) is the mine that is serving cell \( b \) at lowest trade costs. The overall costs of bringing metals from cell \( a \) to cell \( b \) is the sum over all cells \( k \) that the path \( P_{ab} \) passes, i.e., all cells where the indicator function \( I_{P_{ab}}[k] \) for path \( P_{ab} \) is positive.

Assuming that the trader chooses the least-cost path, i.e., selects \( P_{ab}^* \), the first order conditions for this path are then given by:

\[
p_b - c - \frac{\partial \sum_{k \in C} \left( T_k^p + T_{ab,k}^T + T_{ab,k}^B \right) I_{P_{ab}}^* [k]}{\partial M} = 0,
\]

\[(G.5)\]

Hence, prices for metals \( p_b \) are given by the following expressions:

\[
p_b = c + \frac{\partial \sum_{k \in C} \left( T_k^p + T_{ab,k}^T + T_{ab,k}^B \right) I_{P_{ab}}^* [k]}{\partial M}.
\]

Taxes are assumed to be levied on the costs of the product at the mine. Hence,

\[
T_{ab,k}^T = \tau_{ab,k}^T c M,
\]

\[
T_{ab,k}^B = \tau_{ab,k}^B c M,
\]

where \( \tau_{ab,k}^T \) denotes the tax rate as a share of the shipped metals transported from \( a \) to \( b \) by the king ruling in cell \( k \) for the traders (\( \tau_{ab,k}^T = 0 \) if no king rules in cell \( k \)). \( \tau_{ab,k}^B \) is the toll traders have to pay to bandits on metals transported from \( a \) to \( b \) in cell \( k \) if cell \( k \) is not ruled by a king (with \( \tau_{ab,k}^B = 0 \) if a cell is ruled by a king).\(^{52}\) The same assumption is made for transport costs, where the transport costs in cell \( k \) on one unit shipped valued with the production costs at the mine is denoted by \( t_k \).

Hence, prices can be expressed as follows:

\[^{50}\text{These cell-specific transport costs are defined by the cheapest available transport mode in } k:\]

\[
t_k[k] = \begin{cases} 
\alpha_{sea} & \text{if } k \in \text{sea grid}, \\
\alpha_{river} & \text{if } k \in \text{river grid} \\
\alpha_{land} & \text{if } k \in \text{land grid}.
\end{cases}
\]

\[^{51}P_{ab} = \arg \min_{P_{ab} \in P_2} \sum_{k \in C} \left( T_k^p + T_{ab,k}^T + T_{ab,k}^B \right) I_{P_{ab}}[k]\]

\[^{52}\text{One can think about this as the probability of getting raided and loosing everything if one gets raided}\]
\[ p_b = c \left( 1 + \sum_{k \in C} \left( t_k^p + r_{T,ab,k} + r_{B,ab,k} \right) I_{P_{ab}^* [k]} \right). \quad (G.6) \]

As there are potentially different mines that could serve location \( b \), only the one with the lowest marginal costs will actually do so.

As we assume perfect competition, profits for each route \( ab \) will be zero in equilibrium, i.e.,

\[ \pi_{ab}^* = p_b M - c M - \lambda C_{ab} \left( t_{ab}, M, T_{ab} \right) \]
\[ = p_b M - c M \]
\[ - \sum_{k \in C} \left( t_k^p + r_{T,ab,k} + r_{B,ab,k} \right) I_{P_{ab}^* [k]} c M \]
\[ = \left( 1 + \sum_{k \in C} \left( t_k^p + r_{T,ab,k} + r_{B,ab,k} \right) I_{P_{ab}^* [k]} \right) c M - c M \]
\[ - \sum_{k \in C} \left( t_k^p + r_{T,ab,k} + r_{B,ab,k} \right) I_{P_{ab}^* [k]} c M \]
\[ = 0. \]

\section{Foragers}

Foragers are assumed to earn a constant income \( s > 0 \). Under anarchy, some foragers may turn into bandits. Under hierarchy, i.e., when a king emerges, he hires tax collectors among the foragers. Hence, foraging serves as an outside option for bandits and tax collectors.

