Politics-driven Market Access and Its cost: Evidence from China's Grand Canal
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Abstract

Using a grid-year level panel data covering the 8th century to 19th century, we find that (1) the national capital was relocated from the China central (the Tang and Song dynasties) to China north (Yuan, Ming and Qing dynasties) resulted in the redefinition of the Grand Canal to directly connect the national capital to the prosperous China south. Specifically, the optimal route to the national capital could predict the actual Grand Canal. (2) It also changed each region's market access and hence reshape the economic geography. 1% increase in market access and lead to 0.14% increase in population density. (3) Overall, the politics-driven transportation networks enhance the aggregate welfare. Removing the canal can cause 4% - 11% decrease in the total population. But, it also caused misallocation. The redefinition of canal lead to 2.5% - 4% decrease in the total population.

Keywords:
JEL Codes: D74, N45, P48.

*All remaining errors are ours.

I Introduction

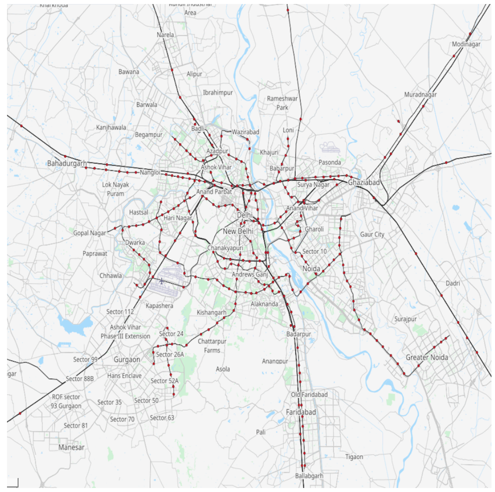
In many countries, the national capital functions as a central hub for transportation networks, shaped by its political and administrative significance. These networks often radiate outward from the capital, linking it to key regions of the nation and solidifying its role as a core of governance, commerce, and connectivity. For example, Beijing's extensive rail and road networks, including its high-speed rail system, create vital links to all corners of China, reinforcing the capital's centrality in national logistics. Similarly, Delhi serves as the anchor of India's transportation system, with its metro network seamlessly integrating the National Capital Region (NCR) and a convergence of national highways ensuring connectivity. Paris exemplifies France's hub-and-spoke transportation model, where the TGV high-speed rail and radial road systems center on the capital to facilitate efficient movement. Moscow mirrors this pattern as Russia's transportation heart, with radial railways and the Trans-Siberian Railway extending from the capital to connect vast, remote regions to the political core.

This widespread phenomenon raises critical development-related questions: Does politics determine transportation networks and hence market access? How does the politically motivated positioning of transportation networks influence economic geography? Does such politically driven infrastructure lead to misallocation of resources by prioritizing the capital over economically efficient alternatives? These issues are not only of theoretical interest but are directly relevant to development policy debates (e.g., World Bank 2009). Despite the growing literature on market access pioneered by scholars like Donaldson and Hornbeck (2016) [1], empirical research specifically addressing the economic impacts of politically influenced transportation networks remains limited. One key challenge is the difficulty of evaluating counterfactual scenarios—national capitals rarely relocate, making it hard to isolate and measure their influence on transportation and economic outcomes.

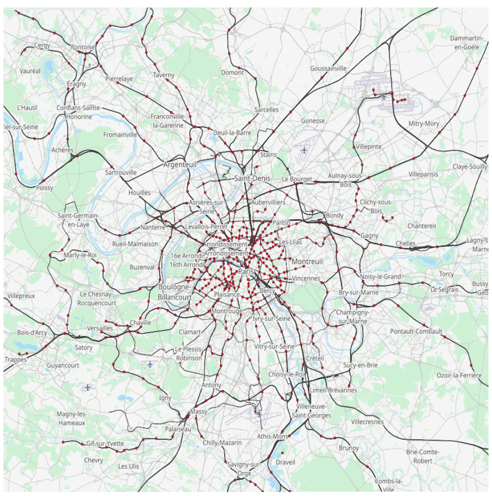
[1] A growing literature estimates the imapcts of market access, such as Hornbeck and Rotemberg (2024),Alder (2016),Balboni (2025),Heblich et al. (2020),Jaworski and Kitchens (2019),Yang (2018), and Duranton et al. (2014) .

Figure 1: National Capital's Transportation Networks in some countries

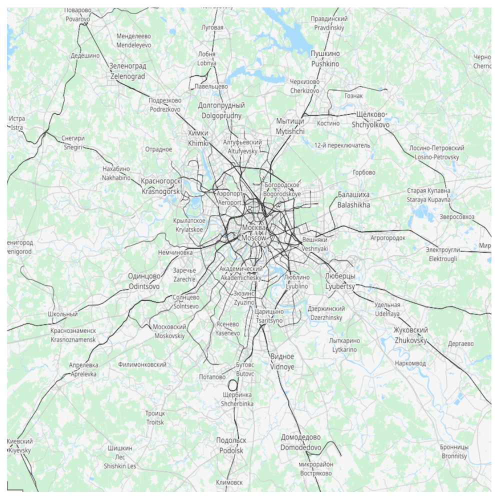
(a) BeiJing



(b) NewDelhi



(c) Paris

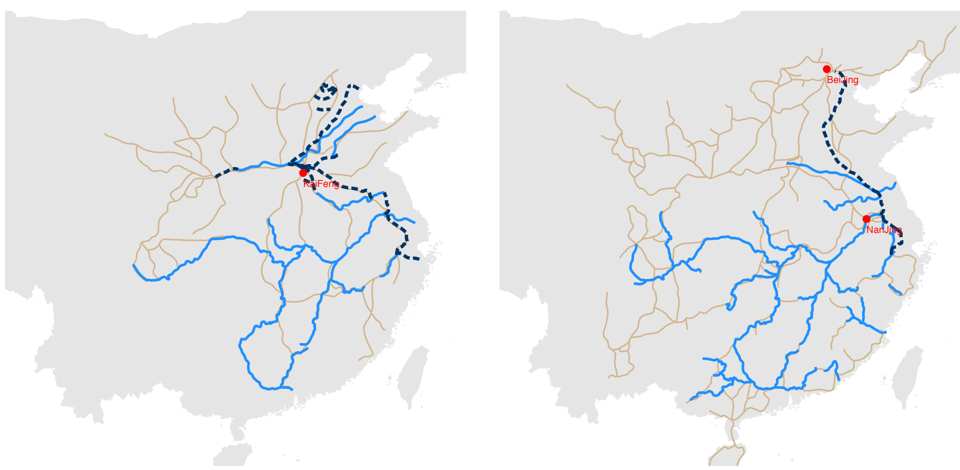


(d) Moscow

This paper addresses this research gap by examining the historical case of China's Grand Canal in the context of national capital relocations during 8th - 19th Centuries. In China proper, the main rivers, such as Yellow River, Huai River, and Yantze River, flow from the West to the East, and are relatively far away with each other. However, they have many tributaries, which are relatively nearby. Then, as early as in 613 BC, China had started to construct canals to connect those natural rivers to facilitate transportation. In 610, the Suiyang Emperor constructed the Grand Canal at the first time by connecting and expanding the existing small canals at the first time. This Canal system was improved and used during the subsequent Tang dynasty, and the Northern Song dynasty. During the Sui, Tang, and Northern Song dynasties, the national capitals were located in the central.

