The roadblock effect
War shocks, modal shifts, and population changes

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May 2023

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ABSTRACT: This paper investigates a novel "roadblock effect," whereby temporary forced route changes catalyse the adoption of a new transport technology. The Taiping Rebellion in 19th-century China ravaged many cities, but also blocked key land routes, triggering investments facilitating steamship trade. Combining a trade model featuring modal and route choice, shipping records, and a new method to estimate historical trade costs, I show that the post-rebellion spatial variation in maritime trade was driven by blocked land routes and the feasibility of sea alternatives. This moved many trade routes to sea and shifted the population towards port cities.

Key words: path dependence, modal choice, trade costs, Taiping Rebellion
JEL classification: F14, N95, R12, R40

*I am deeply indebted to Diego Puga for his support and guidance. I am especially grateful for Paula Bustos and Nezih Guner for their feedbacks. I thank Guillermo Caruana, Jorge De la Roca, Mauricio Drelichman, Keith Head, James Kung, Monica Martinez-Bravo, Joan Monras, Stephen Redding, Daniel Sturm, Matthew Turner, Maisy Wong, Noam Yuchtman and participants at the Meeting of the Urban Economics Association, Virtual Economic History Seminar, NEUDC, Econometrics Society European Meeting, CES North America Virtual Conference, LSE Economic History Graduate Seminar and GEP/CEPR Postgraduate Conference for helpful comments and suggestions. Special thanks to Shuji Cao for sharing historical population data in China. Funding from the European Research Council under the European Union's Horizon 2020 Programme (ERC Advanced Grant agreement 695107 - DYNURBAN) and from Spain's Ministerio de Economía y Competividad (Grants ECO-2016-80411-P, BES-2017-082187 and María de Maeztu Programme for Units of Excellence in R&D, MDM-2016-0684) is gratefully acknowledged. The usual disclaimer applies.

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1. Introduction

This paper uses the Taiping Rebellion in 19th-century China to study the evolution of city populations when shocks hit them, not only directly, through deaths and displacement, but also indirectly, by promoting some trade routes and modes over others. This highlights the complex interplay between large population shocks, shifting natural advantages, the persistence of agglomerations, and substantial changes in trade costs through technology and investment.

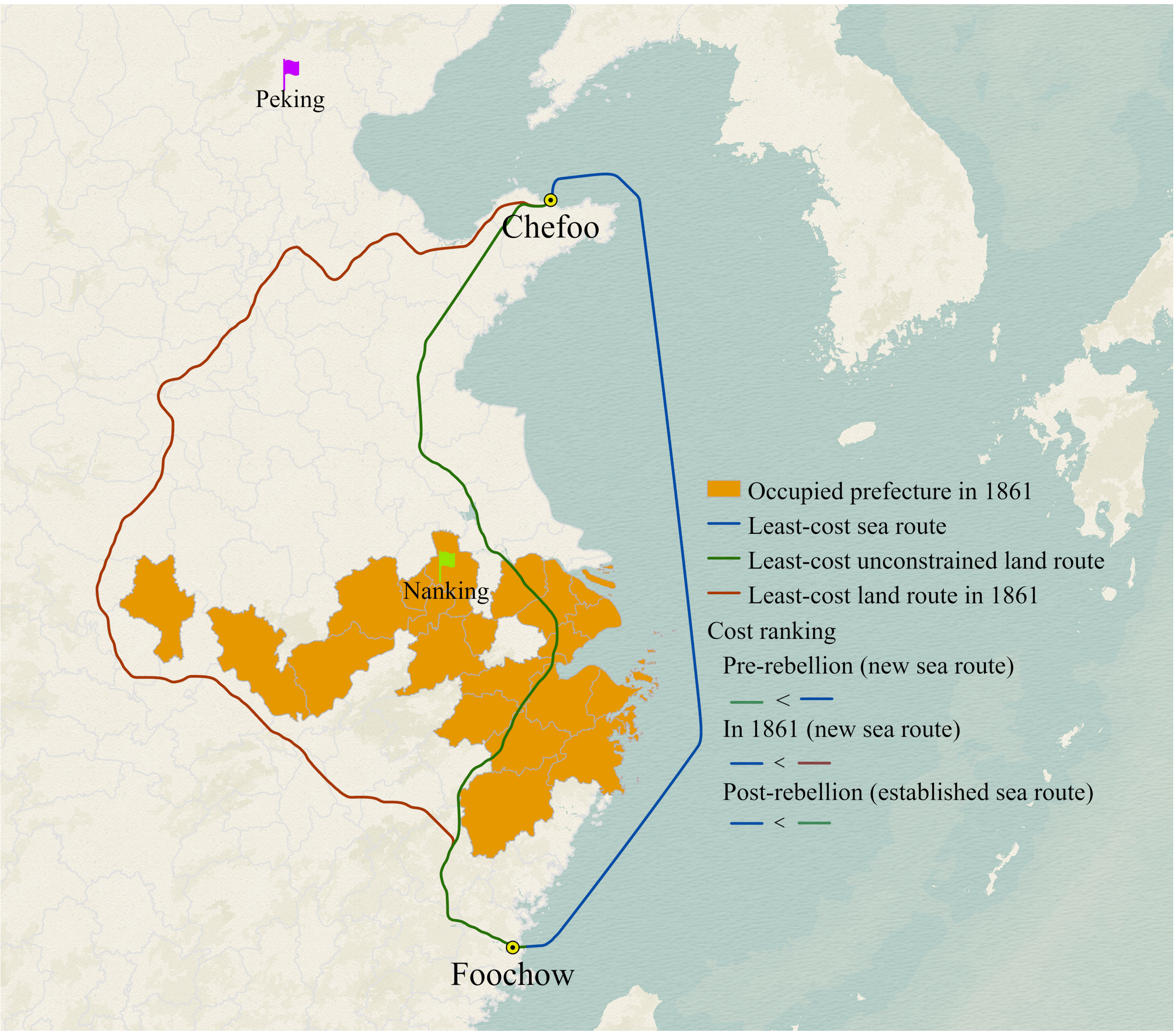
City locations and sizes reflect a combination of natural advantage and agglomeration economies. Natural endowments and technology differ across space, making some potential city locations more suitable than others. At the same time, localised increasing returns make locations that already have many firms and people more attractive to other firms and people. Comparative advantage of locations can change when new technologies emerge. However, agglomeration forces may trap populations in a location even if it is longer superior, whether because of coordination problems or sunk infrastructure costs (e.g., Bleakley and Lin, 2012; Michaels and Rauch, 2017).

Trade costs complicate the analysis of relative city sizes further because, in addition to underlying conditions ("first nature") and the current concentration at each location ("second nature"), we have to consider the access each of them has to a larger market (Krugman, 1993). Trade costs can change over time as new transportation technologies become available, and locations that benefit from them through increase in market access become more desirable. However, new technologies usually require large sunk investments upfront, which may deter the adoption despite their superiority. Moreover, whether or not locations adopt new technologies are often endogenous.

This study exploits the heterogeneous, and plausibly exogenous, incentives to adopt steamship transport through the route and modal changes induced by shocks of civil conflict elsewhere. The Taiping Rebellion was the largest peasant revolt in the history of China. The civil war between the rebels and the Qing government led to the death of one out of every six Chinese people (Ge, Hou and Zhang, 1999). The rebellion caused direct damage and casualties in the war-affected area, concentrated mainly in the rebellion occupied region. At the same time, the indirect effect of the war, operating through changing trade routes and modes, also changed the distribution of population.

Despite a large potential for sea trade, trade activities and population in China remained largely inland before the rebellion. When the rebellion blocked some of the main inland trade routes, this forced a search for alternatives. It triggered substantial investments to facilitate sea trade, notably using steamships, which until then had a slow take-up. After the rebellion, with sunk investment already incurred for establishing sea lanes, many trade routes permanently shifted to sea transport. This in turn catalysed a shift of population towards port cities. An example of this can be seen in Figure 1. The figure shows in green the least-cost land route connecting Chefoo (located in today's Yantai) and Foochow (Fuzhou) before the rebellion. These two coastal cities could also have been connected by steamship, but my estimates show that the cost savings compared with the usual land

Figure 1: An example of the "roadblock effect"



Notes: Least-cost land and sea routes between Chefoo (today's Yantai) and Foochow (Fuzhou) based on travel costs in *Panel A* of Table I. Land routes can combine courier and non-courier land routes with different levels of terrain ruggedness as well as inland waterways. The cost ranking takes into account the cost of using each mode, the cost of inter-modal transfer, and the cost of developing a new land or sea route, as estimated in *Panel B* of Table I.

route was not large enough to incur the sunk costs associated with establishing such a route.[1] The rebellion occupied many of the prefectures traversed by the usual land route between Chefoo and Foochow. The dark shaded area in the map shows the rebellion-occupied prefectures in 1861. To transport goods between Chefoo and Foochow, one would have had to take the large detour marked in red. According to my estimates presented below, the additional cost this detour entailed was large enough to instead incur the sunk cost of establishing a steamship route between these two

[1]These sunk costs can include, but not limited to, learning about the current and dangerous spots along the sea lane; installing navigational aids, staging-posts, bunkering deposits, and logistics.

cities. Although the unconstrained regular land route became once again usable after the rebellion, with the sea route already in operation, steamship trade remained a less costly option. Indeed the data show that there was active sea trade between the two ports immediately after the rebellion. In contrast, regular land routes between other city pairs (e.g., Amoy and Canton) were not blocked by the rebellion and steamship trade between them did not become established. I next explain how I examine this process systematically through my analysis.

I start by providing some historical background in Section 2, then describing the data in Section 3, and characterising the impact of the rebellion on population in Section 4. I find that being occupied during the rebellion was associated with a permanent population loss of 59%, whereas being located on the coast was associated with a 22% population increase. This increase was even greater in coastal cities that saw a surge in domestic sea trade immediately after the rebellion.

To show that population relocated to coastal locations because the rebellion shifted trade routes from land to sea, I exploit regional variations in incentives to take up sea trade. The key for my identification strategy is that, depending on their location along the regular land trade network, locations would have had their trade flows more or less affected. Maritime trade could boom broadly when the general technology of sea transport advanced with the introduction of steamships. At the same time, land trade could be directly hit in areas occupied by the rebellion, since an explicit aim was to cut off supplies from this area to the capital of the Qing government in Peking. However, regions not directly hit by the rebellion may nevertheless have been substantively affected if a regular land trade route became unusable when the rebellion hits some intermediate point on this connection. This provides them with *additional* incentives to adopt steamships compared to those regions where inland trade remained intact during the rebellion, when advances in transport technology became commonly available.[2] Thus, in Section 5, I proceed to show that bilateral trade flows to and from unoccupied locations were affected indirectly and differently depending on the roadblocks on the corresponding routes and the feasibility of sea trade alternatives.

To implement this strategy, I combine new data on historical trade flows with a trade model featuring modal and route choice. I collect a new data set of bilateral maritime trade in 19th-century China by digitising archives of trade reports from the China Maritime Customs Service.[3] Given that only sea trade after the rebellion is observed in the data, some additional theoretical structure needs to be given to the analysis to characterise the indirect effect of the rebellion through trade. Trade models typically do not incorporate modal choice, since trade data is generally not differentiated by which transport method was used to carry the cargoes. Instead, I add modal choice (by land or

[2]In other words, the identification strategy "differences out" common shocks to sea transport over time, such as technological improvement, change of government attitudes towards maritime trade or opening of treaty ports to trade with Western countries. Due to the availability of data, I only compare bilateral trade between treaty ports. While all treaty ports gained access to foreign trade and could have adopted the frontier technology of steamships for domestic trade through technological diffusion, I compare whether domestic trade between any two of these ports is more likely to use sea transport, depending on the heterogeneous increase in inland transport costs caused by the conflict.

[3]The China Maritime Customs Service was a bureaucratic agency set up in 1853 by foreign consuls in Shanghai to collect tariffs that went unpaid when the Qing government was overwhelmed by the Taiping Rebellion.

by sea) to an otherwise standard trade model.[4] Sea trade required fixed investments, and this likely held them back until the blockage of land routes made such investments a necessity. Thus, I also incorporate sunk investment costs into the model.

The model features a "roadblock effect," by which a temporary increase in land trade costs can trigger sunk investments for sea trade, thus having permanent effects on modal choices. Across location pairs, the heterogeneous increase in land trade costs during the rebellion can be linked to the increase in the probability of sea trade immediately after the rebellion, mediated by the incentives to make sunk investments in steamship trade.

The model yields a probability of sea trade after the rebellion for each location pair, which we observe in the data, given relative costs of land to sea transport. The relative cost of using different land trade routes and their sea alternatives is a key driver of the differential take-up of steamships in different geographical areas. The literature on transport costs usually infers them from freight rates, so the lack of data on freight rates by inland transport in 19th-century China imposes a challenge.

In the second part of Section 5, I develop a new method to estimate travel costs by different transportation modes using China's 1903 postal map. The map contains the locations of postal district headquarters and the assignment of prefectures to these. Under the assumption that the assignment was made to minimise transport costs to the postal district headquarters, a rich transport cost function can be parametrised, which includes the typical cost of different transport modes, variations in cost due to road types and the terrain, and the fixed costs associated with transitions between modes (which may be unavailable even in modern times).

Despite the limitations imposed by being able to observe sea trade only immediately after the rebellion, with the estimated transport costs before, during, and after the rebellion, the elasticity of trade costs and sunk investment costs can be pinned down jointly.

The predictions of the model closely match observed modal choices. In particular, the model predicts an average probability of sea trade between "roadblocked" location pairs of 0.696 compared with 0.375 for "non-roadblocked" location pairs immediately after the rebellion in 1867. The respective probabilities in the data are 0.693 and 0.375. The model also suggests that the "roadblock effect" was very important in practice. Under a counterfactual scenario that eliminates roadblocks between roadblocked location pairs, the model estimates that the probability of sea trade between them would have been much lower, 0.365 instead of 0.693. The model, based on parameters estimated using data in 1867, can also match the evolution of trade for the next fifteen years using out-of-sample predictions.

[4] During the rebellion, steamship technology had already been introduced in treaty ports, which also constitute the sample of analysis for trade. According to both contemporary trade reports and historians (Fan, 1985, e.g.,), the new technology was superior to sailing ships and constituted the vast majority of sea trade at treaty ports. The pre-rebellion trade by sailing ships was very limited, therefore many locations leapfrogged from inland trade to steamships after the rebellion. For simplicity, the baseline model assumes that during and after the rebellion the cost of sea transport refers to that of steamships. An extended model with a choice between sail and steam ships generates very similar results.

The "roadblock effect" is not confounded by alternative explanations for the post-rebellion surge in maritime trade. Section 6 builds and estimates an extended model, taking into account the possibility for reduction in investment costs in steamships on sea routes that could previously have sail trade. Given that the tendencies to use sailing ships prior to the rebellion are low and are not systematically different for "roadblocked" and "non-roadblocked" pairs, the estimated "roadblock effect" remains similar. The extended model also allows decomposing the relative contribution of the rebellion to the rise of maritime trade and the part resulting from the technological upgrade from sail to steam ships. The quantification exercise shows that the majority (74%) of the increase in maritime trade after the rebellion is attributable to the "roadblock effect". Section 7 further shows that the "roadblock effect" is robust to accounting for impacts of treaty ports and foreign trade, potential changes in inland transport networks other than roadblocks, and that roadblocks may be more likely to occur for location pairs that are further apart.