\section{Anarchy}

If there is no king in a cell, traders may be raided by bandits. As described before, \( r_{B,ab,k} \) is the toll traders have to pay to bandits on metals transported from \( a \) to \( b \) in cell \( k \).

Income of one bandit in cell \( k \) from trade between cells \( a \) and \( b \) is given by:

\[ R_{ab,k}^B = \frac{r_{B,ab,k} I_{P_{ab}^* [k]} c M}{\lambda(\tau_{B,ab,k})}, \]

where \( \lambda(\tau_{B,ab,k}) \) is the measure of bandits as a function of the toll. The function \( \lambda(\tau_{B,ab,k}) \) is strictly increasing and strictly convex. Bandits are indifferent between staying forager or becoming a bandit. Hence, it has to hold that:
\[
\frac{\tau_{ab,k}^{B} I_{P_{ab}^*}[k] cM}{\lambda(\tau_{ab,k}^{B})} = s \Rightarrow
\tau_{ab,k}^{B} I_{P_{ab}^*}[k] cM = s\lambda(\tau_{ab,k}^{B}).
\]

For all cells that are part of at least one least-cost route, \( I_{P_{ab}^*}[k] = 1 \). Hence,
\[
\tau_{ab,k}^{B} cM = s\lambda(\tau_{ab,k}^{B}).
\]

As \( c, M, \) and \( s \) are identical across cells, we have \( \tau_{ab,k}^{B} = \tau^{B} \).

**J Hierarchy: Kings and Tax Collectors**

We assume that kings possess monopoly power over the use of force in a cell. The establishment of the monopoly power of violence entails a fixed cost, denoted by \( G_0 > 0 \). The monopoly power of violence allows states to deter bandits. The king hires a measure of tax collectors, \( \lambda \), at cost \( s \) per tax collector among the potential foragers. \( \lambda \) can be thought of as the expropriation function and is assumed to depend on the tax rates. We assume that it is the same function as for bandits, and therefore also strictly increasing and strictly convex. Kings are farsighted and maximize net revenue, subject to the constraint that traders and farmers respond to the tax rate. Specifically, the king in cell \( c \) chooses a path-specific tax rate \( \tau_{ab,c}^{T} \) for each path from the mine \( a \) that cheapest serves destination cell \( b \), i.e., lies on the least-cost path \( P_{ab}^* \), to maximize the following tax revenue function under a set of constraints:

\[
\max_{\tau_{ab,c}^{T} \geq 0} R_{ab,c}^{T} = \tau_{ab,c}^{T} I_{P_{ab}^*}[c] (cM) - s\lambda(\tau_{ab,c}^{T}), \tag{J.1}
\]

\[
p_b = c \left( 1 + \sum_{k \in C} \left( t_{k}^B + \tau_{ab,k}^{T} + \tau_{ab,k}^{B} \right) I_{P_{ab}^*}[k] \right). \tag{J.2}
\]

\[
M = \begin{cases} 
1 & \text{in cells with cropland} \\
0 & \text{in cells without cropland} 
\end{cases}. \tag{J.3}
\]

**J.1 Optimal Taxes**

Assuming \( I_{P_{ab}^*} \) is exogenously determined, the first-order condition for \( \tau_{ab,c}^{T} \) is given by:

\[
\max_{\tau_{ab,c}^{T} \geq 0} R_{ab,c}^{T} = \tau_{ab,c}^{T} I_{P_{ab}^*}[c] (cM) - s\lambda(\tau_{ab,c}^{T}), \tag{J.1}
\]

\[
p_b = c \left( 1 + \sum_{k \in C} \left( t_{k}^B + \tau_{ab,k}^{T} + \tau_{ab,k}^{B} \right) I_{P_{ab}^*}[k] \right). \tag{J.2}
\]

\[
M = \begin{cases} 
1 & \text{in cells with cropland} \\
0 & \text{in cells without cropland} 
\end{cases}. \tag{J.3}
\]
The term on the left-hand side captures the direct effect of an increase of taxes, which is positive. The right-hand side captures the costs of tax collecting.