The Grand Canal flowed from Henan province to the southeast to connect Hangzhou in China South, and to the northeast to connect Beijing, as Figure 2a shows. However, the Sino-nomadic wars during 1127 - 1279, destroyed the canals. Then, When the Yuan dynasties reunified China,they need to re-construct the canal. The Yuan was founded by the Mongols, and choose Beijing as the national capital, which was close to their stronghold base. To better connect the China south - the most prosperous region at that time, Yuan dynasty choose an direct connect between the north (Beijing) and the south (Hangzhou), and by pass the central. The Ming dynasty improved this system, and the Qing dynasty followed, until the Grand Canal was gradually abandoned during 1820s-50s (as shown in Figure 2b). The Grand Canal, together with natural rivers and land routes, consist the transportation networks in historical China. By analyzing capital relocations and their influence on the canal's design, we explore two key effects of politically motivated transportation planning: the benefits of enhanced market access and the potential costs of resource misallocation.

Figure 2: National Captial Relocation and Transportation Networks



(a) Song (b) Ming

Notes: The brown lines are land routes, the blue lines are waterways, the dashed lines are the Grand Canal. The red points are national capitals in each dynasty.

We construct a 1-degree × 1-degree grid-year level panel data, which covering the Tang, Song, Yuan, Ming, and Qing dynasties and include rich information on population density, geographical characteristics, as well as crop suitability for various food crops. More importantly, by digitalizing the transportation networks in the five dynasties, which include natural rivers, canals, and land routes, and assuming the transportation cost of each type of routes, we could define the minimum cost route between each pair of grid in each year, and calculate the trade cost (denoted by τ). Following Donaldson and Hornbeck (2016), we calculate the market access measure, denoted by MA_{it}.

Using this grid-year level panel data, we investigate the three abovementioned questions. First, we empirically examine whether the relocation of national capitals led to the redefinition of transportation networks. The purpose of the Grand Canal is to connect the national capital to the politically and economically important region. When the national capitals were located in the central, the canal needs to connect the north, where is the border to defend the invasion of the nomadic people, as well as to connect the south, where is the main source of tax. When national capital was relocated to the north, i.e. Beijing, the only purpose is the connect the south. Then, we choose three points, the national capital location, the north starting point (Beijing), and south end point (Hangzhou), and calculate the optimal route to national capital for each dynasty. We hypothesize that this optimal route could predict the actual canal route. The results support our predictions. Using a two-way fixed effect model based on a grid-year level panel data, we find that 1 km increase in the waterway with optimal canal route could lead to 0.8 km increase in the actual waterway. Moreover, we further construct market access index to measure the position of each grid in the transportation networks in each year, and find that the market access based on the optimal route is significantly correlated with the market access based on the actual transportation networks. 1% increase in the market access based on optimal route and total crop calories can cause 0.5% increase in the actual market access based on actual routes and population.

Second, we investigate how this politics driven market access affected economic development measured by population density. The results show a strong relationship between the two. In terms of magnitude, 1% increase in market access lead to 0.14% increase in population density. We further use the market access based on optimal route as the instrumental variable for market access, and find that the results change trivially. The results remain robust with the inclusion of geographic characteristics and crop suitability of different crops, and also robust to the market access with different trade elasticity (θ) and alternative transportation cost settings. Then we define "market access shock" as the difference in actual market access between Song and Yuan dynasties, to examine the extent to which population density is affected by the sudden change in market access caused by the redefinition of the Grand Canal after the Song dynasty. We interact the market access shock with a full set of year dummies, and display its estimated coefficients in each sample year. The impacts do not show a clear pre-trend before 1102 and suddenly become significantly negative in 1290. The coefficients keep between -0.2 and -0.1 during the periods after 1290, indicating the negative effect is permanent.

We are also interested in the role of Sino-nomadic wars before the founding of Yuan dynasty on the Grand Canal re-routing and population density. The sharp decline in population during the frequent wars may cause the central to be less valuable for the re-constructed Grand Canal. The results show that, the death tolls during the wars significantly decreases the population density after the year 1102, while the number of wars not. More importantly, the significant positive effect of market access on population density persists at 0.09%, indicating that the population decline caused by the war shocks did not determine the redefinition of the Grand Canal. Our empirical results are robust to the inclusion of the political status of provincial capital and the length of surrounding artificial land routes, and to the market access excluding adjacent grids which may be the confounding factors affecting both local market access and population density. We also construct alternative optimal routes to national capital based on Human Mobility Index (FigureA.5) and the shortest straight-line paths (FigureA.6) , although they are not as accurate as the baseline optimal routes, the IV estimations remain robust to the use of these alternative optimal routes in constructing the instruments.

Third, what's the welfare implication of this politics driven infrastructure. Following Donaldson and Hornbeck (2016), we conduct some counterfactual analysis and yield two important findings. (i) The politics-driven canal construction has a positive influence on aggregate welfare. Counterfactual analysis show that removing all canals could lead to 4% - 11% decrease in total population, which shows that although the canal route is motivated by political consideration, it still benefits the overall economy. We further assume that land transportation costs would decrease as the empire would strengthen its overland infrastructure in the absence of the Grand Canal. Counterfactual estimates indicate that land transportation costs would need to decrease by at least 40% to offset the population decline caused by the loss of the canal. (ii) politics-driven canal redefinition due to national capital relocation caused misallocation. If we assume that the Ming and Qing dynasties adopted the Song canal, it is observed 2.5% - 4% increase in total population, while if we assume that the Tang and Song dynasties adopt the Ming canal, there would be 4% - 7% decrease in total population. We also perform some other counterfactual analysis under different assumptions such as with alternative transportation costs and varying parameters.

Our findings can help us understand how politics shape economic geography. Recent studies have shown that political and institutional factors can influence the distribution of economic activities (Bai and Jia (2023); Dell et al. (2018); Dell and Olken (2020)). In contrast to these existing studies, this paper adopts the market access approach in spatial economics. This approach provides a tool for establishing connections between complex theoretical models and reduced-form regression (Ahlfeldt et al. (2015); Allen and Arkolakis (2023); Donaldson and Hornbeck (2016); Redding et al. (2011)). Then, the paper can not only examine how politics determine the positioning of transportation networks and consequently regional economic development but also conduct the welfare analysis at the aggregate level. This allows us to evaluate the cost of politics-driven transportation networks.

II Historical Background

China has a long history of transportation networks. As early as the Qin dynasty, when China was first unified under Emperor Qin Shi, the Qin Chi Road, the earliest "national road," was built to govern the newly unified country (Chen and Li (2023)). This nine-line ancient highway system created a scenario of "all roads leading to Xianyang," covering all territories of the Qin Empire (Chen and Li (2023)). The imperial highways extended across major locations in the country and established courier stations (Yizhan) along the main roads, facilitating information delivery and ensuring national security (Lu et al. (2022)). The well-developed roads and improved postal system were important factors in the initial bureaucratization period, aiding Qin in overcoming administrative challenges and promoting political stability (Kiser and Cai (2003); Zhang and Zhang (2015)). Furthermore, transportation conditions were closely related to economic development and cultural unification. The transportation achievements of the Qin and Han dynasties greatly facilitated the exchange of goods and contributed to a prosperous economic situation (Chen and Li (2023)). Additionally, even before the unification of the Qin dynasty, various canals had been constructed. During the Qin dynasty, the government maintained these canals and also built new ones, such as the Ling Qu, which connected the Changjiang (Yangtze) River system with the Zhujiang River system. Together, the landways, natural rivers, and canals formed the transportation networks of historical China throughout the imperial period.