This paper contributes to the theoretical and empirical literature on whether the spatial distribution of economic activities is uniquely determined and therefore whether temporary shocks can lead to permanent changes in spatial structure (i.e., path dependence).[5] In particular, the paper is closely related to studies that incorporate changing comparative advantage due to innovations in transport technology. Bleakley and Lin (2012) document the continuing importance of historical portage sites as city locations in the United States even though their original advantages have long since become obsolete. Michaels and Rauch (2017) compare the diverging experiences of British and French cities following the collapse of the Western Roman Empire. In Britain, subject to a more intense shock, the urban network was displaced towards emerging navigable waterways. In France, where the ensuing destruction and deurbanisation was more limited, medieval towns instead re-emerged more often on their Roman-era locations. I also consider a historical episode where shifting natural advantage (due to the introduction of steamships) was combined with large but heterogeneous population shocks (due to the Taiping Rebellion). A key contribution of my framework is that, in addition to the direct channel operating through temporary population shocks, I highlight an indirect channel operating through temporary roadblocks and the incentives they provide to invest in new transport technologies.

In this respect, the paper also connects to the literature on the importance of trade costs and market access in determining the distribution of population across cities (e.g., Redding and Venables, 2004; Faber, 2014; Donaldson, 2018) and within cities (e.g., Baum-Snow, Brandt, Henderson, Turner and Zhang, 2017; Tsivanidis, 2018; Heblich, Redding and Sturm, 2020). An important challenge when

[5] Empirical evidence on path dependence is mixed. Davis and Weinstein (2002); Miguel and Roland (2011) find that the long-term distribution of relative city sizes can be highly persistent after wartime bombings. On the other hand, Hanlon (2017) finds that the American Civil War had a permanent impact on British cities specialising in textile production. Redding, Sturm and Wolf (2011) show that the division of Germany led to relocation of air hub from Berlin to Frankfurt. After German reunification, air traffic did not return to Berlin due to the sunk costs of creating hubs. Donaldson and Allen (2020) develop a dynamic quantitative spatial model featuring path dependence as a result of reliance on past infrastructure investment.

trying to evaluate the consequences of transport improvements is the endogeneity of infrastructure investments. An advantage of the setting in this paper is that the Taiping Rebellion creates exogenous variation in the incentives to invest in sea transport technology.

The paper also adds to the literature on the effect of wars and conflicts on urban development (e.g., Glaeser and Shapiro, 2002; Voigtländer and Voth, 2012; Dincecco and Onorato, 2016). While the previous papers have focused on local impacts of war, this paper shows that the indirect effect on other regions via trade disruption and the ensuing incentives to adopt new technologies can be as important.[6]

A debate related to the persistence of city locations also pertains to the failure of adoption of new technologies even when they are obviously superior to old ones. This could be due to the trade-off between the sunk costs of developing and adopting new technologies and the accumulated learning by doing of incumbent technologies (Brezis and Krugman, 1997). In fact, the introduction of a new technology sometimes revitalises innovation of an incumbent technology. Ward (1967) coined the term "sailing ship effect" for this phenomenon, following the analysis by Gilfillan (1935) of advances made in sailing ships in the second half of the 19th century in response to the introduction of steamships. According to Ward, such advances led to greater improvements in sailing ships than those made in the previous three centuries.

The "roadblock effect" that I document and investigate in this paper works in precisely the opposite direction: the temporary blockage of land trade routes during the Taiping Rebellion triggered substantial investments to facilitate the use of steamships instead. This had long-term consequences for the distribution of population across Chinese cities in addition to the direct shocks of the rebellion.

2. Historical background

2.1 The Taiping Rebellion and roadblock

The Taiping Rebellion (1851-1864) was the largest peasant revolt in the history of China and the deadliest civil war in human history. About one out of every six people in China (approximately 70 million) died during the rebellion (Ge et al., 1999)

The rebellion started as guerrilla warfare in the mountainous area of the Kuanghsi province in southwestern China (Figure 2). Peasants rose up against the Qing dynasty, which levied ever-increasing taxes after a series of natural disasters and an economic crisis following its defeat in the First Opium War. The uprising escalated into a civil war with the Qing government when the rebels marched northeastward and occupied Nanking, establishing around it "the Taiping Heavenly

[6] Juhász (2018) also looks at war-induced trade blockade and technological adoption, where temporary protection from trade fostered domestic activity in mechanized cotton spinning in 19th-century France. The interregional trade in 19th-century China, however, consisted mainly of agricultural produces, mandated by local conditions. As a result, locations responded to blockade by finding alternative trade routes rather than adjusting production.

Kingdom" in the mid and lower Yangtze region. When the rebels' attempt to besiege the imperial capital Peking was defeated, wars between the two forces receded to the area occupied by the rebellion, causing massive destruction and civilian deaths. Some prefectures in the occupied region lost up to 80% of their population (Cao and Li, 2000) and many places were razed to ground (Meyer-Fong, 2013).

Before the rebellion, the area around the Yangtze River, especially its lower section, had become the economic heartland of China. The Qing government had relied on the Grand Canal to transport tax-in-kind from this region to the imperial capital. The rebels strategically seized this area as a base to overthrow the Qing dynasty (Kuhn, 1978).[7] They occupied prefectures sitting on the Grand Canal and the Yangtze River, which strangled the flow of goods from the Yangtze region to the imperial capital through the inland routes. According to contemporary witness, the imperial capital was struck by food shortage and price spike when the rebellion started (Ni, 2005). With its supplies through the regular routes combining land, the Yangtze River and the Grand Canal cut off, the Qing government was forced to ship the tribute grain by sea to the imperial capital via Tientsin (Xia, 1995; Dai, 2012).

This paper shows that the modal change was not unique to the transport of tribute grain nor to trade to Tientsin, but instead affected a much broader exchange of goods across the whole country. The military confrontation between the rebellion and the Qing government severely curtailed inland transport (including canals) that previously used trade routes traversing through the rebellion-occupied region, according to contemporary reports from local officials to the imperial court. For example, in 1852 the governor of Kiangxi province wrote to the emperor (Liao, 2010):

> Min Guangdong bandits [The Taiping rebels] invaded the You River [in Kiangxi province], merchants and traders were stuck.[8]

In 1854, the governor of Anhwei province reported:

> Roads were blocked, merchants were wary, tariffs fell short.

The superintendent of Huai-an Pass in Kiangsu province reported in the same year that:

> Kuachow [in Yangchow] and Chinkiang are still occupied by the rebels, trade routes between the north and south are not accessible.

Depending on the roadblock of their usual land routes and the feasibility of sea alternatives, bilateral trade flows between unoccupied locations could be affected differently, triggering investments facilitating steamship trade on some routes but not others, which is investigated in Section 5.

[7] Estimation in Section 4 shows that population growth in occupied region is slightly higher than the non-occupied region before the rebellion, but the difference is not statistically significant and this generates a downward bias (in magnitude) of the direct effect of the rebellion.

[8] This affected the overland transport of bohea tea, a major export to the West at that time, from Fukien to Canton (Liu, 2016). While both places were not under direct attack, the rebels occupied Kianngxi, a intermediate point of the trade route connecting them.

Figure 2: The Taiping Rebellion and Imperial postal districts

Notes: Author's map based on the 1903 postal working map from the China Maritime Customs Postal Series and the China W dataset. Prefectures delimited in light grey and coloured if occupied by the Taiping Rebellion. China's historical postal districts delimited by dashed lines with the district headquarters marked by a green pin.

2.2 The failure to adopt sea trade before the rebellion

Because I will argue that the Taiping Rebellion acted as a catalyst for sea trade, using steamships in particular, this part provides information about the status of sea trade before the rebellion.

One reason for the weakness of sea trade prior to the Taping Rebellion was the concentration of population away from coastal areas. Early during its reign, the Qing dynasty (1644-1912) implemented a sea ban on the mainland. The purpose was to cut off supplies to the Zheng regime in Taiwan, which was founded by loyalists of the previous Ming dynasty (Gu, 1983). As a part of the policy, coastal residents were evacuated to areas 15 to 25 kilometres inland (Gu, 1983). When the Zheng family surrendered in 1683, the ban was lifted and former coastal residents were allowed to return (Huang, 1986). Thereafter, except for a short sea ban placed between 1717 and 1727, maritime trade with foreign countries was acquiesced.[9] Nevertheless, sea trade with foreign destinations did not restore to its glory of the previous dynasties and recovery of population in coastal regions was sluggish.[10]

Traditionally, domestic trade used a combination of land transport and inland waterways (including canals). Use of sea trade was restricted to specific commodities (e.g., export of soy beans from the northeast to Shanghai) and varied substantially from year to year (Liao, 2010). For the most part, trade was conducted by inland routes even though sea transport was much less costly.[11]

In 1842, after the defeat in the First Opium War, China was forced to open up treaty ports, in addition to Canton, to trade with western countries. Foreign steamships started to appear in large numbers on the Chinese coast.[12] Despite the efficiency of sea trade (even by sail) over inland route and these new changes, trade routes remained persistent. Foochow was one of four ports signed to open in 1842, but its celebrated bohea tea from the nearby Wuyi Mountains continued to take a lengthy detour overland to Canton for export. It was not until the outbreak of the Taiping Rebellion, when the regular land route to Canton became blocked, that bohea tea was shipped directly from Foochow in 1853 (Liu, 2016).

The inertia in using established inland routes may be due to the large sunk costs usually associated with establishing new trade routes. Especially for sea trade, mariners need to harness the currents and tides along the way, stay away from dangerous spots, have staging posts ready, and ensure

[9] In 1758, the Qing government established the Canton system, restricting all trade with western countries to only one port, Canton in the South. Seen by some scholars as a closed-door policy, the restriction was not strictly carried out. Foreign ship arrivals in other ports were documented and their numbers increased substantially (e.g., foreign merchant ships arrivals in Canton between 1757 and 1838 increased by 16 times over the previous 72 years and all ports combined Huang (1986)). Trade with non-western countries was not subject to the Canton rule.

[10] Figure 3 shows the estimation result that the increase in coastal population relative to non-coastal population was limited between 1680 and 1851.

[11] The Qing statesman Wei (1826) estimated that sea transport was about one-third as costly and much faster than canal shipping . However, only 25% of grain trade was carried out by sea in the early Qing period (Deng, 2009). Immediately after the rebellion in 1867, 72% roadblocked location pairs had sea trade, compared to 34% non-roadblock location pairs. The model developed in Section 6 can match both pre-rebellion and post-rebellion trade patterns.

[12] Steamships were invented in the early 19th century and first appeared in China sea in the late 1820s and early 1830s (Fan, 1985).

safe anchorage on arrival. Gains from sea transport for individual merchants may not be large enough to compensate for sizeable investment upfront, even though it may prove worthwhile in the aggregate and long-term perspective.[13] While the Qing government assumed responsibility for building and maintaining inland trade routes (Deng, 2009; Dai, 2012), it did not commit to establishing long-term sea routes. The lack of state involvement disincentivized individual merchants from making long-term investments in maritime trade until roadblocks made it a necessity.

3. Data

This paper intends to identify the "roadblock effect," whereby blocked land routes during the Taiping Rebellion catalysed adoption of sea trade and relocation of populations to the coast. This requires data on trade, historical transport costs, population and measures of roadblocks due to the rebellion. I describe each one of them in detail in the following.

I collect a new data set of bilateral domestic maritime trade between treaty ports by digitising archival reports of *Returns of Trade at Treaty Ports* published by the Chinese Maritime Customs Service (henceforth referred to as the CMCS). The CMCS was a bureaucratic agency founded in 1853 by foreign consuls in Shanghai to collect tariffs that went unpaid when the Qing government became overwhelmed by the Taiping Rebellion.[14] The CMCS supervised tariff collection of foreign exports and imports, as well as domestic maritime trade that went through treaty ports. Its statistics department published trade reports following strict statistics standards that are consistent across ports and over time. The trade data from the CMCS is believed to be "the only reliable and comprehensive statistical information" to use in studying China's historical trade (Cheng, 1956). Keller, Li and Shiue (2012) made a thorough introduction of the trade data from the CMCS.

The earliest data on bilateral domestic trade flow is available for 1867, when more accurate and consistent accounting practices were established, which is 3 years after the Taiping Rebellion ended. In addition, I digitised bilateral domestic trade in 1872 and 1877 for out-of-sample prediction.[15] A useful feature of the CMCS data is that exporting and re-exporting are differentiated (Keller, Li and Shiue, 2012), thus I can use direct export to measure trade between treaty ports. The limitation of the CMCS data is that domestic maritime trade only covers treaty ports, which were ports opened to trade with western countries, and only the part of maritime trade carried by steamship (foreign and

[13]The establishment of sea routes after the rebellion resulted in the publication of *Notice to Mariners: first issue, 1862-1882* (Bickers, 2013), which could substantially reduce the cost of using sea transport thereafter.

[14]The CMCS was a Qing government agency, but its staff was a mixture of Chinese, usually in lower rank positions, and foreigners who perform managerial roles. Set out to assess taxes of foreign imports and exports, over time its role extended to collection of domestic tariffs, maintenance of harbours and lighthouses, weather inspection, payment of foreign loans and establishment of the modern postal system in China.

[15]Trade was recorded in Customs Taels, a silver based monetary unit uniform across all ports and for all years except for 1867. In 1867, the southern ports reported their trade value in Mexican dollars and I convert these to the Customs Taels using the contemporary conversion rate. In 1901, the CMCS took over native customs within 25 kilometres of the treaty port, at which point trade data may begin to include trade went through nearby native customs. Therefore, consistent domestic trade data up to 1897 is used.

domestic) and foreign sailing ships (e.g., lorchas) is included. Maritime trade by Chinese sailing ships (e.g., junks) is not reported for the majority of years and ports. Inland trade is also not reported.

To deal with this data limitation, I build a trade model featuring modal and route choice, which helps to infer the missing inland trade. I model whether two locations establish active trade by sea. As less than 1% of coastwise traffic was borne by Chinese ships (Hsiao, 1974), it was highly unlikely that two treaty ports with active sea trade would have used only Chinese junks and not steamers or lorchas.[16] Therefore, I use the data from the CMCS to construct the post-rebellion use of sea trade between any two treaty ports.[17]

Estimation of the model requires the intermediate inputs of transport costs by different modes and routes in 19th-century China. While the literature usually derives transport costs from freight rates or travel speed, this information is not available in historical China. In Section 5.2, I develop a novel method to estimate historical transport costs based on the index to the postal working map in 1903, which lists each prefecture in China under a postal district. Postal districts were subregional divisions of the Imperial post office that was established by the CMCS in 1896 to provide mail delivery service to the general public. The service expanded from postal district headquarters, usually a treaty port, to inland areas through its extensive delivery network (See Figure 2 for postal districts and their headquarters[18]).[19]

The Imperial postal office developed a system of transliterating Chinese places names, referred to as postal romanisation. In this paper, postal romanised place names are used as they appear in trade reports to refer to historical sites. The mapping from the postal names to their current locations is listed in Table A.1.

The inland transport cost is modelled to vary with road types (i.e., courier routes and navigable rivers) and terrain. I obtain the locations of the Qing courier route (1800-1900) from China W dataset, locations of rivers from the CHGIS V4 dataset of coded river in 1820 and terrain ruggedness from Nunn and Puga (2012).[20]

[16]This is corroborated by the CMCS 1871-72 trade report of Newchwang, where junk trade was also recorded. Sea trade from Newchwang to some locations still employed junk sailing ships, but in all these case, steamships or lorchas were always used at the same time. For sea trade to other locations, only steamships or lorchas were used.

[17]The simple baseline model focuses only on adoption of steamships as the data show no steamship trade for domestic trade before the rebellion and the vast majority of post-rebellion maritime trade carried by steamships after the rebellion. The extended model further considers sail transport before the rebellion, the choice between sail and steam ships during and after the rebellion. The estimated effects of roadblocks are very similar.