Several things are noteworthy from Equation (J.4):

1. If the optimal least-cost path from $a$ to $b$ does not go through $c$, i.e., $I_{P^*_{ab}}[c] = 0$, then there is also no tax to be collected.

2. The more central cell $c$ is in the network, and the harder it is to go via alternative routes, the more trade flows will go through cell $c$, i.e., $I_{P^*_{ab}}[c]$ will be equal to one for more trade routes $P_{ab}, a \in C, b \in C$. This allows to collect more taxes. Note that assuming that there is a unique least-cost path between each mine and destination, the betweenness centrality for cell $c$, $x_c$, is given by (see Newman, 2018, for example):

$$x_c = \sum_{a \in C, b \in C} I_{P^*_{ab}}[c].$$

A larger value of the betweenness centrality for cell $c$ implies that kings in cell $c$ have more power, as more metals will pass through their cell. A removal of a cell with a high betweenness centrality will have large effects on the overall costs for trading metals in the network.

Alternatively, we can view $x_c^{\text{w}} = \sum_{a \in C, b \in C} I_{P^*_{ab}}[c] (c M)$, as a weighted betweenness centrality, where $(c M)$ are the weights, i.e., the more metal is passing, the higher the weight of the respective path.

To sum up, the more trade flows through a cell and the more central a cell $c$ is, the higher the tax revenues. This motivates why kings can establish in central cells where many least-cost path pass (i.e., $x_c$ is large), and where there is a lot of trade of metals.

### J.2 Comparing the Optimality Conditions under Anarchy and Hierarchy

Under anarchy we have:

$$\tau^B_{ab,k} I_{P^*_{ab}}[k] (c M) = s \lambda (\tau^B_{ab,k}) \Rightarrow$$

$$I_{P^*_{ab}}[c] (c M) = s \frac{\lambda (\tau^B_{ab,c})}{\tau^B_{ab,c}}. \quad (J.5)$$

Under hierarchy we have:
The left-hand sides of Equations (J.5) and (J.6) are identical. \( \lambda(\tau_{ab,c}) \) is strictly increasing and strictly convex and for \( \tau = 0 \), \( \lambda(\tau = 0) = 0 \), i.e, it follows that \( \frac{\partial \lambda(\tau)}{\partial \tau} > \frac{\lambda(\tau)}{\tau} \) and as a consequence, we hav \( \tau_{ab,c}^B > \tau_{ab,c}^T \). Lower optimal taxes under hierarchy have important welfare consequences for agents in the respective cell. Traders are under perfect competition, but have lower costs of transportation. Kings are covering all their costs, otherwise they would not come into power. And bandits always earn a constant income \( s \). Hence, the ruling of a king in a cell \( c \) leads to welfare-improvements for all agents directly related to cell \( c \).

### K  Blockage Costs

So far we have treated \( I_{P^*_{ab}}[c] = 1 \) as exogenous. However, whether grid cell \( c \) is on a specific least-cost path depends of course on the tax rate in \( c \).

Intuitively (assuming \( c \) is part of the least-cost route \( P_{ab} \)), taxes in \( c \) cannot increase indefinitely, since traders can avoid high tax grids cell by choosing another transport route to circumvent \( c \). The possibility for traders to adjust along the extensive margin places a limit on the maximum tax rate a king can impose in a given grid cell.

For a more formal discussion on the extensive margin of taxation, we focus on the case, when for a given tax rate \( \tau_{ab,c}^T \), the least-cost path \( P_{ab}^* \) passes through cell \( c \), i.e., \( I_{P^*_{ab}}[c] = 1 \).