II.A The Grand Canal, 618 – 1127

The construction of Grand Canal was started as early as 486 BC, and was completed by connecting those small ones until the Sui Dynasty (AD581-618). Besides the Grand Canal, various natural rivers in the central plain were canalized and integrated into the water transport network. This national waterway transport network was constructed for military and tribute grain transportation (caoyun system). The caoyun system made notable contributions for maintaining the political centralization and unity in imperial China (Zhang and Lenzer Jr (2020)).

During the period of Emperor Yang of Sui, to consolidate the political unification and strengthen the control of southern regions, Emperor Yang shifted the capital from Xi'an to Luoyang, and ordered to excavate the Guangji Canal (known as the Bianhe River in the Tang Dynasty) . Since then, the Grand Canal was centred around Luoyang, passing through the Yongji Canal till Beijing and arriving at Hangzhou in the south. The Grand Canal of the Sui Dynasty was built mainly for military purposes, but after the Middle Tang Dynasty, it became the lifeline of the regime due to the growing dependence on the Yangtze-Huai River Basin (Huang et al. (2021)). As the increasing importance of the Grand Canal on economy of the north and south, Kaifeng, the junction of south-north Grand Canal in the Tang Dynasty, became prosperous and populous, and further spurred the commercial development in the central plain (Fu (1985)). Due to the Grand Canal construction, Kaifeng became the Tang's central government's strategic area for controlling canal transportation and maintaining their governance. Then in the Northern Song (960-1127) Dynasty, Kaifeng was adopted as the national capital. The developed water transportation system and the political status as the national capital brought Kaifeng and the surrounding central plains region to the peak of prosperity.

II.B War and the Destruction of the Grand Canal, 1127-1271

In the late Northern Song Dynasty, frequent wars with the Jin Dynasty, political corruption, and frequent flooding of the Yellow River resulted in the deterioration and silting up of the canals. In 1127, the troops of the Jin Dynasty marched south to conquer Kaifeng, leading to the downfall of the Northern Song Dynasty. The Southern Song Dynasty and the Jin Dynasty established the Huaihe River as their boundary and held strong opposition against each other. Following this, the rise of the Mongols in the thirteenth century eventually led to the conquest of the Jin Dynasty in northern China. The conflicts between the Jin Dynasty and the Mongols lasted from 1211 to 1234, resulting in 35-40 million deaths and a 70-80 percent decline in the population. Subsequently, the Mongols began to invade the Southern Song Dynasty. In 1271, the Yuan Dynasty was established, and in 1279, the Southern Song Dynasty came to an end, leading to the reunification of China. The frequent conflicts during the period of 1127-1271 resulted in the destruction of the well-developed water transport network in the central plain.

II.C The Jing-Hang Grand Canal, 1271- 1820

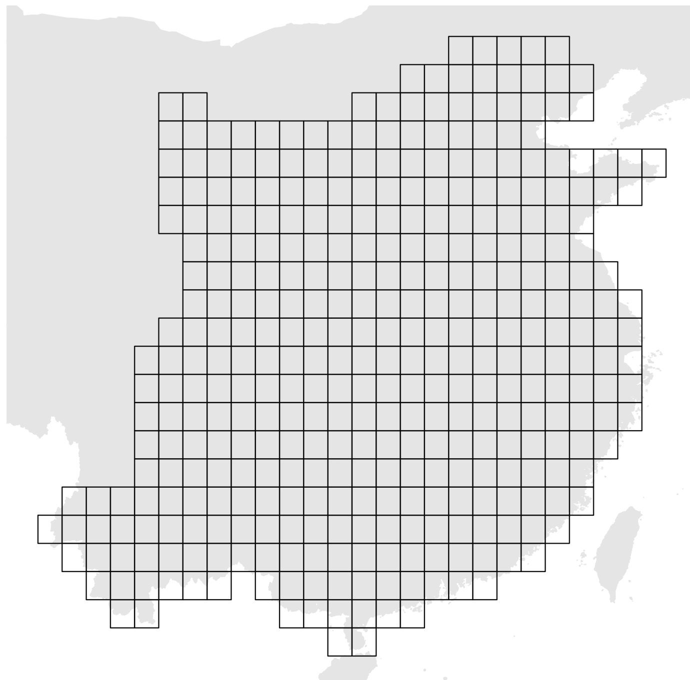
The Yuan Dynasty selected Beijing as its capital, and in order to improve the connectivity between the political center and the economic center, namely the Yangtze Delta, they undertook the reconstruction of the Beijing-Hangzhou Grand Canal between 1283 and 1293. This involved the digging of the Jizhou and Huitong Canals, which created a direct route from Beijing to Hangzhou through Shandong, bypassing the central plain (Yao (1998)). The newly reconstructed Grand Canal spanned over 1,700 kilometers, approximately 900 kilometers shorter than the Sui and Tang Grand Canal. As a result of this shift in the political center and the alteration of the canal route, the central plain lost its previous prosperity. Kaifeng, in particular, saw a decline in its status as a transportation hub and transformed into a more ordinary town within the central. Throughout the Ming and Qing dynasties, the Grand Canal played a significant role in transporting tribute grain to meet the food demands of Beijing. In the early 19th century, approximately 3.5 million quintals of rice were transported annually through the canal (Huang (1918)). The scale of the Grand Canal was unprecedented (Elvin (1973)). However, with the introduction of permanent reforms in sea shipping for tribute grain and reduced investments in canal maintenance, the Grand Canal was gradually abandoned by the middle of the 19th century (Cao and Chen (2022)).

III Data

The research scope of this article is roughly equivalent to ancient ”China proper”, that is, the eighteen provinces south of the Great Wall, accounting for approximately 90% of the country’s population in the late Qing Dynasty (Ge (2000); Bai (2019)). We divide the area into 366 grids with a grid size of 1 degree × 1 degree, as shown in Figure 3 . To measure the impact of market access on economic development, and identify the role of changes in Grand Canal and the national capital after the Song Dynasty, we construct a dataset that can reflect the development of population and transportation network in

China for the period 741-1820.

FIGURE 3: CHINA PROPER:GRIDS



III.A Market Access

We construct one transportation network database starts by digitizing the maps with waterway and land routes in the Tang, Song, Yuan, Ming and Qing dynasties during 741 to 1820, provided by the Historical Maps of China (*ZhongGuoLiShiDiTu*) Cheng and Xu (1980). As examples, Figure 2 shows the transportation network, which includes the waterways (blue lines) and land roads (brown lines), for dynasties Song and Ming – the two periods before and after the Grand Canal route changes. Figure A.2 provides the maps for all the five dynasties. We adopt the following simpler approximation of market access provided by Donaldson and Hornbeck (2016) that is less model dependent in our empirical implementation:

$$MA_o = \sum_{d \neq o} \tau_{od}^{-\theta} L_d \tag{1}$$

Because population size (L_o) is co-determined by the level of market access, we exclude each region's own population in the definition of market access ($d \neq o$). We also explore the robustness to proxying population using the total caloric suitability, namely the interaction between the grid area and Caloric Suitability Index (CSI), a measure of potential crop yield per hectare per year across globe. In Section VI, we follow Donaldson and Hornbeck (2016) to derive this approximation for grid market access in a general equilibrium trade model.