[18]The headquarters of each postal district was usually a treaty port with the custom commissioner as the postmaster, with the exception of two inland postal districts: Peking and Chinan.

[19]There were no major changes in land transportation technology in 19th-century China. China's railways were still in their infancy. In 1903, only regional railways operated surrounding the capital Peking in the North. They were rail lines connecting Chengting to Peking and Peking to Tientsin and Chinchow, and Chinchow to Chinan. Postal districts whose planning could potentially be affected by the railway network are excluded from the estimation (i.e., Peking, Tientsin, Newchwang, and Chinan postal districts).

[20]Rivers are coded with values between 1 to 6. Rivers of an order greater than 4 are used, which corresponds to navigable waterways. The Qing courier routes were built and maintained by the government (Deng, 2009). They consisted of inland waterways and overland roads. When coded rivers overlap with courier route, they are modelled to have river transport cost. The remaining courier routes consist mainly of roads and small rivers.

To measure how the rebellion affected regular inland trade routes, I collected information on prefectures occupied by the rebellion on a monthly basis from Guo (1989) and Hua (1991). By aggregating occupied prefectures within each year during the rebellion, I construct annual data of roadblocks between location pairs from 1853 to 1864.[21]

To look at population evolution before and after the rebellion, I use the 2018 update of historical prefecture population data of Cao (2000). The data was constructed based on government-administered census, and cross-checked with literary accounts, notes and more than 3000 local gazettes. Prefectures are the second level administrative divisions in China. They are subdivisions of provinces, followed by counties and towns. Historical prefecture population is available for the pre-rebellion period in 1680, 1776, 1820, 1851 and post-rebellion period in 1880, 1910 and 1953. I supplement with population data from the 1982 county census and from the 2010 township census and map modern population data to the historical prefecture boundaries in 1820 taken from the China Historical Geographic Information System (CHGIS V4) constructed by the Harvard Yenching Institute and Fudan Center for Historical Geography.

4. The evolution of population

I begin my analysis in this section by examining the long-term evolution of the population of Chinese prefectures (cities and their surroundings). This shows that prefectures directly occupied by the rebellion suffered a huge shock from which they have not recovered even after one and a half centuries. In addition, the population shifted towards coastal areas, in particular those in which domestic sea trade took off. Then, in the next section, I will show that the rapid but heterogeneous adoption of sea trade, notably using steamships, was also an effect of the rebellion through the "roadblock effect," that explains population relocation to coastal regions during this period.

As a motivation, I estimate the following reduced-form relationship between population, occupation during the rebellion, and coastal location using an event-study specification:

$$\ln \text{pop}_{it} = \sum_{t=1680}^{2010} \alpha_t (\mathbb{I}_t \times \mathbb{O}_i) + \sum_{t=1680}^{2010} \beta_t (\mathbb{I}_t \times \mathbb{C}_i) + \sum_{t=1680}^{2010} (X_i \times \gamma_t) + \psi_i + \kappa_t + \epsilon_{it} \;, \tag{1}$$

where pop_{it} denotes the population of prefecture i in year t; $\mathbb{I}_t$ is an indicator for the data year t (taking value 1 if the data year is t and 0 otherwise); the excluded category is the data year 1851, just before the Taiping Rebellion started; the data years 1680, 1776, 1820 belong to the pre-rebellion period and the data years 1880, 1910, 1953, 1982 and 2010 belong to the post-rebellion period; $\mathbb{O}_i$ is an indicator variable that takes value 1 if the prefecture was occupied during the rebellion; $\mathbb{C}_i$ is an indicator variable that takes value 1 if the prefecture is coastal; X_i is a vector of prefecture

[21] Although the earliest uprising took place in Kweiping, Kuangshi in 1851, the impact was local and limited. The rebels grew in power when they advanced to the middle and lower Yangtze region, where they occupied the first prefecture, Chinkiang, in 1853. The last occupied prefectures fell to the Qing government in 1864.

characteristics and γ_t are their time-varying coefficients; while location fixed effects will capture the effect of locational characteristics on population levels, the idea is to further control for location traits that can have a time-varying effect on population, especially if these characteristics correlate with rebellion occupation and coastal location; these are the level of human capital and a set of geographic controls including terrain ruggedness, agricultural suitability for major crops in historical China (i.e., rice, wheat and foxtail millet) and new world crops (i.e., potato, maize and sweet potato), and whether the Grand Canal went through a prefecture; ψ_i is a prefecture fixed effect; κ_t is a data year dummy, controlling for secular changes in population across all prefectures over time and differential growth for different gaps between data years; and ϵ_{it} is an error term. Each observation is one of the 179 prefectures from 13 provinces in the core region of 19th-century China in each data year.[22] Robust standard errors are clustered at the prefecture level to adjust for heteroskedasticity and within-prefecture correlation over time.

The coefficients of interest in Equation 1 are α_t and β_t, which are plotted in Figure 3 (Table C.1 shows the coefficient estimates). The vertical bars represent the 95 percent confidence intervals. The coefficient α_t has a "difference-in-difference" interpretation, where the first difference compares the natural logarithm of population in occupied and non-occupied prefectures and the second difference compares the evolution of the first difference relative to the year 1851 (i.e., just before the rebellion started) for each preceding or succeeding data year. The estimated coefficients are shown on the left panel of Figure 3. The coefficients for the pre-rebellion data years are all small and statistically insignificant. This indicates that evolution of population in occupied and non-occupied prefectures is similar before the rebellion after controlling for the time varying effects of other locational characteristics.[23] However, the coefficients for the post-rebellion data years decline sharply, capturing the additional population drop in occupied prefectures relative to non-occupied prefectures after the rebellion. For instance, the estimated coefficient for the year 1880 indicates that immediately following the rebellion, population in occupied prefectures dropped by an additional 59% compared to non-occupied prefectures. Over time population in occupied prefectures caught up as indicated by smaller coefficients (in absolute terms) in later years but the gap has not closed. In 2010, the average population in occupied prefectures was still 49% lower than the non-occupied prefectures compared to the pre-rebellion level. This is in sharp contrast to Davis and Weinstein (2002), where Japanese cities quickly reverted to their relative sizes after the Allied bombings.

[22] As Qing troops from all parts of the empire were transferred to suppress the Taiping Rebellion, the military vacuum spurred uprisings in Yunan, Shensi, Kansu, Szechuen and Kueichow at the same time. These were periphery regions inhabited also by non-Han minority groups, so they are dropped from the analysis. Nomadic regions of the Qing dynasty including the northeastern provinces (Kirin, Heilungchiang and Shengching), Outer Mongolia, Inner Mongolia, Xinjiang, and Tibet are also excluded. The panel is balanced except for Taiping prefecture, whose population in 1982 is missing. Despite sharing the same name, this prefecture is not related to the rebellion.

[23] A negative coefficient for a pre-rebellion data year indicates a higher population growth in occupied prefectures before the rebellion. This leads to underestimation, if any, of the effect of the rebellion on population loss in occupied prefectures using the post-rebellion coefficients. Table C.2 shows estimation results with a simple difference-in-difference specification of population change before and after the rebellion, which allows controlling explicitly for the pre-rebellion trends.

I hypothesise that the Taiping Rebellion permanently changed the spatial distribution of population because it coincided with a period when the comparative advantage of locations was changing with the potential of maritime trade, especially with the introduction of steamships, and Section 5.1 shows that the rebellion itself facilitated the adoption of sea transport. In other words, in addition to the direct impact of the rebellion on war-torn areas, the rebellion could affect relative attractiveness of locations through diverting trade routes to sea. Locations that stood to benefit from sea trade would be coastal prefectures, and the evolution of coastal population is captured by the coefficient β_t. Similar to α_t, the "difference-in-difference" coefficient β_t measures the additional change in population of coastal prefectures compared to non-coastal ones relative to their difference in 1851. As the right panel of Figure 3 shows, the coefficients are close to zero before 1851, meaning that evolution of population between non-coastal and coastal locations was similar before the rebellion. However, the positive and significant coefficient in 1880 indicates that immediately after the rebellion, population in coastal prefectures experienced a relative increase of about 22%. Although the effect attenuated over time, coastal population was still 18% higher than non-coastal ones a century later. After 1949, as government policies inserted a greater impact on regional development in China, with early period prioritising inland provinces and later reforms favouring coastal provinces, population in coastal prefecture shrank slightly in 1980 but expand further in 2010.

Figure 3: Estimated log population change in occupied and coastal prefectures

Notes: Estimation based on Equation 1. The left panel shows estimated coefficient α_t of an interaction between the occupied prefecture indicator and a year dummy. The right panel shows estimated coefficient β_t of an interaction between the coastal indicator and a year dummy. Vertical lines indicate 95% confidence intervals with standard errors clustered by prefecture. The specification includes prefecture and year fixed effects, and controls for the time-varying effects of other determinants of population (i.e., agricultural suitability, terrain ruggedness, canal access and human capital).

We can also estimate the average population change after the rebellion using the prefecture population data of Cao (2000) with the following specification:

$$\ln \text{pop}_{it} = \alpha(\text{post}_t \times \mathbb{O}_i) + \beta(\text{post}_t \times \mathbb{C}_i) + \sum_{t=1680}^{1953} (X_i \times \gamma_t) + \psi_i + \kappa_t + \lambda_o(\mathbb{O}_i t) + \lambda_c(\mathbb{C}_i t) + \epsilon_{it} \ , \quad (2)$$

where variables are defined in the same way as in Equation 1, except for post_t, which is an indicator variable denoting whether a data year t is after the rebellion, and λ_o and λ_c, which denote a linear time trend for occupied prefectures and coastal prefectures, respectively. Instead of interacting rebellion occupation or coastal indicator with each of the data year as in Equation 1, here I interact them with a post-rebellion indicator and therefore the coefficients α and β can be interpreted as the average change of population in occupied and coastal locations after the rebellion. The specification also allows to control for differential time trends for occupied (λ_o) and coastal prefectures (λ_c). I exclude the observations from data years 1980 and 2010 as government policies shaped regional development to a greater extent after 1949, although the results including them would be very similar.

The estimation results are displayed in Table C.2 of AppendixC. Consistent with the findings in Figure 3, I find a substantial drop in the population of occupied prefectures after the rebellion. The estimated population loss is even slightly greater, about 59% on average, after accounting for the pre-existing population trend as the occupied locations would have grown at a higher rate.

On the other hand, the average population increase in coastal population was 22% after the rebellion, after controlling for the direct effect of the rebellion on the occupied region and the pre-existing trend. I also show that port cities with a surge in domestic maritime trade following the rebellion, rather than foreign maritime trade, experienced the strongest population growth after the rebellion.

Nevertheless, the evidence of a greater increase in coastal population with a surge in domestic maritime trade is based on a small sample of ports and needs to be taken with a grain a salt. Fortunately, trade data come in more detail (e.g., information about who trades with whom by sea immediately after the rebellion). By exploiting the heterogeneous incentives to adopt sea trade through roadblocks during the rebellion, the next section further advances evidence that population relocation to coastal regions found in this section can be a result of the "roadblock effect."

5. The roadblock effect

In this section, I identify the "roadblock effect" by exploiting the heterogeneous incentives for locations to adopt sea trade depending on whether the rebellion blocked their regular inland trade routes and the feasibility of sea alternatives. Given only trade by sea after the rebellion is observed in the data, the analysis needs some additional theoretical structure. Therefore I build a trade model with modal and route choice in Section 5.1. An essential input of the model is the relative transport costs of using different inland routes and their sea alternatives. As we lack information about the transport costs in 19th-century China, in Section 5.2, I develop a novel method to estimate historical transport costs. Section 5.3 shows the estimation and prediction of the model using trade data immediately after the rebellion. I use counterfactual predictions to quantify the effect of the rebellion on adoption of sea trade. I also show out-of-sample prediction on trade for the subsequent periods.

5.1 Model set-up

We consider a country with J cities (prefectures in historical China), indexed by $j = 1, 2....J$. A continuum of symmetric firms in each city produces a distinct product, which can be consumed locally as well as in other locations subject to iceberg trade costs.[24] If we assume that consumers have constant elasticity of substitution utility and that firms face monopolistic competition, the profit function of a firm in location j exporting its product to i at time t can be written as:[25]

$$\pi_{ijt} = (1-\alpha)(\frac{\tau_{ijt}^{m} c_{jt}}{\alpha P_{it}})^{1-\epsilon} Y_{it}. \tag{3}$$

The elasticity of substitution is denoted as α, which falls between 0 and 1. To keep the notation concise, I introduce $\epsilon = 1/(1-\alpha)$. As standard in trade models, the profit increases with income Y_{it} and the Dixit-Stiglitz price index P_{it} in the destination $(1-\epsilon < 1)$ and decreases with the cost of production c_{jt}, which can be thought of as labour cost and is common to all firms in origin j.

Departing from the standard setting, I allow the iceberg trade cost τ_{ijt}^{m} to vary with transport mode m. Firms can either choose land transport or sea transport, which I denote l, s respectively. The baseline model assumes that sea transport uses the new technology of steamships between treaty ports during and after the rebellion.[26] There was no steamship trade for the sample considered.[27] In Section 6, I also consider the possibility of pre-rebellion sail trade in affecting adoption of steamship when it became available and incorporate the choice between sail and steam ships during and after the rebellion in an extended model. Because the probability of sail trade was low before the rebellion, the results do not change much.

In addition to making the trade cost a function of the transport cost D_{ijt}^{m} that takes into account optimal route choice within each mode, I incorporate intertemporal investment for establishing new

[24]Recent trade models have incorporated heterogeneous firms (e.g., Helpman, Melitz and Rubinstein, 2008; Tintelnot, 2017), but since only aggregate but not firm level trade data are available in 19th-century China, there is no gain from modelling heterogeneous firms here.

[25]While monopolistic competition is used to characterise the market structure here, as it will become evident later, the results do not depend on this assumption. The key assumption is that firms choose the least-cost transportation mode (taking into account sunk investment cost).

[26]Steamship technology was available during and after the rebellion when treaty ports became established and was the dominant mode of sea transport. According to the CMCS reports of trade in 1873, at both a river port (Chinkiang) and a seaport (Ningpo), more than 90% of sea trade was borne by steamship.

[27]Steamship trade existed between Hong Kong, Macau and Canton, and between Hong Kong and Shanghai before the rebellion. As (parts of) Hong Kong and Macau had become colonies, bilateral trade with Hong Kong and Macau was not accounted as domestic trade by the CMCS and is not included in the sample.

trade routes for sea transport, I_t^s, and land transport, I_t^l.[28] The mode-dependent iceberg trade costs are:

$$(\tau_{ijt}^l)^{1-\epsilon} = (D_{ijt}^l I_t^l)^{-\gamma} e^{\eta_{l,ijt}}, \quad (\tau_{ijt}^s)^{1-\epsilon} = (D_{ijt}^s I_t^s)^{-\gamma} e^{\eta_{s,ijt}} \tag{4}$$

for land and sea transport respectively. The investment cost is modelled here as a multiplier to the transport cost, so that we can interpret it as the cost ratio of establishing a new route over using an existing route.[29] The investment cost of sea transport I^s depends on whether a sea route has already been established in the previous period. Define S_{ijt} as indicator for whether sea trade happens in period t. We have:

$$I_t^s = \begin{cases} I^s, & \text{if } S_{ij,t-1} = 0; \\ 1, & \text{if } S_{ij,t-1} = 1. \end{cases} \tag{5}$$

If a sea route was established in the previous period, there is no extra cost of using sea trade in addition to the transport cost. If, instead, sea trade was not used in the previous period, firms need to incur the sunk investment cost I^s for establishing a new sea route in order to use sea transport. Analogously, in order to use a new land transport route, it is assumed that firms need to incur an investment cost of I_t^l.