Using \( \tau_{ab,k}^B = \tau^B \), the least-cost path through \( c \) is then given by:

\[
LC_{ab} (t_{ab}, M, T_{ab}) = \min_{P_{ab} \in P_b} \sum_{k \in C} \left( t^p_k + \tau_{ab,k}^T + \tau_{k,ab}^B \right) I_{P_{ab}}^* [k] (cM),
\]

which gives the minimum costs for destination cell \( b \) to obtain metals, defining the optimal mine \( a \) and least-cost path \( P_{ab}^* \).

What is scope to increase taxes in \( c \)? To see this, we next calculate the least-cost route to serve \( b \) when we remove \( c \) from the network, i.e., when traders circumvent \( c \):

\[
LC_{ab}^{\backslash_c} (t_{ab}, M, T_{ab}) = \min_{P_{ab} \in P_b} \sum_{k \in C \backslash c} \left( t^p_k + \tau_{ab,k}^T + \tau_{k,ab}^B \right) I_{P_{ab}}^* [k] (cM),
\]

Hence, \( LC_{ab}^{\backslash_c} (t_{ab}, M, T_{ab}) \) gives the optimal path of serving cell \( b \) with metals when going through cell \( c \) is not feasible. The difference \( LC_{ab}^{\backslash_c} (t_{ab}, M, T_{ab}) - LC_{ab} (t_{ab}, M, T_{ab}) \) yields the
maximum tax increase that is possible in \( c \) before traders become indifferent in switching to another transport route, circumventing \( c \) and avoiding to pay taxes in \( c \).

In the same vain, we can calculate, the total maximum tax across all least-cost paths a king can levy in cell \( c \). To do so, we simply calculate the sum of the differences between all least-cost paths traversing \( c \) and their respective second best-routes (without \( c \)) that traders can take. In other words we block grid cell \( c \) for transit trade:

\[
B_c = \sum_{a \in C \setminus c, b \in C \setminus c} B_{ab, c} = \sum_{a \in C \setminus c, b \in C \setminus c} \left( LC_{ab}^c - LC_{ab} \right)
\]

\[
= \sum_{a \in C \setminus c, b \in C \setminus c} \left( \min_{P_{ab} \in P_b} \sum_{k \in C \setminus c} \left( t_k^P + \tau_{ab,k}^T + \tau_{ab,k}^B \right) I_{P_{ab}}^* [k] (cM) \right)
\]

\[
- \min_{P_{ab} \in P_b} \sum_{k \in C \setminus c} \left( t_k^P + \tau_{ab,k}^T + \tau_{ab,k}^B \right) I_{P_{ab}}^* [k] (cM) \right)
\]

\[
= \sum_{a \in C \setminus c, b \in C \setminus c} \left( \min_{P_{ab} \in P_b} \sum_{k \in C \setminus c} \left( t_k^P + \tau_{ab,k}^T + \tau_{ab,k}^B \right) I_{P_{ab}}^* [k] \right)
\]

\[
- \min_{P_{ab} \in P_b} \sum_{k \in C \setminus c} \left( t_k^P + \tau_{ab,k}^T + \tau_{ab,k}^B \right) I_{P_{ab}}^* [k] \right) (cM).
\]

\( B_c \) are the total blockage costs of cell \( c \), and \( B_{ab, c} \) the blockage costs of cell \( c \) for a specific path from \( ab \), \( P_{ab} \). The blockage costs \( B_c \) are similar in spirit to the efficiency centrality (see Wang, Du and Deng, 2017) and the modified efficiency centrality (see Wang, Wang and Deng, 2019). They represent the total trade cost increase the network will incur, if grid cell \( c \) is removed from the network.

Several things are noteworthy from Equation (K.2):

1. The more central cell \( c \) is in the network, and the harder it is to go via alternative routes, the more trade flows will go through cell \( c \), i.e., \( I_{P_{ab}}^* [c] \) will be equal to one for more trade routes \( P_{ab}, a \in C, b \in C \). This will lead to higher blockage costs, as more least-cost path will have to change and therefore \( \min_{P_{ab} \in P_b} \sum_{k \in C \setminus c} \left( t_k^P + \tau_{ab,k}^T + \tau_{ab,k}^B \right) I_{P_{ab}}^* [k] \) will be larger. Note that this also implies that a higher optimal tax \( \tau_{ab,c}^T \) can be set.