III.A.1 Transportation Cost (τ_{od})

We construct a transportation cost database to capture the trade cost (τ_{od}) of each pair of grids to measure market access, which mainly consists of three steps, including (i) the creation of transportation network, (ii) selection of cost rate parameters and (iii) calculation of the minimum trade cost matrix. The following sections detail the construction of the new database and the definitions and sources of variables used in the empirical estimation.

(i) The transportation networks during the five dynasties were presented in Figure A.2. To ensure the connectivity throughout the network, we break the routes into segments to permit turns at each intersection, including the intersection of waterway and land routes. we also need to connect the individual grids to the transportation routes to complete the network. Specifically, we additionally create the shortest straight-line paths from the centroid of each grid to the nearby waterway or land routes and treat the paths as trail routes. According to the Fogel (1964)'s adjustment factor, the mile travelled is about 1.4 times the shortest straight-line distance.

(ii) We then determine the trade cost rate parameters for each mode of transport. There are four modes of transportation in our model, waterway transportation includes the Grand Canal and natural waterways, overland transportation includes land routes shown on the map and manually created straight-line trails. Based on the historical documents on relevant transportation information, we set the cost rate for natural waterway, canal, land routes, and trails.[2] The cost rate of natural waterways is much lower than that of the Grand Canal, since the natural waterway transport is dominated by the tides and wind power while the Grand Canal transport mainly relies on human power. At the same time, the land transportation is dominated by horse-drawn carriages, while the trail transportation relies on people and pack animals, so the cost rate of trail transportation is significantly higher than that of land routes .

[2]The details on the reference materials and applied methods to determine these cost rates are shown in Appendix A.B.

(iii) We calculate the minimum transportation cost for every pair of grids by year. We first calculate the least transport cost between two grids along the transportation network using the baseline set of cost rates. But it is unreasonable to directly take this cost as the final minimum cost, because the transport cost along the network may be greater than the cost of a straight-line trail between two grids, especially for adjacent grids that are far away from the transportation network. Hence we estimate the cost of the straight-line trail between two grids, and take the smaller one of the two costs as the final cost. Finally we obtain a transportation cost matrix for each sample year.

III.A.2 Limitation

There are several limitations to the transportation cost database. First, the cost rates remain constant across grids and periods, and are not allowed to vary with the direction. In reality, transportation costs are highly dependent on specific transport conditions. Water transportation costs exhibit significant variations due to the influence of water flow direction. But as Donaldson and Hornbeck (2016) argue, maintaining a constant cost rates eliminates the potential endogeneity between regional variation of transport cost rates and local economic development. In such case, changes in market access are determined by changes in transportation networks, which facilitates empirical estimates. Therefore we employ the average transport cost rates over the study regions and periods. Additionally, we explore the robustness of our results to other possible cost rates of waterway and land routes.

Second, we only take the grain consumed during transportation as the transportation cost, without considering other potential costs. In fact, transportation involves many other costs such as storage and inventory expenses for slow-moving shipments, loading fees, water-land transshipment costs, and maintenance expenses for vessels and grain trucks. In robustness tests, We show that the baseline results are robust to the comprehensive transportation costs derived using the "price difference method".

Third, we suppose overland transportation employs a fixed-length segmented land transportation (100km).We assume that supply markets are located at every 100 kilometers along the land routes. However, in actual transport operations, the distance between markets may be shorter or longer than 100 kilometers. In such cases, grain transport vehicles must carry additional grain to cover consumption within the extra segment, causing fluctuations in land transport costs. We permit variations in land transport costs, as detailed in Table A.1.

III.A.3 Trade Elasticity (θ)

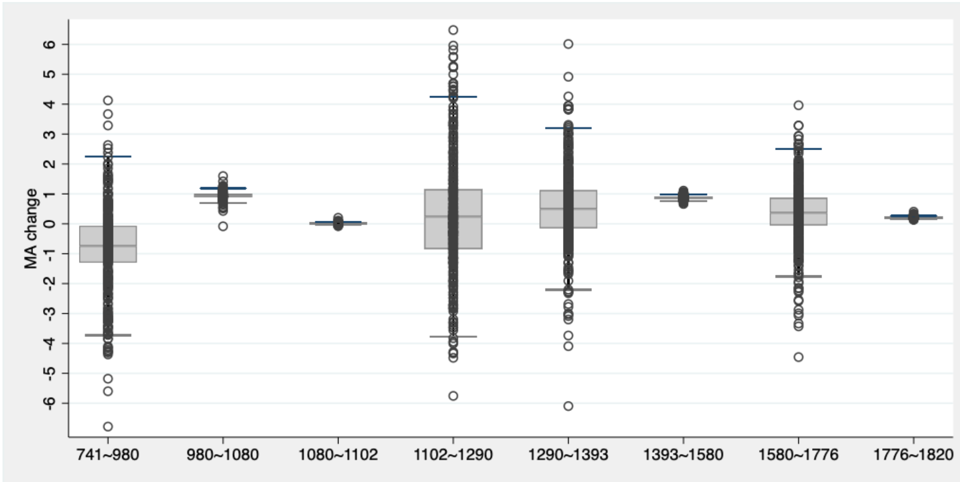
Another issue is on the estimate of θ. θ represents the "trade elasticity", a lower θ means dispersed distribution of a grid's productivity, creating a larger trade motivation across grids. The value of θ depends on the empirical contexts. Eaton and Kortum (2002) gives a range of possible value of θ between 3.60 and 12.86, and the value they preferred is 8.28. Donaldson and Hornbeck (2016) estimate θ is equal to 8.22 across the counties in the United State from 1870 to 1890. We set the $\theta = 9.22$ drawn from a Nonlinear Least Square (NLS) routine, taking the theta value that fits our data and model best (see Section VI.A.3). The estimated value of 9.22 has a 95% confidence interval between 8.98 and 9.64 based on bootstrapping at the grid-level, with 300 replications. We also test the robustness of our results to alternative theta values in the empirical analysis.

III.A.4 Description

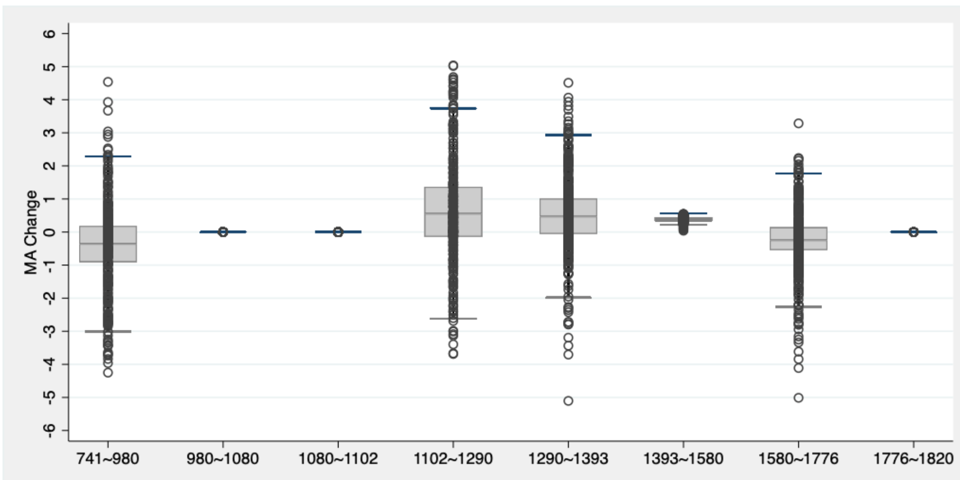
Based on Equation (1), we calculate the market access for each grid in 741, 980, 1080, 1102, 1290, 1393, 1580, 1776, and 1820. Baseline market access is based on the population in each grid. For robustness and to mitigate the endogeneity to the population density, we use the Caloric Suitability Index (CSI) provided by Galor and Özak (2016), which captures annual potential crop yield measured in calories per hectare, to indicate the population that the grid can support.