Trade costs are subject to shocks. The shocks to land and sea transport $\eta_{l,ijt}$ and $\eta_{s,ijt}$ are assumed to be log normal and independent:

$$\eta_{l,ijt} \sim \mathcal{N}(0, \sigma_l^2), \quad \eta_{s,ijt} \sim \mathcal{N}(0, \sigma_s^2). \tag{6}$$

At the beginning of each period, firms observe origin-destination specific shocks to land and sea transport and choose either land or sea transport. From the model set-up, the probability of sea trade immediately after the rebellion can be written as:

$$\Pr(S_{ij,post} = 1) = \Phi\Big(\frac{\gamma}{\sigma} \ln \frac{D_{ij,post}^l}{D_{ij,post}^s} - \mathbb{1}(S_{ij,reb} = 0) i^s\Big), \tag{7}$$

which depends first on the post-rebellion transport cost by land relative to sea $(D_{ij,post}^l / D_{ij,post}^s)$. The elasticity of trade with respect to the transport cost γ, normalised by the standard deviation of transport shocks $\sigma = \sqrt{\sigma_l^2 + \sigma_s^2}$, governs how responsive usage of sea trade is to the relative cost of land transport. Second, it depends on the sunk investment cost for sea transport, which may or may not have been incurred during the rebellion. To keep the notation concise, I introduce the transformed sunk investment cost $i^s = (\gamma/\sigma) \ln I^s$, which measures the contribution of sea

[28] D_{ijt}^m is the lowest-cost route effective distance using the terminology of Donaldson (2018) but with one distinction. Here the effective distance is calculated separately for sea and inland transport.

[29] The implicit assumption is that sunk investment is proportional to the transport cost. Sunk costs associated with establishing a new sea route such as learning about the tides and dangerous spots, and installing navigational aids and staging posts along the lane increase with distance.

transport sunk investment cost to the probability of sea trade. If sea trade was used during the rebellion, and therefore sea routes were established ($\mathbb{1}(S_{ij,reb} = 0) = 0$), firms do not need to incur the sunk investment cost in the post-rebellion period, thus increasing the probability of using steamships afterwards.

Therefore, the post-rebellion steamship trade depends on whether location pairs started sea transport during the rebellion. The probability of sea trade during the rebellion period is:

$$\Pr(S_{ij,reb} = 1) = \Phi\left(\frac{\gamma}{\sigma} \ln \frac{D^l_{ij,reb}}{D^s_{ij,reb}} + roadblock_{ij} \times i^l - i^s\right). \tag{8}$$

Equation 8 shows how the rebellion can affect incentives to make sunk investment in sea transport through the lens of the model. First, for locality pairs whose regular inland route was blocked as the rebels occupied prefectures that it previously traversed (indicator $roadblock_{ij} = 1$), finding alternative inland routes entailed an investment cost I^l (the transformed sunk investment cost $i^l = (\gamma/\sigma) \ln I^l$ measures its contribution to sea trade probability). Second, as the new route was not the unconstrained optimal one, the relative cost of land transport to sea ($D^l_{ij,reb}/D^s_{ij,reb}$) increased. Both raised the relative desirability of using sea transport during the rebellion, which induce "roadblocked" location pairs to incur the sunk investment cost for sea trade during the rebellion.

We can link the post-rebellion probability of sea trade with sea trade during the rebellion via the inter-temporal decision of making sunk investment in sea trade. By conditioning on trade during the rebellion, the probability of sea trade after the rebellion can be written as:

$$\begin{aligned} \Pr(S_{ij,post} = 1) =& \Pr(S_{ij,reb} = 1)\Pr(S_{ij,post=1} | S_{ij,reb} = 1) \\ &+ \Pr(S_{ij,reb} = 0)\Pr(S_{ij,post=1} | S_{ij,reb} = 0). \end{aligned} \tag{9}$$

Combining Equations 7, 8 and 9, the post-rebellion probability of sea trade is:

$$\begin{aligned} \Pr(S_{ij,post} = 1) =& \Phi\left(\frac{\gamma}{\sigma} \ln \frac{D^l_{ij,reb}}{D^s_{ij,reb}} + \text{roadblock}_{ij} \times i^l - i^s\right) \Phi\left(\frac{\gamma}{\sigma} \ln \frac{D^l_{ij,post}}{D^s_{ij,post}}\right) \\ &+ \Big(1 - \Phi\left(\frac{\gamma}{\sigma} \ln \frac{D^l_{ij,reb}}{D^s_{ij,reb}} + \text{roadblock}_{ij} \times i^l - i^s\right)\Big) \Phi\left(\frac{\gamma}{\sigma} \ln \frac{D^l_{ij,post}}{D^s_{ij,post}} - i^s\right), \end{aligned} \tag{10}$$

which is a function of (1) whether the locality pairs had roadblocks, the relative cost of land transport compared to sea during and after the rebellion, and (2) the parameters of the model (γ/σ, i^s and i^l).

Equation 10 highlights that the model generates the "roadblock effect," by which temporary increase in land transport cost during the rebellion could have a long-lasting effect on transport modal choices, through facilitating investment in sea transport.[30] It also shows that the effect of the

[30] The post-rebellion probability is a weighted average of probabilities $\Phi\left(\frac{\gamma}{\sigma} \ln \frac{D^l_{ij,post}}{D^s_{ij,post}}\right)$ and $\Phi\left(\frac{\gamma}{\sigma} \ln \frac{D^l_{ij,post}}{D^s_{ij,post}} - i^s\right)$. The weight on the higher probability $\Phi\left(\frac{\gamma}{\sigma} \ln \frac{D^l_{ij,post}}{D^s_{ij,post}}\right)$ becomes larger when roadblocks happen.

rebellion on trade hinges crucially on whether the regular land route became unusable when the occupied region hit some intermediate point on its connection, how lengthy a detour was needed compared to the cost of sea alternatives. This requires knowledge about availability roads, river and terrain along different inland trade routes and the sea alternatives and their associated costs. If we know the relative costs of theses, the parameters of the model can be estimated by maximising the likelihood of observing post-rebellion sea trade in the data. Therefore, before turning to the estimation of the model, the next section shows the intermediate step of obtaining estimates of relative transport costs in 19th-century China.

5.2 Estimation of historical transport cost

The increase in inland transport costs due to roadblocks and their sea alternatives is a key determinant of the differential impacts of the rebellion on steamship take-up in different locations. This demands knowledge about the costs of using different trade routes, which depends in turn on the cost of using various transport infrastructure underlying them. While the previous literature on transport costs usually infers relative costs from freight rates or travel speed, lack of data on them in 19th-century China imposes a challenge.

To deal with this problem, I develop a novel method of estimating historical transport costs based on China's postal map in 1903. I allow the typical cost of different transport modes (e.g., land and waterways), variations in cost due to terrain, as well as a fixed cost associated with transitions between modes (which can be unavailable even in modern times).

The index to the postal working map in 1903 lists each prefecture in China under a postal district. The postal districts were regional divisions of the Imperial post office, which expanded the mail delivery service from the postal headquarters, usually a treaty port, to inland prefectures (See Figure 2). Under the assumption that the allocation of prefectures to postal districts was made to minimise transport costs to their postal headquarters, we can infer the cost of using different transport infrastructure available along the route.

The surface of China is divided into 0.1 degree by 0.1 degree cells (553 $\times$ 826 cells in total, a cell at 30 degree latitude covering approximately 90 km^2 area) and overlaid with rivers, courier routes, and terrain (See Figure B.1). Each cell is assigned a (relative) cost to traverse based on whether it falls in a river, courier route or point of transition between land and waterway transport. Given a set of travel costs for a courier land route cell, a non-courier land route cell, a river cell, a cell involving land to river modal transition, and penalties for ruggedness, we can use the Fast Marching Method (FMM) to find the least-cost travelled postal headquarters for each prefecture.

The optimal relative transport costs are pinned down by maximising the number of matches between actual and FMM allocations of prefectures to postal headquarters using iterations. In the best scenario, 173 out of 199 prefectures can be matched to the actual postal districts compared to 114 when using distance alone. The majority of the unmatched prefectures (24 out of 26) are very close to be matched to their actual headquarters as their neighbouring prefectures are matched to those headquarters.

The estimation based on postal districts renders the transport cost by inland waterways.[31] To obtain the transport cost by sea, I use the information about travel time for sea transport relative to river as variable transport cost such as coal consumption and crew wage increases proportionally with travel time. According to the CMCS trade reports in 1879 and 1881, steamship trip between river ports Chinkiang and Hankow took half a week whereas a trip between seaports Ningpo and Wenchow took 26 hours. The distance ratio between the two is 1.63. Therefore, the implied cost by sea is half the cost by river.

The estimation results of transport costs are summarised in *Panel A* of Table I. The cost of travelling by land without any road infrastructure and with 0 ruggedness is normalised to one so that the unit transport costs by other modes is relative to that by flatland. The cost of using courier routes was 18 % of the cost of non-courier land routes. The cost of using inland waterways was 8% of that by non-courier land transport and the cost by sea was only 4% of that by non-courier land transport. An increase in terrain ruggedness by one standard deviation was associated with a 32% increase in transport cost. Regarding transition, I convert the cost into equivalence to distance travelled by waterways. The transition cost from land to water transport amounted to the cost of travelling by inland waterways for 82.5 kilometres and by sea for 165 kilometres. In other words, for a sea trip between Shanghai and Ningpo, about half the transport cost will be borne by transshipment.

Using the estimated historical transport costs, in AppendixD I estimate the elasticity of migration with respect to transport costs in historical China. I construct novel migration flow data based on the number of migration villages founded by people from outside and information about their ancestral origin. Reassuringly, the estimated elasticities are similar to those estimated with modern data and for other parts of the world. The magnitude of the elasticity using transport costs (i.e., lowest-cost route effective distance) is also larger than the elasticity using distance alone.[32]

More generally, this method can be applied to estimate transport costs for any region at any time, as long as the following two inputs are available. The first input needed is the assignment of locations to a larger area, which is presumably done to minimise transport costs (e.g., postal maps, administrative maps). The second input is the location of transport infrastructure. Even though roads may be lost over the course of a long history, terrains and rivers tend to be stable over time. Thus, if there exists an allocation based on transportation cost minimization, we can at least obtain estimates of relative transportation costs for different terrains, river, sea, or fixed costs for transitions.

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[31] The trip from prefectures to their postal headquarters would not involve sea transport and therefore transport cost by sea cannot be obtained based on the allocation.

[32] Distance is a proxy for transport cost that can be subject to measurement error. Therefore, the coefficient of distance can suffer from attenuation bias.

5.3 Model estimation and prediction

With transport costs in 19th-century China in hand, we can now proceed to estimate the model and use it to predict the probability of sea trade, using steamships, with and without roadblocks. I also show out-of-sample predictions for trade in subsequent periods using parameters estimated using the 1867 data.

I calculate the least cost route for each locality pair before and after the rebellion, and for each year during the rebellion when the two locations are not occupied. For each trade pair during the rebellion, I identify whether their inland trade needed a detour as the occupied region hit some intermediate point of their optimal inland route. I use the average increase in land transport cost due to roadblocks to calculate the relative inland transport cost $D^{l}_{ij,reb}/D^{s}_{ij,reb}$ in Equation 10 if roadblocks happened in multiple years and the required detours were different as occupied regions change over time.[33]

The estimation sample includes all treaty ports that were opened before or during the rebellion, which are the same set of treaty ports that were active in 1867. Trade between two river ports is excluded because it does not involve sea transport.[34] Two extreme cases, Shanghai, which had active maritime trade with all other treaty ports, and Chinkiang, which had no sea trade with any other ports in 1867, are excluded from the model estimation.[35]

With the estimated relative transport costs of land compared to sea during and after the rebellion and their increase during the rebellion due to roadblocks, we can obtain estimates of the parameters in the model by maximising the likelihood of observing maritime trade immediately after the rebellion in the data.

The results of the baseline model are presented in *Panel B* of Table I. The elasticity of using sea transport with respect to the ratio of land to sea transport cost is positive as expected, indicating that location pairs are more likely to use maritime trade when in comparison the cost of using inland transport is high. The cost associated with initialising sea trade is substantial. The estimate implies that the cost of using a new sea route is approximately 20 times the cost of an existing one

[33] The estimated effects are similar if the maximum detour instead of the average is used (not shown).

[34] In other words, trade between seaports as well as direct trade between a sea port and a Yangtze River port that does not involve any road transit are included. In the CMCS trade report, if export from a seaport is transferred to a Yangtze port by inland route, it is recorded under transit trade instead. Steamship trade between Yangtze ports and sea ports was allowed after 1861 according to agreement after the Second Opium War (Fan, 1985), and the estimation takes into account the timing.

[35] Shanghai was surrounded by occupied prefectures throughout the rebellion and land transport to Shanghai was impossible according to my estimate ($D^{l}_{ij,reb}/D^{s}_{ij,reb}$ would be infinitely positive). Shanghai was also the only port that had sea trade with all other ports in 1867. To show that the "roadblock effect" is not entirely driven by this exceptional example, it is dropped from the estimation. Although Chinkiang was not occupied for the later part of the rebellion, sitting next to the rebellion capital, it was caught by warfare and greatly damaged, which could explain lack of trade immediately after the war in 1867. According to the CMCS trade report for the years 1871-1872, Chinkiang was "gradually recovering from the state of ruin in which they were left by the rebels" and between 1871-1872 started to export rice to the southern provinces by sea, which "was quite a new feature."

Table I: Estimation of roadblock effect: trade cost and model prediction

Panel A: Estimation results on transport costs

Unit cost relative to flat land		Punishment of ruggedness by one std.
Flat land (without courier route)	1.00	32% increase in transport cost
Courier route	0.18	Transition cost from land to waterways
Inland waterways	0.08	Equivalent to 82.5 km by inland waterways
Sea	0.04	Equivalent to 165 km by sea

Panel B: Estimation results on trade model parameters

	Parameter	Value
Elasticity of probability of sea trade w.r.t. land/sea cost ratio	γ/σ	0.723
		(0.192)
Sunk cost of new sea route (adjusted)	i^s	2.170
		(0.469)
Sunk cost of new land route (adjusted)	i^l	1.202
		(0.390)
Observations		88

Panel C: Mean probability of steamship trade after the rebellion

	Observations	Data	Model prediction	
			With rebellion	Without rebellion
	(1)	(2)	(3)	(4)
Roadblocked pairs	56	0.696	0.693	0.365
			(0.020)	(0.020)
Unaffected pairs	32	0.375	0.379	0.379
			(0.045)	(0.045)

Notes: In *Panel A*, transition costs are measured in cost travelled by the corresponding waterway in kilometres. In *Panel B*, the estimates imply that the cost ratio of new sea route over existing route is 20 ($I^s = \exp(i^s \times \sigma/\gamma)$). The implied cost ratio of new land route over existing one is 5 ($I^l = \exp(i^l \times \sigma/\gamma)$). Standard errors in parentheses. In *Panel C*, the model prediction is based on parameters estimates of *Panel B*. The prediction with roadblocks in column (3) provides the mean estimated probability for city prefecture pairs for which the least costly land route was roadblocked by the rebellion, taking into account whether the required detour was costly enough to incur the sunk cost of starting to trade by sea between those locations, and whether the cost saving once that sunk cost was incurred was large enough to keep trading by sea after the rebellion. Column (2) provides the actual mean probability observed in the data. Column (4) estimates the same mean probability under a counterfactual where the route had not been roadblocked by the rebellion. Bootstrap standard errors using 500 replicates in parentheses.