The blockage costs of cell \( c \) for the path from \( ab \), \( P_{ab} \), determine the maximum amount of taxes that the king can collect on path \( P_{ab} \) so that the traders are indifferent between staying on this path and going through cell \( c \) before switching to another path. Hence, if a king in cell \( c \) already taxes traders bringing metals from mine \( a \) to farmers in cell \( b \) by an amount of \( \tau_{ab,c}^T \), the maximum amount of the additional tax \( \bar{\tau}_{ab,c}^T \) the king can collect before traders would avoid going through cell \( c \) is given by:
\[ \tau^{T,\star}_{ab,c} = \max \left\{ \min_{P_{ab} \in P} \sum_{k \in C \setminus c} \left( t^0_k + \tau^{T}_{ab,k} + \tau^B \right) I_{P^{\star}_{ab}}[k] \right\} \]

Whenever the optimal tax is above the current level plus the maximum additional amount of the tax, i.e., \( \tau^{T}_{ab,c} + \tilde{\tau}_{ab,c} \), tax revenues will be zero. Hence, \( \tilde{\tau}_{ab,c} \) is directly linked to the indicator function:

\[ I_{P^{\star}_{ab}}[c] = \begin{cases} 1 & \text{if } \tau^{T,\star}_{ab,c} < \tau^{T}_{ab,c} + \tilde{\tau}_{ab,c}, \\ 0 & \text{else}. \end{cases} \]

Using the definition of \( \tilde{\tau}_{ab,c} \), we can write the blockage costs as follows:

\[ B_c = \sum_{a \in C \setminus c, b \in C \setminus c} \tilde{\tau}_{ab,c} (cM). \]

Note that the blockage costs are now given by the maximum additional amount of taxes that the king can collect on path \( P_{ab} \) per unit of shipped metals, \( \tilde{\tau}_{ab,c} \), multiplied the amount of metals shipped (valued by the costs of metals). Hence, the blockage costs are equal to the maximum amount of the additional total tax revenues of a king in cell \( c \) (additional to the income already obtained by \( \tau^{T}_{ab,c} \)).

Assume \( \tau^{T}_{ab,c} = 0 \) for all \( a \) and \( b \). Then \( B_c \) gives the total maximum amount of taxes that the king in cell \( c \) can collect. Given the fixed costs \( G_0 > 0 \), there is a lower limit on the total tax revenue for a king in cell \( c \) to be viable. Hence, we have \( B_c \geq R^T_c = \sum_{a \in C \setminus c, b \in C \setminus c} R^{T}_{ab,c} \geq G_0 \).

**L Computing the blockage cost**

We compute the blockage cost for a given grid cell \( g \) using the following procedure:

1. Block cell \( g \) for transit trade.
2. For all other cells \( j \neq g \), identify the cost-minimising copper and tin mine and compute the associated total transport cost for grid \( j \) to these mines \( (TB_j^g) \).
3. Compute the difference between the transport cost in the restricted and unrestricted case (i.e., when trade through all cells is possible).

Formally:

\[ \Delta T^g_{j} = TB^g_{j} - TU_{j}, \]
where $\Delta T^g_j$ represents the additional transport costs incurred by cell $j$ when grid $g$ is blocked. The total cost in the unrestricted case is represented by $TU_j$.

4. Compute the total blockage cost resulting from blocking cell $g$ as the weighted sum of additional transport costs across all cells $j \neq g$. The weights are given by the croplands area and reflect the fact that cells with more croplands have a higher demand for metals. Formally:

$$B^g = \sum_{j \neq g} \text{Crop}_j \times \Delta T^g_j,$$

where $B^g$ is the total blockage cost for $g$ and $\text{Crop}_j$ symbolizes the croplands area of cell $j$. 
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