To illustrate how the market access changed over time, we visualize market access differences in adjacent sample years in Figure 4a, which shows great over-time changes. The changes in market access come from two sources - population change and transportation network change. We find that although population changed significantly over time, the main source is the change in transportation network. To show that, In Figure 4b, we use Calories-Suitability Index (CSI) of each grid to replace population to calculate the market access and redraw Figure 4a, we find that the pattern does not change a lot. Since the CSI only changed before and after 1500, the age of discovery and the introduction of the New World Crops, it did not change within the pre-1500 and post-1500 period. It suggest that the first difference in market access within the pre-1500 and the post-1500 period only captures the change in transportation networks.

Figure 4: First Difference of Market Access Shock



(a) Population-based



(b) CSI-based

Notes:The upper/lower cap is mean+/- 2 standard deviation. The box is the range of 25% 75%.

It can be seen that the range of changes in CSI-based market access is the largest and most dispersed between 1102 and 1290, indicating that transportation networks change the most after the Song Dynasty. Changes in transportation networks may come from two sources. The first is the changes in the land transportation network across dynasties. The other is the changes in the waterway network caused by the diversion of the Grand Canal after the Song Dynasty. Changes in the first source can be captured by changes in market access during which dynasties changed but canals did not, such as 741-980 (Tang and Song), 1290-1393 (Yuan and Ming) and 1580- 1776 (Ming and Qing Dynasties).

We find that although market access also changed significantly during these periods, the greatest changes occurred during the Song and Yuan dynasties. Differences in market access changes between 1102 and 1290 and other dynasty-change periods may have arisen from the rerouting of the Grand Canal, as the Song Canal was destroyed during the war, and the Yuan Dynasty re-built a new version of Canal as we mentioned in Section II.

III.B Population Density and Control Variables

Our main measure of economic development is population density during AD 741-1820, which can be obtained based on information on population size and geographical area in each grid. We collected pertinent population information from Ge (2000) and Liang (2008) and converted it into a grid population based on the overlap area between the grid and different regions for each sample year (The details are shown in Appendix A.A). We finally have a nine-year balanced panel data for population in 361 grids.

The development of ancient regional economies largely depends on the local geographical environment and the suitability of major crops. Therefore, we control for a rich set of geographical conditions and agricultural suitability variables in our estimates. Geographic variables include whether the grid has plains, major rivers, whether it is located on the coast, the macro-region it belongs to, the grid's average slope, elevation, grid area, and centroid longitude and latitude. Agricultural variables include suitability of wheat, rice, fox millet, maize and sweet potato.

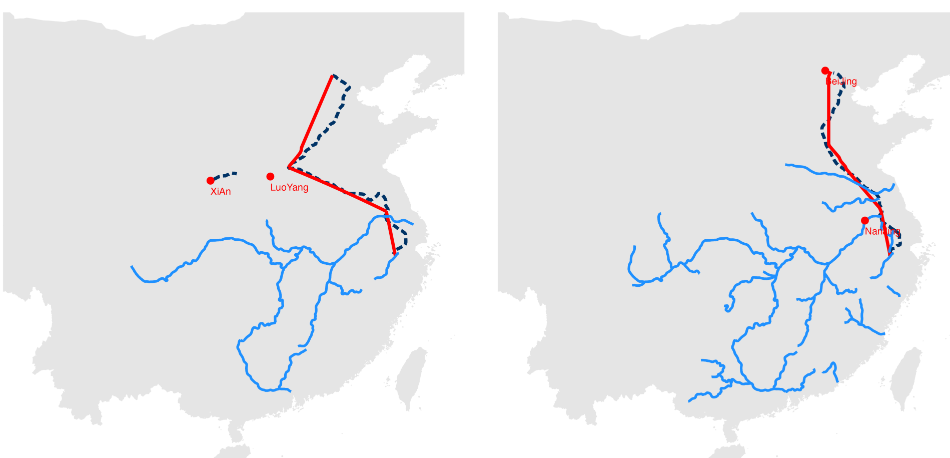
We finally obtained a nine-year panel data covering market access and economic development from the Tang Dynasty to the Qing Dynasty. Table A.2 lists the summary statistics and sources of the variables employed in the baseline estimation.

IV National Capital Relocation and Canal Redefinition

We examine whether the national capital relocation led to the canal redefinition. The purpose of the Grand Canal is to transport tax, grains, and other resources from the economic developed region (the south), to the national capital, and also transport resources from the national capital to military important region (the north). When the national capital was relocated, the optimal route among the economic region (the south), military important region (the north), and national capital will change. Then, we empirical test whether the optimal routes to the national capital could predict the actual canal route.

Since the excavation of the canal needs to go around mountainous areas, we cannot directly use a straight line as the best canal route. Therefore, we first obtain the maximum elevation of the Grand Canal based on the current Digital Elevation Model (DEM) map and define areas with elevations higher than that as mountainous areas. We then create a shortest path in the non-mountainous region passing through some specific points (the northern starting point, the turning point in the Central Plains before the Yuan Dynasty, the southern points Yangzhou and Hangzhou) as the optimal canal route for each dynasty. The details on drawing the optimal route are shown in Appendix A.C. As one example, we compare the actual Grand Canal and the optimal route for the Song and Ming dynasties (Figure 5). The red line is the optimal route and the blue dotted line is the actual Grand Canal, and the optimal route matches the canal very well. Therefore ,the actual Grand Canal can be regarded as the optimal route connecting northern regions, southern regions and national capital. Figure A.4 displays the maps of the optimal routes and actual waterways for all dynasties.

Figure 5: Optimal Routes to the National Capital and Actual Grand Canal



(a) Tang (b) Ming

Notes: The blue lines are waterways, the dashed lines are the actual Grand Canal, the red lines are optimal canals to national capital. The red points are national capitals in each dynasty.

In order to rigorously test the association between optimal and actual waterway routes, we further examine the impact of optimal route length/passage on actual waterway length/passage in each grid based on the following specification:

$$Waterway_{it} = \alpha_0 OptimalRoute_{it} + \sum_{t=1}^{t=9}(Z_i \times I_{\rho=t})\gamma^{\rho} + \lambda_t + \eta_t + \epsilon_{it} \quad (2)$$

Table 1 shows the estimation results. The results in columns (1)-(4) show a large and significant positive relationship between the optimal waterway length and actual waterway length, even with the various control variables. Specifically, as shown in column (4), 1 km increase in the optimal water route lead to approximately 0.9km increase in the actual waterway. Columns (5)-(8) show similar results for the two route passages in the grid. Combined with the route comparison in Figure 5, we can affirm that the optimal routes we created confirm to the actual water routes to a large extent.