($I^m = \exp(i^m \times \sigma/\gamma)$). Compared to sea transport, the investment cost for land transport is modest. The cost ratio of using a new land route over an existing route is about 5.

The parameter estimates in *Panel B* can be used to predict the probability of maritime trade after the rebellion, which is shown in *Panel C*. The observations are divided into two groups:

locality pairs that experienced roadblocks during the rebellion and ones whose regular inland routes remained intact. In the data, shown in column (2), the average probability of sea trade immediately after the rebellion in 1867 was 0.696 for "roadblocked" pairs and 0.375 for unaffected pairs. Column (3) shows the prediction from the model, which matches well the observed modal choices. The average predicted probability of maritime trade is 0.693 for "roadblocked" pairs and 0.379 for "non-roadblocked" pairs. In column (4), I calculate probabilities of maritime trade under a counterfactual scenario in which the rebellion did not happen. As unaffected pairs did not have roadblocks to begin with, their counterfactual probability in column (4) is the same as in column (3). For "roadblocked" pairs, however, their counterfactual probability of maritime trade would be only 0.365 without roadblocks, which is close to the unaffected pairs. This suggests that if it were not for the rebellion, the adoption of sea trade for the two groups would have been similar. Roadblocks substantially increase the use of sea trade after the rebellion, raising the probability by about 90% from 0.365 to 0.693.

Out-of-sample prediction We can use the parameters estimated using the 1867 data to predict subsequent evolution of trade. Notice that the roadblocks took place from 1853 to 1864. Therefore, one period in the model corresponds to approximately 5-10 years. I use the model parameters estimated using the 1867 data and observed trade in 1867 to make an out-of-sample prediction for trade in the subsequent period. Table II shows the results. As before, I divide observations into location pairs that had roadblocks and ones that did not and show their probability of sea trade in the data (in 1872 or 1877) in columns (2) and (3). The model prediction of trade for one period after 1867 is shown in column (4). The out-of-sample prediction is very close to the observed trade in 5 and 10 years. The probability of sea trade is slightly lower than 1867 for "roadblocked" pairs but is higher for "non-roadblocked" pairs. This pattern is borne by both the data and the model. Intuitively, the adoption of sea trade would increase over time for "non-roadblocked" pairs after the new technology of steamship was introduced with treaty ports. In the presence of shocks and inter-temporal sunk investment, the adoption of sea trade would not be immediate but gradually grow. For "roadblocked" pairs, however, because of the overwhelming effect of roadblocks in incentivising adoption of sea trade during the rebellion, the probability of sea trade would not rise further but would instead undergo a slight decline after the rebellion.

6. Model extension

In this section, I extend the model developed in Section 5.1 by considering the pre-rebellion possibility of trade by sail ships and the post-rebellion choice between sail and steam ships. Although we do not observe pre-rebellion bilateral trade by sail, the model structure can be used to estimate a probability of sail trade between location pairs before the rebellion. The extended model takes into account the possibility that some location pairs had sail trade before the rebellion and therefore

Table II: Out-of-sample model prediction of sea trade

	Observations	Data		Model prediction
		1872	1877	
	(1)	(2)	(3)	(4)
Roadblocked pairs	56	0.679	0.643	0.687
				(0.047)
Unaffected pairs	32	0.406	0.467	0.457
				(0.069)

Notes: Columns (2) and (3) provide the mean probability observed in 1872 and 1877. Column (4) shows the out-of-sample model prediction for one period after 1867, based on parameters estimates in Table I. Bootstrap standard errors using 500 replicates in parentheses.

may not need to incur the sunk investment of establishing a new sea route when steamship was introduced. It also allows to break down the relative contribution of roadblocks to the increase in sea trade and that derived from the technological upgrade from sail to steam ships, which is discussed further in Section 7.

In addition to land transport and sea transport using steamships, it is assumed that firm k in city i can also export to j using sail ships with an iceberg trade cost:

$$(\tau_{ijt}^{sail})^{1-\epsilon} = (D_{ij}^{sail} e^{\iota_{kijt}} I_t^s)^{-\gamma} e^{\eta_{s,ijt}}, \tag{11}$$

where D_{ijt}^{sail} is the transport cost of sailing ships and $e^{\iota_{kijt}}$ is a shock or preference for sail trade for firm k following a normal distribution with a mean of zero and standard deviation of σ_{sail}. The trade costs by land and steamer are the same as before:

$$(\tau_{ijt}^{l})^{1-\epsilon} = (D_{ijt}^{l} I_t^{l})^{-\gamma} e^{\eta_{l,ijt}}, \quad (\tau_{ijt}^{steam})^{1-\epsilon} = (D_{ijt}^{steam} I_t^{s})^{-\gamma} e^{\eta_{s,ijt}}$$

It is further assumed that the manager of a firm who has a log utility decides transport mode and sunk investment after observing location specific shocks to land and sea transport ($e^{\eta_{l,ijt}}$ and $e^{\eta_{s,ijt}}$). Afterwards, firm-specific shocks to sailing ship ($e^{\iota_{kijt}}$) are realised. A fraction of firms exporting from location i to j will choose sail over steam ship when both technologies of sea transport are available.[36] The transport cost by sea can be summarised as:

$$D_{ijt}^{s} = \begin{cases} D_{ijt}^{sail}, & \text{before rebellion;} \\ (D_{ijt}^{steam})^{\theta} (D_{ijt}^{sail})^{1-\theta}, & \text{during and after rebellion;} \end{cases} \tag{12}$$

where $\theta = \Phi(\frac{\ln(D_{ijt}^{sail}/D_{ijt}^{steam})}{\sigma_{sail}})$ is the probability that a firm prefers steam to sail ships conditional on sea trade.

[36]Because shocks to land and sea transport are common to trade for a specific location pair, firms exporting for the same location pair will make the same modal choice between sea and inland transport.

Pre-rebellion sea trade can only use sail. Therefore, the probability of sea transport in time t before the rebellion is:

$$
\begin{aligned}
\Pr(Sail_{ijt}=1) =& \Pr(Sail_{ij,t-1}=1)\Phi\Big(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,pre}}{D^{sail}_{ij}}\Big) \\
&+\big(1-\Pr(Sail_{ij,t-1}=1)\big)\Phi\Big(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,pre}}{D^{sail}_{ij}}-i^{s}\Big).
\end{aligned} \tag{13}
$$

Suppose that the probability of sail trade between any location pair has reached a steady state before the rebellion. This probability can be calculated by equalising $\Pr(Sail_{ijt}=1)$ and $\Pr(Sail_{ij,t-1}=1)$ for any location pair i and j. Denote the steady state probability of sail trade as ρ_{ij}.[37] We have:

$$
\rho_{ij} = \frac{\Phi\big(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,pre}}{D^{sail}_{ij}}-i^{s}\big)}{1+\Phi\big(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,pre}}{D^{sail}_{ij}}-i^{s}\big)-\Phi\big(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,pre}}{D^{sail}_{ij}}\big)}. \tag{14}
$$

Therefore, we can obtain the post-rebellion probability of sea trade by further taking into account the pre-rebellion tendency to use sailing ships:[38]

$$
\begin{aligned}
\Pr(S_{ij,post}=1|Sail) =& \rho_{ij}\Big(\Phi\big(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,reb}}{D^{s}_{ij,reb}}+\text{roadblock}_{ij}\times i^{l}\big)\Phi\big(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,post}}{D^{s}_{ij,post}}\big) \\
&+\Big(1-\Phi\big(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,reb}}{D^{s}_{ij,reb}}+\text{roadblock}_{ij}\times i^{l}\big)\Big)\Phi\big(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,post}}{D^{s}_{ij,post}}-i^{s}\big)\Big) \\
&+(1-\rho_{ij})\Big(\Phi\big(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,reb}}{D^{s}_{ij,reb}}+\text{roadblock}_{ij}\times i^{l}-i^{s}\big)\Phi\big(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,post}}{D^{s}_{ij,post}}\big) \\
&+\Big(1-\Phi\big(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,reb}}{D^{s}_{ij,reb}}+\text{roadblock}_{ij}\times i^{l}-i^{s}\big)\Big)\Phi\big(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,post}}{D^{s}_{ij,post}}-i^{s}\big)\Big).
\end{aligned} \tag{15}
$$

As convoluted as Equation 15 may seem, the post-rebellion probability of sea trade boils down to the relative transport costs of different transport modes, their change during the rebellion due to roadblocks and parameters of the model, as Equation 10. Therefore, we can estimate the parameters

[37] Simulations show that it is very likely that the steady state of sail trade has been reached before the rebellion starting from zero trade during the sea ban ended in 1683. Notice that a single realisation of trade does not reach a steady state equilibrium because subject to shocks, at any time, either sea or inland transport can be chosen. However, the use of sail trade between two locations reaches a steady state in expected terms.

[38] The assumption underlying the full model is that if in the period before the rebellion, sailing ships are used, steamship trade requires no further investment during the rebellion. In contrast, the base model in Section 5.1 can be viewed as one in which using the novel technology of steamship for location pairs requires separate and new investment from sailing ships.

of the model by maximising the likelihood of observing post-rebellion sea trade. An additional input is needed, which is the relative transport cost of sail to steam ship to calculate the sea transport cost D^s_{ijt}, and therefore I show model estimates and predictions under different transport costs by sail within reasonable ranges.

Notice that Equation 15 assumes that if bilateral sail trade took place immediately before the rebellion, then the location pair would not need to incur the sunk investment for steamships during the rebellion.[39]

I present the estimation results of the extended model in Table III with my preferred cost ratio of sail to steam ship 2, which matches the share of grain trade by sail ships (25.6%) before the rebellion according to Deng (2009).[40] Table A.2 also shows estimates under different cost ratios of sail to steam ships. The lower bound of the cost ratio is one, which indicates that sail ships have the same variable transport cost as steam ships. The upper bound is 2.25, which indicates that sail ships have the same variable cost as courier routes.

The estimates are similar to Table I, lying within the 90% confidence interval of the estimates under the baseline model. Compared to the baseline model, the estimated elasticity of trade and transformed sunk cost of new land route are smaller, indicating that both the estimated sunk cost for new sea route and for new land route are larger in the extended model. This is because the extended model takes into account the possibility that some location pairs would incur smaller or no sunk cost in establishing a new trade route by sea while the baseline model would calculate an average sunk investment costs including these pairs with potentially reduced or zero costs. In *Panel B*, I show the prediction of the mean probability of sea trade using the corresponding parameters in *Panel A*. Column (5) shows that "roadblocked" pairs are predicted to have a slightly lower probability of sea trade by sail before the rebellion. Therefore, the observed post-rebellion difference in sea trade with steamship technology is unlikely a result of "roadblocked" pairs already having a higher tendency to use sea trade by sail before the rebellion. The implied "roadblock effect" is also similar to the baseline model. Under the counterfactual scenario in which the rebellion did not happen, the probability of maritime trade would be only 0.367 (column (4)) for "roadblocked" pairs, similar to unaffected location pairs. This counterfactual indicates that roadblocks increase the probability of sea trade by 87% on average, from 0.367 to 0.685.

[39]In reality, however, it is possible that in addition to the shared investment in sea trade such as learning about routes and other logistics costs, steamships may require additional investment specific to the new technology. In Table A.3, I present estimation results assuming that only a fraction of the investment costs for steamships is deductible if sail trade occurred previously although the results are very similar.

[40]Deng (2009) estimated that the grain trade by inland navigation and sea combined was about 80 million piculs (1 picul $\approx$ 60 kilogrammes) while the sea trade consisted of 20.5 million piculs. Using Wang and Huang (1989)'s classification of grain export and import regions during the Qing dynasty, I calculate the probability of sea trade for each grain trade pairs given their transport costs by sail and inland routes. I then use monte-carlo simulation to calculate the average share of trade by sail. The volume of trade is assumed to be proportional to the origin and destination population and inversely proportional to the transport cost (based on the naive gravity equation). The share of trade by sail is 25.6% if the cost ratio between sail and steam is 2. For comparison, the share would be 36% and if the cost ratio is 1 and 23.6% if the cost ratio is 2.25.

Table III: Estimation of roadblock effect: extended model prediction

Panel A: Estimation results on trade model parameters		
	Parameter	Value
Elasticity of probability of sea trade w.r.t. land/sea cost ratio	γ/σ	0.530
		(0.117)
Sunk cost of new sea route (adjusted)	i^s	2.027
		(0.388)
Sunk cost of new land route (adjusted)	i^l	1.604
		(0.495)
Observations		88

Panel B: Mean probability of sea trade before and after the rebellion					
	Observations	Data	Model prediction		
			Post-rebellion sea		Pre-rebellion sail
			With roadblock	W/o roadblock	
	(1)	(2)	(3)	(4)	(5)
Roadblocked pairs	56	0.696	0.685	0.367	0.257
			(0.017)	(0.020)	(0.017)
Unaffected pairs	32	0.375	0.387	0.387	0.290
			(0.046)	(0.046)	(0.041)

Notes: In *Panel A*, the estimates imply that the cost ratio of new sea route over existing route is 46 ($I^s = \exp(i^s \times \sigma/\gamma)$). The implied cost ratio of new land route over existing one is 21 ($I^l = \exp(i^l \times \sigma/\gamma)$). Standard errors in parentheses. In *Panel B*, the model prediction is based on parameters estimates of *Panel A*. The prediction with roadblocks in column (3) provides the mean estimated probability for city prefecture pairs for which the least costly land route was roadblocked by the rebellion, taking into account the pre-rebellion sail trade, whether the required detour was costly enough to incur the sunk cost of starting to trade by sea between those locations if pre-rebellion sea trade was not established, and whether the cost saving once that sunk cost was incurred was large enough to keep trading by sea after the rebellion. Column (2) provides the actual mean probability observed in the data. Column (4) estimates the same mean probability under a counterfactual where the route had not been roadblocked by the rebellion. Column (5) provides the mean estimated pre-rebellion probability of sail trade. Bootstrap standard errors using 500 replicates in parentheses.

The extended model, after accounting for the pre-rebellion probability of sail trade, allows to decompose the relative contribution of technological change and that of roadblocks to the post-rebellion surge in sea trade. This naturally depends on the relative cost ratio of sail to steam transport. If the cost of sail to steam ratio is low, steamships are not significantly superior to the incumbent technology, therefore the increase in sea trade due to technological improvement would be small and the increase due to roadblocks would be relatively large. On the other hand, if steamships are much more superior to sail ships, the relative contribution of technological improvement would be more substantial, although this would be true for both “roadblocked” pairs and “non-roadblocked” pairs pairs and the gap between their adoption of sea trade can be attributed to the “roadblock effect”.

Table III shows that under a cost ratio of 2, which is towards the upper limit of steamship superiority, the implied contribution of roadblocks to the rise of sea trade during this period is still large. The predicted probability of sea trade by sail before the rebellion for "roadblocked" pairs is 0.257 on average and if roadblocks did not happen, the post-rebellion sea trade would have been 0.367. The increase in the probability from 0.257 (column (5)) to 0.367 (column (4)) represents the contribution of technological change, which is only 11 percentage points. The majority of the increase (74%) comes from roadblocks, raising the probability of sea trade from 0.367 (column (4)) to 0.685 (column (3)). Similarly, for "non-roadblocked" pairs, the model predicted probability of sea trade increases by 0.097, from 0.29 to 0.387 with the introduction of steamship. A more thorough discussion on the role of technological change and whether it confounds the "roadblock effect" can be found in Section 7.