Table 1: Optimal Route to National Capital and Actual Waterway

Dependent variable	Waterway Length				Waterway Cross			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Waterway Length (DEMcanal)	0.905***	0.868***	0.877***	0.868***				
	(0.037)	(0.044)	(0.043)	(0.044)				
Waterway Cross (DEMcanal)					0.846***	0.819***	0.822***	0.822***
					(0.038)	(0.042)	(0.042)	(0.041)
Grid FE	Y	Y	Y	Y	Y	Y	Y	Y
Dynasty FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl1 × Dynasty FE		Y	Y	Y		Y	Y	Y
GeoControl2 × Dynasty FE			Y	Y			Y	Y
AgriControl × Dynasty FE				Y				Y
R-squared	0.960	0.964	0.963	0.964	0.947	0.949	0.950	0.951
Observations	1,805	1,805	1,805	1,805	1,805	1,805	1,805	1,805

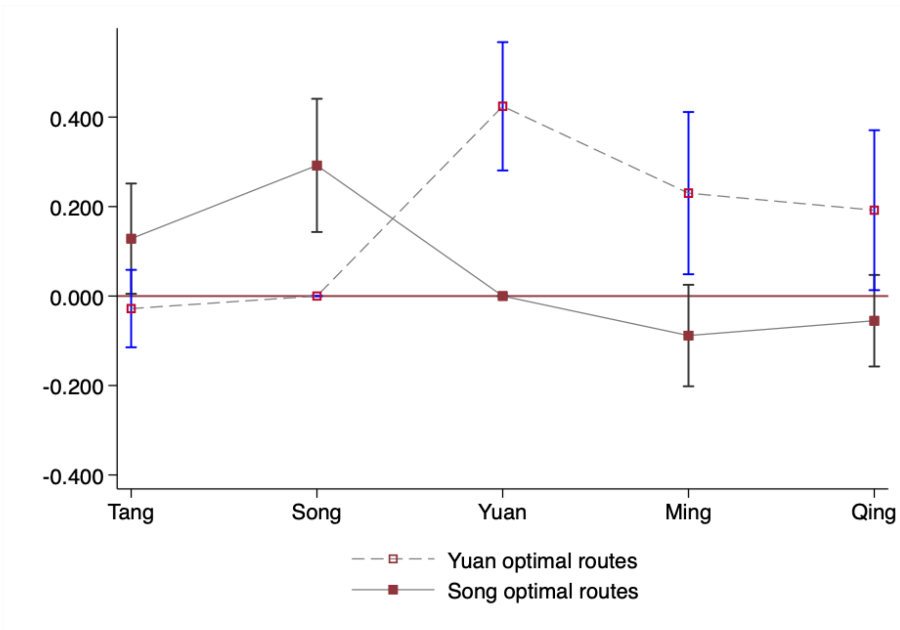
Note: GeoControl1 includes the grid's average slope, elevation, grid area, and centroid longitude and latitude; GeoControl2 includes whether the grid has plains, major rivers, whether it is located on the coast, the macro-region it belongs to; AgriControl includes suitability of wheat, rice, fox millet, maize and sweet potato; Standard errors displayed in parentheses are clustered at grid level. ** $p < 0.01$, * $p < 0.05$, $p < 0.1$.

An Event Study. The most striking change in the waterway happened during the Song-Yuan transition, since the national capital moved from the central to the north. Then, we define $OptimalRoute_{i,Song}$ and $OptimalRoute_{i,Yuan}$, and examine its impact on waterway over time based on the following specification:

$$\begin{aligned} Waterway_{id} = & \sum_{d=1}^{d=5}(OptimalRoute_{i,Song/Yuan} \times I_{\rho=d})\alpha^{\rho} \\ & + \sum_{d=1}^{d=5}(Z_i \times I_{\rho=d})\gamma^{\rho} + \lambda_i + \eta_d + \epsilon_{id} \end{aligned} \quad (3)$$

As Figure 6 shows, the influence of the optimal route to the Song national capital decreased when the national capital moved from the central plain to Beijing. In contrast, the optimal route to Beijing is more likely to predict the waterway since the Yuan dynasty, while it is not the case during the Tang and Song dynasties. It suggests that the grid along the optimal route to the Song national capital is less likely to have the waterway when the national capital move from the central China to Beijing, while the grid along the optimal route to the Yuan national capital become more likely to have the waterway since the national capital relocation.

Figure 6: Effects of Song-Yuan Optimal Routes to the National Capital



Notes: The solid line represents the effect of Song optimal routes on the actual waterway by dynasty, while the dashline represents the effect of Yuan optimal routes.

We then construct a market access index which is relatively exogenous to artificial route selection and population changes. Specifically, we use the optimal water routes to replace the actual transportation networks, and use the total caloric suitability which captures the potential crop yield in calories to proxy for population in each grid, which has following specification:

$$MA_{i,t}^{opt,csi} = \sum_{d \neq t} \tau_{id,opt,t}^{-\theta} CSI_{d,t}$$

where $\tau_{od,opt}$ refers to the trade cost along the optimal water transportation network, and

CSI_d is the sum of CSI values in grid d. We examine the impact of this CSI-optimal-waterway-based market access index on the actual market access using the following specification:

$$\ln MA_{it} = \alpha \ln MA_{it}^{opt,csi} + \sum_{t=1}^{t=9} (Z_i \times I_{\rho=t})\gamma^{\rho} + \lambda_t + \eta_t + \epsilon_{it} \quad (4)$$

Table 2 examines whether the CSI-based market access for optimal water networks can capture the characteristics of market access for the entire transportation networks. The results show that, the relative exogenous market access has a significant positive impact not only on population-based baseline market access, but also on CSI-based baseline market access.For the complete specifications shown in the columns (4) and (8), a 1% increase in CSI-optimal-waterway-based market access leads to approximately 0.5% increase for both population-based and CSI-based market access.Therefore, the optimal water networks and CSI are reliable indicators of actual transportation networks shown in Figure 2 and actual population in each grid. The results are robust to market access with different values of θ and different cost rate parameters as shown in Table B.1.

Table 2: Market Access based on Optimal Route and Actual Market Access

Dependent variable	lnma(Rawroute,Popu-based)				lnma(Rawroute,CSI-based)			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
lnma(DEMcanal,waterway,CSI)	0.638***	0.568***	0.539***	0.518***	0.555***	0.508***	0.492***	0.470***
	(0.045)	(0.049)	(0.048)	(0.049)	(0.037)	(0.044)	(0.043)	(0.044)
Grid FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl1 × Year FE		Y	Y	Y		Y	Y	Y
GeoControl2 × Year FE			Y	Y			Y	Y
AgriControl × Year FE				Y				Y
R-squared	0.860	0.884	0.893	0.904	0.845	0.865	0.872	0.885
Observations	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249

Note: Control variables are same as those listed in Table1. Standard errors displayed in parentheses are clustered at grid level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

V The Impact of Market Access

For the impact of market access on population density, we begin by regressing the log of population density in grid i and year t on log market access as the following specification:

$$\ln PopDensity_{it} = \beta \ln MA_{it} + \sum_{t=1}^{t=9} (Z_i \times I_{\rho=t})\gamma^{\rho} + \lambda_i + \eta_t + \epsilon_{it} \quad (5)$$

in which Z_i is a set of control variables on grid's time-invariant geographical conditions and agricultural suitability as described in section III.B. Given that population and artificial route selection might be endogenous, we further use $\ln MA_{it}^{opt,csi}$ as the instrument variable for $\ln MA_{it}$, as shown in Equation 4, to identify its impact on logged population density.

V.A Baseline Results

Table 3 reports our baseline result with Ordinary Least Square (OLS) and Instrumental Variable (IV). Market access is estimated to have a large and statistically significant impact on population density with only grid and year fixed effects: a 1% increase in market access increases population density approximately by 0.18% (column (1)). Columns (2)-(4) show the OLS estimation results with adding the control variables on geographical environment and agricultural suitability step by step. The estimated impact of market access decreases slightly from 0.18% (column (1)) to around 0.14% (column (4)), showing that the impact of market access is stable under different control variables. Columns (5)-(8) reports the two-stage least square (2SLS) estimations. The impact of market access on population density remains significantly positive. In terms of magnitude, taking the complete setting of specifications in column (8) as an example, a 1% increase in market access will lead to an increase in population density of approximately 0.14%, which is trivially different with the OLS estimate.

Table 3: Effect of Market Access on Population Density

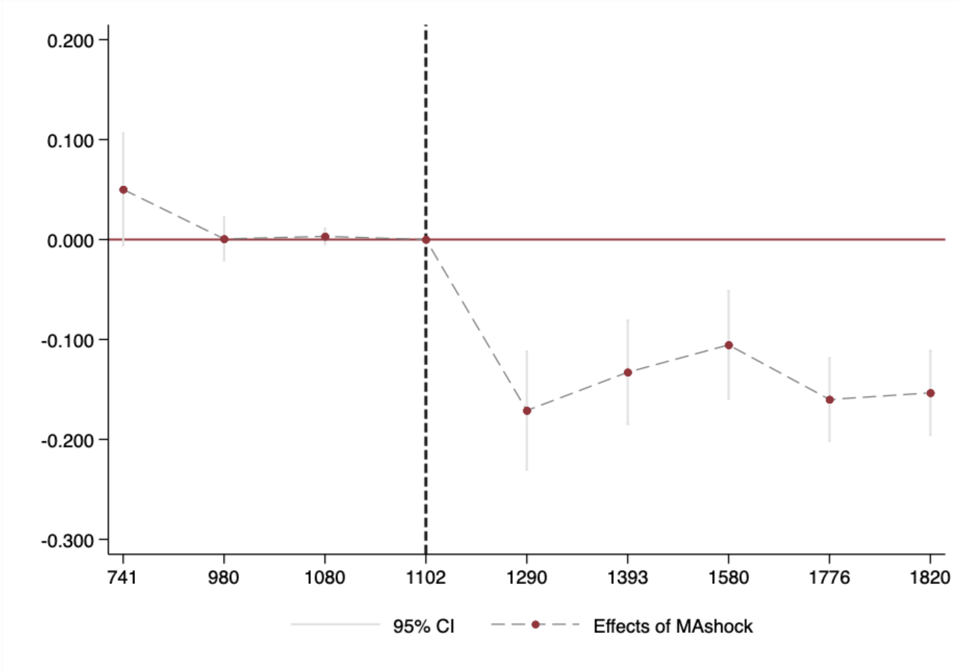
Dependent variable	ln(Population Density)							
	OLS				IV:2SLS			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
lnma(rawroute,popu-based)	0.175***	0.162***	0.150***	0.137***	0.115***	0.145***	0.136***	0.143***
	(0.020)	(0.016)	(0.016)	(0.017)	(0.039)	(0.035)	(0.039)	(0.043)
Grid FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl1 × Year FE		Y	Y	Y		Y	Y	Y
GeoControl2 × Year FE			Y	Y			Y	Y
AgriControl × Year FE				Y				Y
R-squared	0.805	0.871	0.879	0.891	0.064	0.071	0.060	0.051
Observations	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249

Note:Control variables are same as those listed in Table1. Standard errors displayed in parentheses are clustered at grid level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

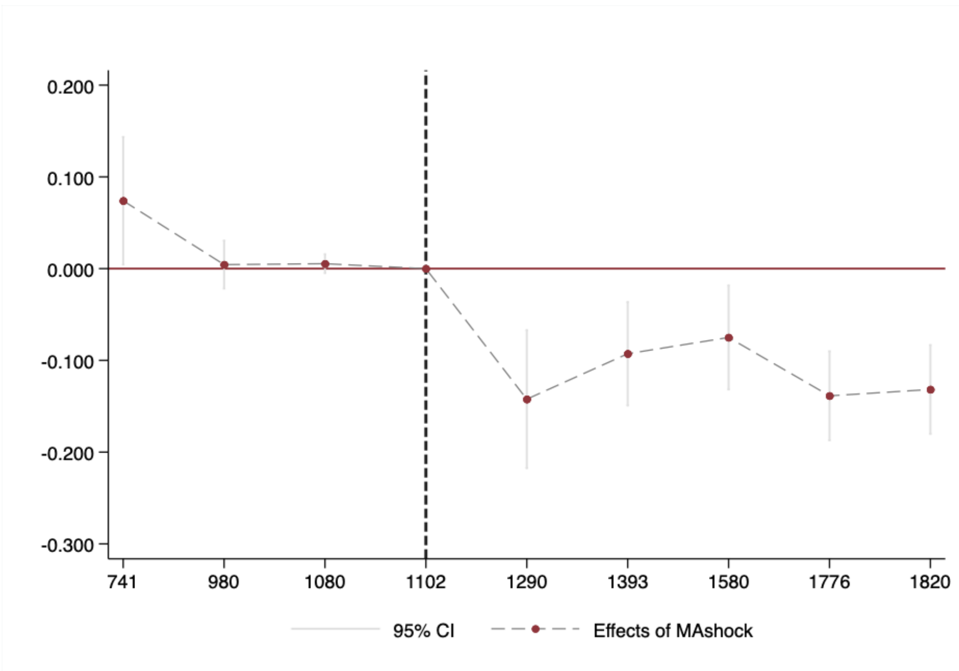
Varying Parameters Table B.2 shows the result is robustness to market access with different values of θ (the "trade elasticity") and alternative transportation cost settings. In columns (1) to (6), we set different values of θ for market access taken by other empirical researches as mentioned in Section III.A.3, while hold the transportation costs for each route type unchanged. Specifically, we set $\theta = 1$, 3.6, 8.22, 8.98, 9.64 and 12.86, respectively, corresponding to the range of possible θ values [3.60-12.86] in Eaton and Kortum (2002), the θ value 8.22 taken by Donaldson and Hornbeck (2016), and the 95% confidence interval [8.98-9.64] for our estimated θ value 9.22. Columns (7) to (11) adopt alternative cost parameters in Table A.1,as described in Appendix A.B.1, and keep the value of θ at 9.22. Regardless of the changes in θ values or transportation costs, the positive relationship between the market access and population density remains robust.

Market Access shock and Event Study We have shown that increased market access can promote population density. So to what extent the population density is affected by the sudden change of market access caused by the shortening of the Grand Canal after Song Dynasty? To answer this question, we first define "market access shock" as actual market access in 1102 minus that in 1290, which is equivalent to the negative of market access difference between 1102 and 1290 shown in Figure 4a. Theoretically, the shock should only have impact on the population density after the Song Dynasty. To examine the parallel trends in the effects, we interact the market access shock with a full set of period dummies, and display the estimated coefficients of market access shock in each sample year in Figure 7a. The impact of market access shock does not show a clear pre-trend before 1102, and suddenly becomes negatively significant in 1290 with a magnitude of 0.171. The impact then rebounds to -0.133 in1393 and keeps between -0.2 and -0.1 in the subsequent sample years, indicating the impact is permanent.