7. Alternative explanations

This section discusses alternative explanations for the growth of maritime trade during this period and provides evidence that the "roadblock effect" is not confounded by them.

Treaty ports and foreign trade The "roadblock effect" is not confounded by opening up of treaty ports to trade with western countries. The average population growth in coastal prefectures that did not have treaty ports was also substantial: 15% immediately after the rebellion.[41] Regarding the results on trade, I only compare bilateral trade between treaty ports due to data availability. While all treaty ports had access to foreign trade and could adopt the frontier technology of steamships for domestic trade, the identification is through comparing whether domestic trade between any two of them is more likely to use sea transport depending on the heterogeneous increase in their inland transport costs due to the conflict.

Another potential channel that domestic trade patterns could be affected by the introduction of treaty ports is through transit trade for re-exporting domestic goods or importing foreign goods. The rebellion could affect transit and domestic trade routes in a similar manner. Before the rebellion, exporting to foreign destinations was mainly through Canton (today's Guangzhou) and Shanghai. Due to roadblocks, a treaty port could either export the goods directly from itself when regular land trade routes to Canton became blocked, or transit goods by sea to Canton first, similar to decisions for domestic trade route between them. While there could be scale economies for sea trade, I also show that the magnitudes of the "roadblocked effect" are similar by excluding Canton and Shanghai in Table A.4.

[41] In addition, I find that the population increase in treaty ports correlates positively with domestic sea trade value, but not foreign trade value, although this evidence is more suggestive than conclusive as the sample size for which the trade value is available is small.

Technology improvement One may wonder whether the adoption of sea trade after the rebellion was due to availability of the new technology of steamship instead of the rebellion. My results show that even when new and superior technology became available, adoption was not guaranteed. Holding (new) technology constant, I show that location pairs subject to shocks to their inland route were much more likely to adopt steamship than location pairs unaffected by the rebellion. The counterfactual probability of using steamship without rebellion for "roadblocked" pairs is similar to "non-roadblocked" pairs. These provide evidence that the rebellion catalysed the adoption of the new technology.

While my identification strategy to examine the effect of the rebellion on transport modes exploits the *difference* in sea trade due to exposure to wars, it is true that the increase in the *level* of sea trade during this period can be a combination of both technological progress and roadblocks. However, quantification exercise using the extended model suggests that the contribution of technological improvement to the increase in the level of sea trade immediately after the rebellion would be relatively small. Under a cost ratio of sail to steam of 2 (which corresponds to the level of pre-rebellion grain trade by sail), column 5 of Table III shows that the counterfactual probability of sea trade for "roadblocked" pairs without the rebellion would be 0.367, an increase of 0.11 compared to their pre-rebellion probability using sailing ships. The majority of increase in sea trade (0.318/0.428=74%) can be attributed to the "roadblock effect". Similarly, for "non-roadblocked" pairs, their estimated increase in the probability of sea trade with the introduction of steamship after the rebellion is only 0.097.

In fact, even before the introduction of steamship, sea trade by sail had proved to be far more efficient than inland routes, yet was not widely adopted for domestic trade.[42] As discussed in Section 2, due to the sea ban in the early Qing dynasty, population relocated away from the coastal region. Even after the ban was lifted, the court decided not to promote sea trade but instead allocated substantial resources to the maintenance of inland trade routes (including the Grand Canal). The large sunk investment needed to start sea trade, even after it was allowed, could discourage individual merchants from maritime trade despite its cost-savings. The model simulation supports the possibility that in the presence of large sunk investment, sail trade will remain at low levels albeit with a lower variable cost than inland routes.

Alternative changes in inland transport Another potential mechanism that could confound the "roadblock effect" is the Yellow River shifting course in 1855, which flooded and paralysed the northern part of the Grand Canal.[43] While the flooding problem occurred throughout the history,

[42]The transport of tribute grain largely relied on the Grand Canal before the rebellion. Because the Yellow River constantly flooded the canal, the emperor launched a trial to transport the tribute grain by sea in 1826. According to a contemporary statesman Wei Yuan, sea transport was about one-third as costly and much faster than canal shipping (Wei, 1826). However, the initiative was quickly abandoned due to political opposition.

[43]The Yellow River is the second-longest river in China, after the Yangtze River. The name derives from the yellow sediments discharged into its middle stream from loess deposits.

the change of the river course in 1855 was arguably also a result of the rebellion because the Qing government was unable to finance its maintenance as before with mounting military expenses (Jia, 2009; Dai, 2012). Nevertheless, I show that the "roadblock effect" is not mainly driven by this alternative impact of the rebellion.

First, I take into account the potential change of the Yellow River in computing the transport costs. In particular, I assume that from 1856 onwards, the abandoned part of the Yellow River and the part of the Grand Canal that could be flooded by the new river (the part in Shantung province) were unusable. To make estimation results comparable, I use the same classification of "roadblocked" pairs as before. Hence, location pairs that could be affected by both roadblocks and the Yellow River are classified as "roadblocked" pairs whereas location pairs affected only by the Yellow River are "non-roadblocked" pairs.[44] Column (4) of Table A.3 shows that the prediction of the model incorporating the increase in inland transport costs due to changes in the Yellow River and the Grand Canal generates very similar results to the baseline prediction in column (1).

Second, I estimate the effect by dropping all observations that could be affected by potential changes in the river and canal, including those that could be affected by both roadblocks and the river/canal. This leaves us with a smaller sample of 62 location pairs. For this sub-sample of "roadblocked" pairs, their regular trade routes would not be affected by potential changes in the Yellow River and the Grand Canal. Still their probability of sea transport after the rebellion is 0.639 in the data, substantially and statistically larger than the "non-roadblocked" pairs. The model prediction based on parameters estimated from the full sample overestimates the post-rebellion probability for this sub-sample of "roadblocked" pairs, but not by much (25 out of 36 pairs instead of 23 out of 36). On the other hand, the sub-sample of "non-roadblocked" pairs has a similar probability of sea trade after excluding observations that can be affected only by potential changes in the canal and river. Both suggest that the effect of the rebellion through changes in the Yellow River, if any, was limited.

To summarise, the "roadblock effect" is robust to incorporating potential increase in transport costs due to the river/canal change as well as restricting to observations that can be affected solely by the rebellion occupation. This provides evidence that the "roadblock effect" is not mainly driven by the Yellow River shifting course during the rebellion.

Long-distance trade Trade routes between distant location pairs can have a higher probability of crossing any given region, including the rebellion region. At the same time, two regions further apart may be more likely to adopt sea trade. Sea transport has a lower variable cost than inland

[44] This can also be justified by the observation that for locations pairs subject only to changes in the Yellow River, a small fraction of their trade routes would be affected and the frequently-travelled courier routes were nearby. Therefore, they may not need to incur the cost of finding a new trade route. In fact, the probability of maritime trade for location pairs affected only by the canal and the river was only 0.25 on average after the rebellion. On the other hand, location pairs whose optimal land route was affected by rebellion occupation required a much larger detour to distant areas (e.g., Figure1).

transport methods, therefore it gains more advantage for long-distance trade, conditioning on the cost of alternative inland routes. Further, a fixed cost of transition between land and sea transport will also make sea transport more profitable for longer distance. To the extent that the models in Section 5.1 and 6 have taken into account correctly the effect of relative transport costs and their cost of transition and that they are main determinants of transport modes, this would not affect the estimated effect of roadblocks. That is why, instead of using geographical distance or borrowing transport cost parameters from other contexts, this paper develops a new method to obtain a precise estimate of the transport costs specific to China during this period in Section 5.2.

Nevertheless, one may still be concerned that there could be other reasons why location pairs further apart engage in sea trade, and the estimated "roadblock effect" is capturing them instead. To this end, I focus on a smaller sample which consists only of "roadblocked" pairs whose geographical distance as well as absolute differences in latitude and longitude are similar to "non-roadblocked" pairs. I use propensity score matching to match each "non-roadblocked" pair with a "roadblocked" pair based on log distance and their absolute differences in longitude and latitude.[45] Table A.5 shows that after matching, the two groups are comparable in both geographical distance and differences in longitude and latitude. I also show that the transport costs by sea and land, which are inputs of the model and not used directly for propensity score matching, are also balanced after matching.

Column (6) of Table A.3 shows that for the matched "roadblocked" pairs, their probability of sea trade after the rebellion is 0.75 in data, which is also substantially higher than the 0.375 probability of "non-roadblocked' pairs. The differences in probability in sea trade in data suggests that the roadblock effect is not driven by "roadblocked" observations that are further apart than "non-roadblocked" pairs. The model prediction based on parameters estimated using the full sample also matches well the mean probability of sea trade for this sub-sample of "roadblocked" pairs that are similar to the "non-roadblocked" pairs in terms of distance, differences in longitude and latitude, as well as relative transport costs. This further suggests that conditional on the relative transport costs and their change during the rebellion due to roadblocks, sea trade does not seem to favour more distant location pairs than less distant ones. The counterfactual probability for this subsample of "roadblocked" pairs without the rebellion would be 0.403, which indicates a 82% increase in probability of sea trade.[46][47]

[45] Because "roadblocked" observations have both longer distance and shorter distance trade pairs while "non-roadblocked" have shorter distance trade pairs, I match each "non-roadblocked' pair with a "roadblocked" pair instead of the other way around.

[46] The reason that the subsample of "roadblocked" pairs that are less distant have even a slightly higher probability of sea trade, both in the data and predicted by the model, is that for long-distance trade, inland trade routes can more often use the more efficient courier routes.

[47] Column (6) of Table A.4 shows the prediction of the extended model incorporating the choice of sail ships. The estimated roadblock effect is similarly large for the sub-sample of "roadblocked" pairs matched to the "non-roadblocked" pairs in distance and absolute differences in longitude and latitude.

8. Concluding remarks

Concentration of population in a location can remain persistent even when the location is no longer advantageous due to change in technology. The introduction of new transport technology, for example steamships, may increase the relative attractiveness of coastal locations by reducing their trade costs to other locations and thus increasing their market access. However, the presence of the large sunk investment usually needed for new technology could hold it back. Failure to adopt the superior technology, however, can trap populations in sub-optimal locations.

This paper uses the Taiping Rebellion in 19th-century China to study population changes and technological adoption after a large but temporary shock to city sizes. In contrast to the large literature on the persistence of relative city sizes after war shocks, I find a permanent loss in population of about 59% in war-ravaged cities and an increase of 22% in coastal cities after the rebellion. I provide evidence that this is because, in addition to the direct impact of war through death and displacement, the rebellion affected populations indirectly through trade routes and transport technologies. Before the rebellion, the limited use of sea transport despite its large potential was due to persistence of population away from the coastal locations and lack of state investment. Even when superior technology became available, adoption of sea transport may not take place. I show that the spatial variations in maritime trade immediately after the rebellion was driven by blocked land routes and feasibility of sea alternatives. The rebellion blocked regular inland trade routes, forcing some location pairs to search for alternatives, and this triggered substantial investment to facilitate sea trade, notably using steamship. After the rebellion, with sunk investment already incurred, many trade routes permanently moved to sea and this catalysed a shift of population towards port cities.

I develop a simple trade model with transport modal and route choice and a novel method to estimate historical transport costs to identify this "roadblock effect." The model estimates find a substantial cost associated with starting maritime trade. The counterfactual analysis using the model suggests that the probability of maritime trade after the rebellion would be much lower without roadblocks. The results of the paper highlight substantial forces of persistence in population and trade routes, the role of sunk investment in holding back superior technology, the importance of incentives for technology adoption, and population changes through trade costs and technology.

References

Allen, Treb and Costas Arkolakis, "Modern spatial economics: a primer," in "World Trade Evolution," Routledge, 2018, pp. 435–472.

Baum-Snow, Nathaniel, Loren Brandt, J Vernon Henderson, Matthew A Turner, and Qinghua Zhang, "Roads, railroads, and decentralization of Chinese cities," *Review of Economics and Statistics*, 2017, *99* (3), 435–448.

Bickers, Robert, "Infrastructural globalization: lighting the China coast, 1860s–1930s," *The Historical Journal*, 2013, *56* (2), 431–458.

Bleakley, Hoyt and Jeffrey Lin, "Portage and path dependence," *The Quarterly Journal of Economics*, 2012, *127* (2), 587–644.

Brezis, Elise S and Paul R Krugman, "Technology and the life cycle of cities," *Journal of Economic Growth*, 1997, *2* (4), 369–383.

Cao, Shuji, *Zhongguo yi min shi [The migration history of China]*, Fujian Education Press, 1997.

_ , *Zhongguo ren kou shi [The demographic history of China]*, Fudan University Press, 2000.

_ **and Yushang Li**, "The effect of Taiping Rebellion on population in Zhejiang," *Fudan Journal (Social Sciences Edition)*, 2000, *5*, 5.

Cheng, Yukuei, *Foreign trade and industrial development of China: An historical and integrated analysis through 1948*, University Press of Washington, 1956.

Dai, Angang, "The rise and fall of the transport of grain by water to Beijing in Qing dynasty and sailor, boat tracker," *Historical Research in Anhui*, 2012, (6), 24–28.

Davis, Donald R and David E Weinstein, "Bones, bombs, and break points: the geography of economic activity," *American Economic Review*, 2002, *92* (5), 1269–1289.

Deng, Yibing, *Qingdai qianqi shangpin liutong yanjiu [A study of commodity circulation in the early Qing dynasty]*, Tianjin Classic Publishing House, 2009.

Dincecco, Mark and Massimiliano Gaetano Onorato, "Military conflict and the rise of urban Europe," *Journal of Economic Growth*, 2016, *21* (3), 259–282.

Donaldson, Dave, "Railroads of the Raj: Estimating the impact of transportation infrastructure," *American Economic Review*, 2018, *108* (4-5), 899–934.

_ **and Treb Allen**, "Persistence and path dependence in the spatial economy," *NBER Working Paper*, 2020, *28059.*

Faber, Benjamin, "Trade integration, market size, and industrialization: evidence from China's National Trunk Highway System," *Review of Economic Studies*, 2014, *81* (3), 1046–1070.

Fan, Baichuan, *Zhonguo lunchuan hangyunye de xingqi [The rise of China's steamship industry]*, Sichuan People's Press, 1985.

Ge, J, Y Hou, and G Zhang, *Population and the modernization of China since 1850*, Xuelin Press, 1999.

Gilfillan, S Colum, *Inventing the ship: a study of the inventions made in her history between floating log and rotorship; a self-contained but companion volume to the author's "Sociology of invention"; with 80 illustrations, bibliographies, notes and index*, Follett, 1935.

Glaeser, Edward L and Jesse M Shapiro, "Cities and warfare: The impact of terrorism on urban form," *Journal of Urban Economics*, 2002, *51* (2), 205–224.

Gu, Cheng, "Qingchu de qianhai [The sea ban in the early Qing dynasty]," *Journal of Beijing Normal University (Social Sciences)*, 1983, (3), 60–72.

Guo, Yisheng, *The atlas of the Taiping Heavenly Kingdom*, SinoMaps Press, 1989.

Hanlon, W. Walker, "Temporary Shocks and Persistent Effects in Urban Economies: Evidence from British Cities after the U.S. Civil War," *The Review of Economics and Statistics*, 03 2017, *99* (1), 67–79.

Heblich, Stephan, Stephen J Redding, and Daniel M Sturm, "The making of the modern metropolis: evidence from London," *The Quarterly Journal of Economics*, 2020, *135* (4), 2059–2133.

Helpman, Elhanan, Marc Melitz, and Yona Rubinstein, "Estimating trade flows: Trading partners and trading volumes," *The Quarterly Journal of Economics*, 2008, *123* (2), 441–487.

Hsiao, Liang-Lin, *China's foreign trade statistics, 1864-1949*, East Asian Research Center, Harvard University distributed by Harvard University Press,, 1974.

Hua, Qiang, *The geography of the Taiping Rebellion*, Guangxi People Press, 1991.

Huang, Qichen, "Qingdai qianqi haiwai maoyi de fazhan [Development of overseas trade in the early Qing dynasty]," *Historical Research*, 1986, (4), 151–170.

Jia, Guojing, "Dispute of Yellow River's new and old course after the bursting at Tongwaxiang," *Journal of Historical Science*, 2009, (12), 56–63.

Juhász, Réka, "Temporary protection and technology adoption: Evidence from the Napoleonic blockade," *American Economic Review*, November 2018, *108* (11), 3339–76.

Keller, Wolfgang, Ben Li, and Carol H Shiue, "The evolution of domestic trade flows when foreign trade is liberalized: Evidence from the Chinese Maritime Customs Service," *Institutions and Comparative Economic Development*, 2012, pp. 152–172.

Krugman, Paul, "First nature, second nature, and metropolitan location," *Journal of Regional Science*, 1993, *33* (2), 129–144.

Kuhn, Philip A., *The Taiping Rebellion*, Vol. 10 of *The Cambridge History of China*, Cambridge University Press, 1978.

Liao, Shengfeng, *Studies on native custom and regional economics in the Qing dynasty*, People's Press, 2010.

Liu, Zubi, "Qingdai Fujian Wuyi cha chukou shangdao chutan [A preliminary study on the evolution of Fujian Wuyi tea exporters' road in the Qing dynasty]," *Fujian Historical Records*, 2016, (1), 33–36.

Meyer-Fong, Tobie, *What remains: Coming to terms with civil war in 19th century China*, Stanford University Press, 2013.

Michaels, Guy and Ferdinand Rauch, "Resetting the urban network: 117–2012," *The Economic Journal*, 2017, *128* (608), 378–412.

Miguel, Edward and Gerard Roland, "The long-run impact of bombing Vietnam," *Journal of Development Economics*, 2011, *96* (1), 1–15.

Ni, Yuping, *Qingdai caoliang haiyun yu shehui bianqian [Transport of tribute grain by sea and social changes in the Qing dynasty]*, Shanghai People's Press, 2005.

Nunn, Nathan and Diego Puga, "Ruggedness: The blessing of bad geography in Africa," *Review of Economics and Statistics*, 2012, *94* (1), 20–36.

_ **and Nancy Qian**, "The potato's contribution to population and urbanization: evidence from a historical experiment," *The quarterly journal of economics*, 2011, *126* (2), 593–650.

Redding, Stephen and Anthony J. Venables, "Economic geography and international inequality," *Journal of International Economics*, 2004, *62* (1), 53–82.

Redding, Stephen J, Daniel M Sturm, and Nikolaus Wolf, "History and industry location: evidence from German airports," *Review of Economics and Statistics*, 2011, *93* (3), 814–831.

Tintelnot, Felix, "Global production with export platforms," *The Quarterly Journal of Economics*, 2017, *132* (1), 157–209.

Tsivanidis, Nick, "The aggregate and distributional effects of urban transit infrastructure: Evidence from Bogotá's TransMilenio," *Working paper*, 2018.

Voigtländer, Nico and Hans-Joachim Voth, "The three horsemen of riches: Plague, war, and urbanization in early modern Europe," *Review of Economic Studies*, 2012, *80* (2), 774–811.

Wang, Yehchien and Guoshu Huang, "Shiba Shiji Zhongguo Liangshi Gongxu de Kaocha [An Investigation into the China's Suppy-Demand of Grain in the Eighteenth Century]," *Collection on Rural Economic History of Modern China*, 1989.

Ward, WH, "The sailing ship effect," *Physics Bulletin*, 1967, *18* (6), 169.

Wei, Yuan, *Daoguang bingyu haiyun ji [Memo of sea shipping in 1826* 1826.

Xia, Mingfang, "The Qing government's management of the Yellow River after the Tongwaxiang burst," *The Qing History Journal*, 1995, (4), 40–51.

AppendixA. Table appendix

Table A.1: Mapping between postal names and current locations

Postal name (Romanisation)	Current location (Pinyin)	Postal name (Romanisation)	Current location (Pinyin)	Postal name (Romanisation)	Current location (Pinyin)
Amoy	Xiamen	Heilungchiang	Heilongjiang	Nanking	Nanjing
Anhwei	Anhui	Hopeh	Hebei	Newchwang	Yingkou
Canton	Guangzhou	Kansu	Gansu	Ningpo	Ningbo
Chefoo	Yantai	Kiangsi	Jiangsi	Peking	Beijing
Chekiang	Zhejiang	Kiangsu	Jiangsu	Shantung	Shandong
Chengting	Shjiazhuang	Kiangsu	Jiangsu	Shengching	Liaoning
Chinan	Jinan	Kirin	Jilin	Shensi	Shaanxi
Chinchow	Jinzhou	Kiukiang	Jiujiang	Swatow	Shantou
Chinkiang	Zhenjiang	Kuachow	Guazhou	Szechuen	Sichuan
Foochow	Fuzhou	Kuanghsi	Guangxi	Tientsin	Tianjin
Fukien	Fujian	Kueichow	Guizhou	Wenchow	Wenzhou
Hankow	Hankou	Kweiping	Guiping	Yangchow	Yangzhou

Table A.2: Estimation of roadblock effect: model with sail trade

	(1)	(2)	(3)	(4)	(5)	(6)
Sail to steam cost ratio	1	1.25	1.5	1.75	2	2.25
Panel A: Estimation on model parameters						
γ/σ (elasticity of trade)	0.452	0.468	0.494	0.514	0.530	0.544
	(0.103)	(0.102)	(0.108)	(0.113)	(0.117)	(0.122)
i^s (sunk cost of new sea route)	1.808	1.955	1.994	2.017	2.027	2.034
	(0.409)	(0.402)	(0.395)	(0.391)	(0.388)	(0.386)
i^l (sunk cost of new land route)	1.676	1.850	1.751	1.670	1.604	1.543
	(0.594)	(0.580)	(0.539)	(0.512)	(0.495)	(0.483)
Panel B: Prediction of mean probability of sea trade						
Roadblocked pairs:						
Pre-rebellion	0.364	0.318	0.294	0.275	0.257	0.240
	(0.020)	(0.019)	(0.019)	(0.018)	(0.017)	(0.017)
Post-rebellion with rebellion	0.652	0.678	0.681	0.683	0.685	0.687
	(0.016)	(0.016)	(0.017)	(0.017)	(0.017)	(0.017)
Post-rebellion w/o rebellion	0.364	0.351	0.356	0.362	0.367	0.372
	(0.020)	(0.020)	(0.020)	(0.020)	(0.020)	(0.020)
Observations	58	56	56	56	56	56
Non-roadblocked pairs:						
Pre-rebellion	0.419	0.362	0.336	0.312	0.290	0.272
	(0.047)	(0.044)	(0.043)	(0.042)	(0.041)	(0.040)
Post-rebellion	0.419	0.392	0.390	0.388	0.387	0.386
	(0.047)	(0.045)	(0.046)	(0.046)	(0.046)	(0.046)
Observations	30	32	32	32	32	32

Notes: *Panel A* shows model prediction with different sail to steam cost ratios. Standard errors in parentheses. *Panel B* shows the corresponding prediction based on parameter estimates of *Panel A*. Bootstrap standard errors using 500 replicates in parentheses.

Table A.3: Estimation of roadblock effect: robustness results of extended model

	(1)	(2)	(3)	(4)	(5)	(6)
Sail to steam cost ratio	1	1.25	1.5	1.75	2	2.25
Panel A: Estimation on model parameters						
γ/σ (elasticity of trade)	0.438	0.482	0.523	0.559	0.590	0.619
	(0.097)	(0.105)	(0.112)	(0.120)	(0.127)	(0.133)
i^s (sunk cost of new sea route)	1.845	1.952	1.998	2.032	2.057	2.079
	(0.424)	(0.406)	(0.402)	(0.401)	(0.399)	(0.398)
i^l (sunk cost of new land route)	1.707	1.823	1.699	1.598	1.515	1.437
	(0.617)	(0.586)	(0.549)	(0.525)	(0.508)	(0.497)
Panel B: Prediction of mean probability of sea trade						
Roadblocked pairs:						
Pre-rebellion	0.364	0.332	0.319	0.306	0.292	0.278
	(0.020)	(0.020)	(0.021)	(0.021)	(0.021)	(0.020)
Post-rebellion with rebellion	0.652	0.676	0.678	0.680	0.682	0.684
	(0.016)	(0.016)	(0.017)	(0.017)	(0.017)	(0.017)
Post-rebellion w/o rebellion	0.364	0.351	0.357	0.363	0.370	0.376
	(0.020)	(0.020)	(0.021)	(0.021)	(0.021)	(0.021)
Observations	58	56	56	56	56	56
Non-roadblocked pairs:						
Pre-rebellion	0.419	0.377	0.360	0.344	0.327	0.312
	(0.047)	(0.046)	(0.047)	(0.047)	(0.047)	(0.047)
Post-rebellion	0.419	0.392	0.391	0.390	0.389	0.389
	(0.047)	(0.046)	(0.047)	(0.047)	(0.047)	(0.047)
Observations	30	32	32	32	32	32

Notes: The robustness estimation assumes that location pairs with previous sail trade would stick to the incumbent technology even when steamships became available whereas Table III assumes that steamships were adopted. *Panel A* shows model prediction with different sail to steam cost ratios. Standard errors in parentheses. *Panel B* shows the corresponding prediction based on parameter estimates of *Panel A*. Bootstrap standard errors using 500 replicates in parentheses.

Table A.3: Prediction of roadblock effect: robustness results of base model

	(1) Baseline sample	(2) Excl. Tientsin.	(3) Excl. Canton	(4) Change river	(5) Excl. river	(6) Matched sample
Roadblocked pairs:						
Data	0.696	0.705	0.674	0.696	0.639	0.750
Prediction with roadblock	0.693	0.710	0.697	0.698	0.699	0.733
	(0.020)	(0.022)	(0.024)	(0.020)	(0.026)	(0.026)
Prediction w/o roadblock	0.365	0.383	0.366	0.370	0.382	0.403
	(0.020)	(0.022)	(0.023)	(0.020)	(0.030)	(0.027)
Observations	56	44	46	56	36	32
Non-roadblocked pairs:						
Data	0.375	0.346	0.417	0.375	0.385	0.375
Prediction	0.379	0.374	0.395	0.380	0.392	0.378
	(0.045)	(0.048)	(0.051)	(0.045)	(0.043)	(0.045)
Observations	32	26	24	32	26	32

Notes: Estimation of parameters of the model in Section 5 with different robustness specifications. Column (1) shows the baseline estimation as in Table I for comparison. Column (2) excludes trade with Tientsin, whose trade may be directly affected by the civil war. Column (3) excludes major ports for foreign trade (Canton in addition to Shanghai). Column (4) takes into account the potential change in the Yellow River and the Grand Canal during the war when calculating transport costs. Column (5) excludes trade pairs that may be affected by changes in the Yellow River and the canal. Column (6) uses a subsample matched in geographical distance and differences in latitude and longitude. Bootstrap standard errors using 500 replicates in parentheses.

Table A.4: Prediction of roadblock effect: robustness results of extended model

	(1) Baseline sample	(2) Excl. Tientsin.	(3) Excl. Canton	(4) Change river	(5) Excl. river	(6) Matched sample
Roadblocked pairs:						
Data	0.696	0.705	0.674	0.696	0.639	0.750
Prediction with roadblock	0.685	0.700	0.688	0.689	0.695	0.718
	(0.017)	(0.019)	(0.020)	(0.017)	(0.023)	(0.022)
Prediction w/o roadblock	0.367	0.386	0.369	0.371	0.386	0.408
	(0.020)	(0.024)	(0.023)	(0.020)	(0.031)	(0.027)
Observations	56	44	46	56	36	32
Non-roadblocked pairs:						
Data	0.375	0.346	0.417	0.375	0.385	0.375
Prediction	0.387	0.382	0.403	0.388	0.399	0.387
	(0.046)	(0.049)	(0.053)	(0.046)	(0.044)	(0.047)
Observations	32	26	24	32	26	32

Notes: Estimation of parameters of the model in Section 6 with different robustness specifications. Column (1) shows the baseline estimation as in Table I for comparison. Column (2) excludes trade with Tientsin, whose trade may be directly affected by the civil war. Column (3) excludes major ports for foreign trade (Canton in addition to Shanghai). Column (4) takes into account the potential change in the Yellow River and the Grand Canal during the war when calculating transport costs. Column (5) excludes trade pairs that may be affected by changes in the Yellow River and the canal. Column (6) uses a subsample matched in geographical distance and differences in latitude and longitude. Bootstrap standard errors using 500 replicates in parentheses.

Table A.5: Summary statistics of distance

	Full sample					Matched sample				
	(1) Long.	(2) Lat.	(3) Dist.	(4) Sea	(5) Land	(6) Long.	(7) Lat.	(8) Dist.	(9) Sea	(10) Land
Roadblock	1.358	5.419	0.756	0.442	0.386	0.458	0.392	0.152	-0.075	0.043
	(0.462)	(0.871)	(0.110)	(0.182)	(0.089)	(0.432)	(0.856)	(0.115)	(0.201)	(0.099)
Constant	2.925	4.419	6.273	1.065	3.071	2.925	4.419	6.273	1.065	3.071
	(0.323)	(0.537)	(0.095)	(0.174)	(0.071)	(0.325)	(0.540)	(0.095)	(0.175)	(0.071)
Observations	88	88	88	88	88	64	64	64	64	64
R-squared	0.079	0.257	0.381	0.093	0.181	0.018	0.003	0.027	0.002	0.003

Notes: The constants show for the "non-roadblocked" location pairs, the average difference in longitude and latitude, distance, sea transport and land transport costs between trade pairs. The indicator *roadblock* shows the difference for "roadblocked" pairs relative to the "non-roadblocked" pairs. Robust standard errors in parentheses.

AppendixB. Figure appendix

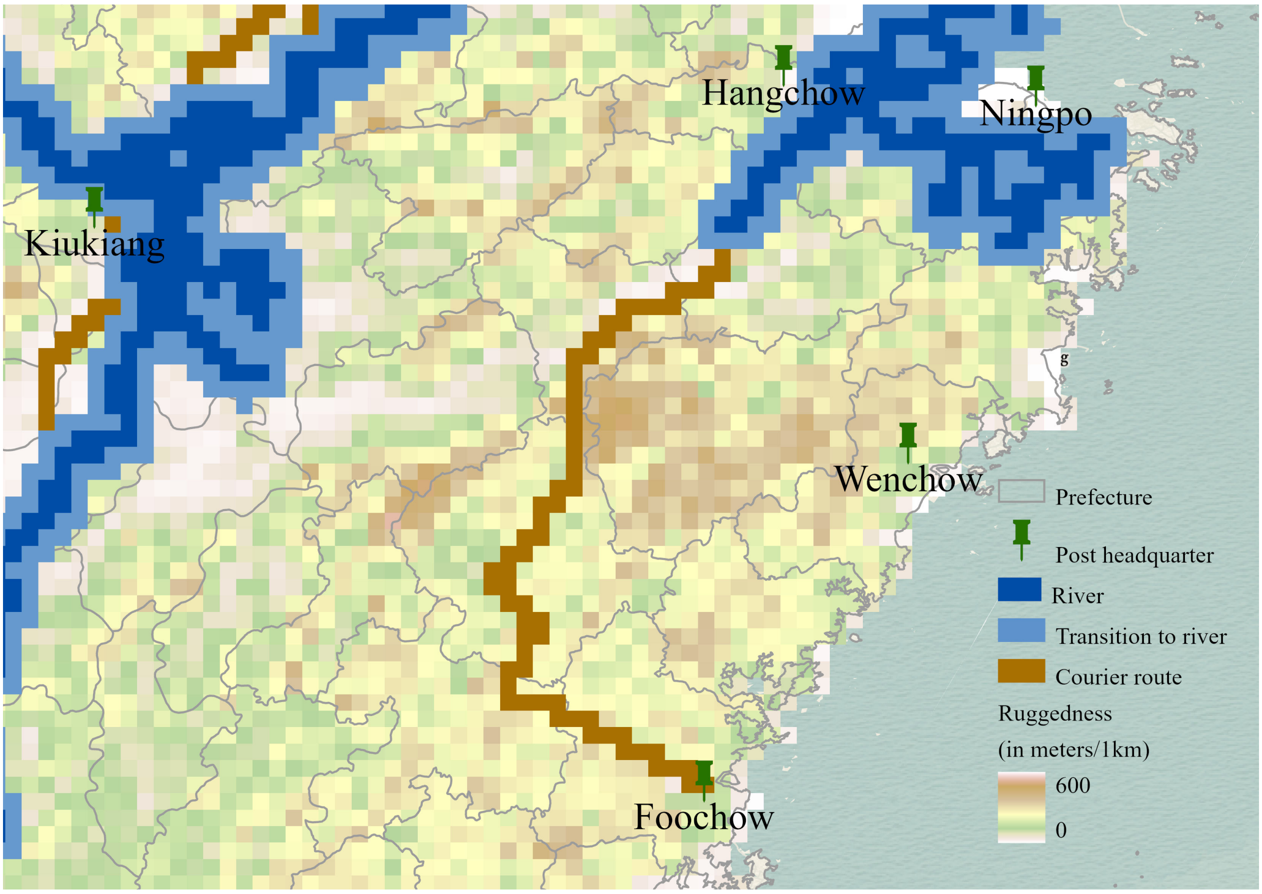

Figure B.1: Transport cost in 19th-century China

Notes: 0.1 degree by 0.1 degree cells covering the land area of China overlaid with rivers, courier routes, terrain ruggedness, transition between land and inland waterways.

AppendixC. Additional results on population

This section provides estimation results of prefecture population evolution. Table C.1 shows the reduced-form relationship between population, occupation during the rebellion and coastal location using event-study specifications. The excluded category is the data year 1851. Therefore, the coefficients represent the population change of the treatment group relative to the control group compared to their difference in 1851, just before the Taiping Rebellion started. Prefecture fixed effects are included to control for time-invariant prefecture heterogeneity in population and time fixed effects account for secular trends.

Column 1 shows the results when only the interactions between year indicators and the indicator for occupied prefectures during the rebellion are included in the regression. Column 2 additionally include the interactions between year indicators and the indicator for coastal locations. Column 3 shows the estimation results of Equation 1 and its coefficients estimates are plotted in Figure 3. It further includes the interactions between year indicators and other locational characteristics, capturing any time-varying effects of these characteristics on population. These are the level of human capital and a set of geographic controls including terrain ruggedness, agricultural suitability of major crops and new world crops, and whether the prefecture had access to the Grand Canal. The results show that population evolution of occupied and non-occupied prefectures was similar before the rebellion, but the occupied prefectures suffered a substantial population loss that persisted until 2010. Meanwhile, population in coastal locations increased immediately after the rebellion.

I proceed to estimate an average change of population after the rebellion based on Equation 2. This specification similarly allows for time-invariant prefecture heterogeneity in population with prefecture fixed effects and secular trends over time with year fixed effects. Furthermore, it allows controlling for differential population growth of occupied prefectures and coastal prefectures, respectively.

The estimation in Column (1) includes the interaction between post-rebellion and occupied indicators. The coefficient of the interaction indicates that population in occupied prefectures has an additional drop of about 67% after the rebellion. In Column (2), I further include a post-rebellion and coastal interaction to estimate the change of coastal population after the rebellion. The estimated coefficient shows a 22% increase in coastal population after the rebellion.

Population growth in coastal regions immediately after the rebellion could be driven by other characteristics of coastal areas. While prefecture fixed effects account for the population differences across prefectures in levels, those characteristics may have a differential impact on population growth after a large shock to population sizes. For instance, coastal areas may have better agricultural productivity, which could attract migration after the rebellion. More generally, as locational fundamentals change over time, prefecture with certain characteristics may experience more or less population growth at different points of time.

Table C.1: Prefecture population evolution 1680–2010: event study

	Dep. var.: Ln (population)		
	(1)	(2)	(3)
1680 × occupied	-0.059	-0.058	-0.033
	(0.040)	(0.040)	(0.062)
1776 × occupied	-0.044	-0.044	-0.011
	(0.022)	(0.022)	(0.038)
1820 × occupied	-0.019	-0.020	0.017
	(0.016)	(0.016)	(0.030)
1880 × occupied	-0.680	-0.670	-0.589
	(0.091)	(0.089)	(0.106)
1910 × occupied	-0.642	-0.635	-0.559
	(0.074)	(0.074)	(0.098)
1953 × occupied	-0.603	-0.597	-0.496
	(0.084)	(0.084)	(0.113)
1982 × occupied	-0.618	-0.614	-0.497
	(0.078)	(0.078)	(0.106)
2010 × occupied	-0.587	-0.576	-0.486
	(0.087)	(0.084)	(0.110)
1680 × coastal		0.005	0.007
		(0.044)	(0.043)
1776 × coastal		-0.013	-0.027
		(0.018)	(0.020)
1820 × coastal		-0.015	-0.022
		(0.012)	(0.013)
1880 × coastal		0.240	0.216
		(0.053)	(0.059)
1910 × coastal		0.159	0.180
		(0.054)	(0.060)
1953 × coastal		0.142	0.176
		(0.073)	(0.073)
1982 × coastal		0.098	0.172
		(0.071)	(0.070)
2010 × coastal		0.251	0.270
		(0.089)	(0.085)
Year indicators × controls			Yes
Year fixed effects	Yes	Yes	Yes
Prefecture fixed effects	Yes	Yes	Yes
Number of observations	1,610	1,610	1,565
Number of prefectures	179	179	174
Number of coastal prefectures	35	35	35
R-squared	0.803	0.808	0.851

Notes: Controls in column (3) are the level of human capital proxied by the natural logarithm number of graduates from the Imperial Exam in the 1840s and a set of geographic controls including terrain ruggedness, agricultural suitability from FAO GAEZ v4 for major crops in historical China (i.e., rice, wheat and foxtail millet) and new world crops (i.e., potato, maize and sweet potato), and whether the Grand Canal went through a prefecture. Robust standard errors clustered by prefecture are reported in parentheses.

Table C.2: Prefecture population evolution 1680–1953

	Dep. var.: Ln (population)				
	(1)	(2)	(3)	(4)	(5)
Post-reb. × occupied	-0.668	-0.659	-0.592	-0.681	-0.633
	(0.081)	(0.079)	(0.101)	(0.090)	(0.124)
Post-reb. × coastal		0.217	0.220	0.365	0.361
		(0.055)	(0.061)	(0.066)	(0.102)
Post-reb. × coastal × domestic trade				0.379	0.173
				(0.067)	(0.095)
Post-reb. × coastal × foreign trade				-0.089	-0.078
				(0.047)	(0.050)
Occupied linear time trend	0.0005	0.0004	0.0004	0.0006	0.0004
	(0.0002)	(0.0002)	(0.0003)	(0.0002)	(0.0004)
Coastal linear time trend	0.0008	-0.0002	-0.0001	-0.0003	-0.0004
	(0.0003)	(0.0002)	(0.0002)	(0.0006)	(0.0006)
Year indicators × controls			Yes		Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Prefecture fixed effects	Yes	Yes	Yes	Yes	Yes
Number of observations	1,253	1,253	1,218	1,064	1,029
Number of prefectures	179	179	174	152	147
Number of coastal prefectures	35	35	35	8	8
R-squared	0.623	0.633	0.696	0.607	0.682

Notes: In columns (4) and (5), trade val. is the natural logarithm of domestic maritime trade value relative to the average in 1867, which is only available for 8 treaty ports out of 35 coastal prefectures (and the interaction is 0 for all 144 non-coastal prefectures). In columns (3) and (5), controls include the initial human capital is proxied by the natural logarithm number of graduates from the Imperial Exam in the 1840s, which is not available for 5 prefectures; an indicator for whether the Grand Canal passed through, terrain ruggedness, and categorical variables for agricultural suitability from FAO GAEZ v4 for major crops in historical China and new world crops. Robust standard errors clustered by prefecture are reported in parentheses.

Therefore, in Column (3), I include a variety of locational traits (i.e., the level of human capital and a set of geographical controls) interacted with all year indicators.[48] The positive coefficient estimate of the interaction on post-rebellion and coastal dummies is robust to inclusion of differential impacts of these locational characteristics on populations in different data years, showing a similarly 22% increase in the level of population in coastal prefectures after the rebellion.

To provide suggestive evidence that populations relocated because trade activities were diverted to the coast as the rebellion blocked regular inland trade routes, in column (4), the post-rebellion × coastal interaction is further interacted with the natural logarithm of the value of domestic and foreign trade by sea relative to its average in 1867 reported by the CMCS, which consists mainly of steamship trade, to see whether port cities with a surge in steamship trade had an increase in population after the rebellion.

[48]This specification is similar to Nunn and Qian (2011).

Since trade data is only available at treaty ports, which were large ports that had trade with western countries, the number of observations drops. For this subset of large ports, the post-rebellion $\times$ coastal interaction indicates that their post-rebellion population increase was about 37% on average. The post-rebellion$\times$coastal$\times$domestic trade triple interaction indicates that a 1% increase in domestic sea trade reported by CMCS was associated with a 0.38% increase in coastal population after the rebellion. However, the association between coastal population and foreign sea trade was much weaker as shown by the post-rebellion$\times$coastal$\times$foreign trade triple interaction.[49] This suggests that the increase in coastal population during this period was shaped by patterns of domestic sea trade.

On the basis of column (4), column (5) further controls for locational characteristics interacted with year dummies. The general picture remains the same, indicating that the positive association between population and domestic sea trade was not confounded by other locational characteristics that could at the same time correlate with sea trade.

[49] While both the volume of trade and population growth could be greater in larger cities, using the value of trade per capita gives very similar results.

AppendixD. Estimation of historical migration gravity

The following equation is used for the estimation of migration gravity:

$$\ln L_{ijt} = \eta_{it} + \psi_{jt} + \kappa \ln D_{ijt} + \nu_{ijt}.$$

The dependent variable is the natural logarithm of the migration flow from location i to j at time t. The origin and destination fixed effects, η_{it} and ψ_{jt} respectively, can vary over time. κ measures the elasticity of migration flows to migration costs D_{ijt}. ν_{ijt} is an error term.

Historical migration flows are rarely available. Here I construct a new data set of migration flows in historical China based on studies that trace the origin of modern villages. Historically, many villages in China were founded by clans from outside areas when the local living conditions worsened. By virtue of the tradition of keeping a rich family history, Cao (1997) was able to collect information about migration villages regarding the place of origin of their founders and the formation time frame. We can thus use the number of villages at location i founded by people from location j at time t to proxy for the migration flow from i to j at t.[50]

The following tables present the estimation results on the migration gravity using the number of migration villages to proxy for migration flows. Table D.1 shows results by using transport costs estimated in Section 5.2 to measure migration cost. Table D.2 shows results using distance.[51] Column (1) of Table D.1 shows that migration flows respond negatively to transport cost, as expected, and the elasticity is about -1.5. This is also similar to migration elasticities estimated by Allen and Arkolakis (2018) using international migration between 1960 and 2000 and intranational migration within the United States between 1850 and 2000.

The survey by Cao (1997) focuses primarily on migration villages in Kiangsi province, but also includes nearby prefectures in other provinces. To the extent that migration to prefectures outside Kiangsi may have different patterns, in column (2), I restrict the sample to only migration flows to Kiangxi province. The resulting elasticity is about -1.3. For all specifications, the origin and destination fixed effects are allowed to vary by time, but the distance elasticity itself can also vary over time. Therefore, I divide the sample into two periods in column (3) and column (4). In column (3), I restrict the sample to migration villages formed before 1722 and in column (4) to villages

[50] The implicit assumption here is that the initial population when the villages were founded is similar across villages. For a subset of villages where their recent population is available, I calculate the implied annual population growth rate to confirm that this is a reasonable assumption.

[51] Instead of the exact year of formation, we only know if the migration time falls between 1643 and 1722, 1643 and 1796, 1723 and 1796 or 1796 and 1912. When pooling observations for different time frames, I divide each observation by the number of years for the time frame it belongs to, to account for that the number of migrants/migration villages will be larger for longer time periods. The destinations are counties. For the majority of villages, only the origin province is known and for others the prefectures or counties are known. For observations that only the origin province is available, I calculate transport cost/distance to the nearest prefecture in the province. The estimate of elasticity using the average cost/distance to prefectures in the province generates statistically significant but much larger elasticity (in absolute value) than the rest of the sample where information about the prefecture/county is available.

formed after 1723. The results show that over time migration flows respond more to transport costs as the elasticity becomes more negative.

Table D.2 shows the results on migration elasticities using distance instead of transport costs. In the extreme case that distance does not correlate with transport costs and if we believe that migration flows correspond solely to transport costs, then the relationship between migration and distance will be null. In the intermediate scenario that distance is a noisy predictor of transport costs, the negative association between migration flows and transport costs using distance as a proxy will be attenuated. Results in Table D.2 suggests this is the case. Distance approximates transport costs reasonably well and migration flows still decrease with distance, but the estimated migration elasticity using distance is reduced by 50% compared to using transport cost.

Table D.1: Migration gravity: transport cost

	Dep. var.: Ln (number of villages)			
	All (1)	Kiangsi only (2)	1643-1722 (3)	1723-1912 (4)
Ln (transport cost)	-1.464	-1.306	-0.975	-1.679
	(0.385)	(0.333)	(0.451)	(0.499)
Origin fixed effects	Yes	Yes	Yes	Yes
Destination fixed effects	Yes	Yes	Yes	Yes
Observations	113	93	45	56
R-squared	0.884	0.829	0.816	0.914

Notes: Columns (1) and (2) include time variant origin and destination fixed effects. The time frame for 12 observations is between 1643 and 1796 and therefore they are not included in columns (3) and (4). Robust standard errors are reported in parenthesis.

Table D.2: Migration gravity: distance

	Dep. var.: Ln (number of villages)			
	All	Kiangsi only	1643-1722	1723-1912
	(1)	(2)	(3)	(4)
Ln (distance)	-1.016	-0.873	-0.773	-0.965
	(0.385)	(0.333)	(0.451)	(0.397)
Origin fixed effects	Yes	Yes	Yes	Yes
Destination fixed effects	Yes	Yes	Yes	Yes
Observations	113	93	45	48
R-squared	0.893	0.837	0.830	0.914

Notes: Columns (1) and (2) include time variant origin and destination fixed effects. The time frame for 12 observations is between 1643 and 1796 and therefore they are not included in the columns (3) and (4). Robust standard errors are reported in parenthesis.