Figure 7: Dynamic Effects of Song-Yuan Market Access Shock



(a) Population-based market access shock



(b) CSI-based market access shock

Notes: The solid line represents the effect of Song-Yuan market access shock on population density.

Market access shocks may come from two sources, one is the shortening of the Grand Canal, which is of our interest; the other is endogenous demographic changes related to wars, trade costs and in local political status. To extract the part of impact caused by the rerouting of the Grand Canal, we use the pre-1500 CSI to represent the population in the construction of the market access shock from 1102 to 1290. The annual impact of CSI-based market access shock is shown in Figure 7b. The trend of the impact is similar to that in Figure 7a, without a clear pre-trend before 1102, becomes significant negative at around -0.15 in 1290, and fluctuates between -0.2 and -0.05 in the following periods. The persist negative impacts of CSI-based market access shock reflect that, change in canal routes has a permanent negative effect on population density in ancient China through changing market access.

The Impact of Sino-nomadic War The determination on shortening the Grand Canal may depends on two historical events. The first one is the relocation of the national capital from Kaifeng to Beijing from the Yuan Dynasty. The Grand Canal is aimed at transporting tribute grains to northern national capital, it is not necessary to go through the Central Plains as the political center shifted to Beijing. Second, frequent wars occurred before the founding of the Yuan Dynasty, which led to a sharp decline in the population of the Central Plains. Therefore, it is not valuable to build a canal through the Central Plains. Based on the history of the Mongol conquest described in Section II.B, in this section we focus on the wars between AD 1211 and 1279, which can change market access and population density by reducing the population. We measure the warfare in terms of the number of wars occurred in each grid during 1211-1279, and the number of deaths measured by the difference in the logarithm of population between the year 1102 and 1290.

Table 4 shows the results with the control of warfare shocks between AD1211-1279. As shown in column (2), one additional war will decrease the population density by 2.6% after the year 1102, but the negative impact of the number of wars is not statistically significant. At the same time, column (3) indicates that 1% increase in death tolls during the war can significantly decrease the population density by 0.21% after the year 1102. Furthermore, when controlling for the number of deaths, the estimated coefficient of market access drops significantly from 0.137 to 0.094, while controlling for the number of wars has no impact on the estimate of market access. We finally control for both two variables on the war shock in the column (4) and find that the negative effect of the number of deaths holds in both significance level and magnitude, while the negative effect of the number of wars disappears. But the most noteworthy point is that, the positive effect of market access on population density persists even if its magnitude decreases from 0.14% to 0.09%, while the IV estimates only decreases from 0.14% to 0.12%.

Table 4: The Role of Sino-nomadic War

Dependent variable	ln(Population Density)							
	OLS				IV:2SLS			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
lnma(raw route,popu)	0.137***	0.136***	0.094***	0.094***	0.143***	0.144***	0.122***	0.122***
	(0.017)	(0.017)	(0.017)	(0.017)	(0.043)	(0.043)	(0.039)	(0.039)
post1102 × number of wars		-0.026		0.008		-0.026		0.007
		(0.021)		(0.019)		(0.021)		(0.019)
post1102 × death tolls			-0.213***	-0.214***			-0.204***	-0.206***
			(0.035)	(0.036)			(0.035)	(0.036)
Grid FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl1 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl2 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
AgriControl × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
R-squared	0.891	0.891	0.900	0.900	0.051	0.052	0.125	0.126
Observations	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249

Note: Control variables are same as those listed in Table1. Standard errors displayed in parentheses are clustered at grid level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

CSI Based Market Access Baseline market access is based on the population in each grid. For robustness and to mitigate the endogeneity to the grid population, we use the Caloric Suitability Index (CSI) provided by Galor and Özak (2016), to indicate the population that the grid can support, denoted by $MA_{i,t} = \sum_{d \neq i} \tau_{id,t}^{-\theta} CSI_{d,t}$. Table B.3 shows that CSI-based market access has a significantly positive effect on population density. In terms of magnitude, 1% increase in market access leads to 0.10% increase in population density (column (1)). With the consideration of the role of Sino-nomadic War, a 1% increase in CSI-based market access leads to approximately 0.07% significantly increase in population density (column (4)).When instrumented by the optimal-route-based market access across columns (5) to (8), the impacts of CSI-based market access remain robust. In addition, the effects of Sino-nomadic War is also similar to that in the table 4, that the negative effect of the number of deaths keeps in both significance level and magnitude, while the number of wars has no effect.

V.B Robustness Checks

The Role of Provincial Capital We also explore whether the political status of provincial capital can affect the local market access by improving regional transportation network, and thereby increasing local population density. We follow Bai and Jia (2023) and include the dummy variable indicating whether a provincial capital is located in the grid. The results in Table B.4 demonstrate that, being a provincial capital can significantly increase local population density by approximately 25% (column (4)), but cannot effectively explain the positive impact of market access on population density. This shows that provincial capital status has limited effect on the development of local transportation network, including the new route of the Grand Canal.

The Length of Routes We further concern about the endogenous selection of land routes, which may cause spurious relationship between population density and market access. Although the route selection may by determined by some exogenous factors such as politics, terrain and connecting big cities, it may also prefer to pass through the prosperity regions. We therefore study changes in market access orthogonal to changes in artificial routes in and around the grid, by controlling the length of land routes in and around each grid. results are reported in Table B.5, where column (1) repeats the OLS result with the control of Sino-nomadic-war-related variables (column (4) in Table 4) as a basis for comparison. Column (2) controls for the length of land routes in each grid. Columns (3) and (4) add controls on the length of land routes in the neighbor grids and neighbor's neighbor grids, respectively. The estimated impact of market access on population density decreases slightly with increasing control on land routes, from 0.094 to 0.081, and remains statistically significant. Meanwhile, the 2SLS estimations are robustness to the Table 4 with the inclusion of land route length in and around the grid, as shown across columns (5) to (8).

Alternative Optimal Route to National Capital We define different type of optimal route to construct the instrumental variable to check the robustness of the results. We first obtain the canal route with the least travel time by introducing the Human Mobility Index (HMI) provided by Özak (2018). Specifically, HMI estimates potential minimum travel times (in hours) around the world, taking into account human biological limitations, as well as the geographic and technological factors that determined travel times before the widespread use of steam power (Figure A.5). Second, we directly take the shortest straight-line (STL) path connecting major locations as an approximation of the Grand Canal, without considering elevation issues (Figure A.6). Although these optimal routes are not as precise as the baseline optimal routes shown in Figure5, they can predict the actual canal routes to a certain extent. Table B.6 shows the IV estimations of these two instrumental variables with alternative optimal canal routes. Specifically, columns (1)-(4) show the impact of market access instrumented by HMI-based optimal canal routes, and columns (5)-(8) show the impact of market access instrumented by STL-based optimal canal routes. For both alternative IV estimations, the positive impact of market access on population density persists at 0.15%-0.16% with the complete controls (columns (4) & (8)), similar to the magnitude of baseline IV estimates shown in the column (8) in Table 4. In addition, the first-stage results suggest that both of the market access based on HMI-optimal canal routes or shortest straight-line canal routes are credible predictors of the market access based on actual transportation network. Therefore, the impact of market access on population density is robust to these alternative instrumental variables.

Market Access beyond Adjacent Grids It is possible that some local economic factors may affect both market access and economic development. To rule out this concern, we use the measure of market access only to the regions beyond surrounding grids. Such market access mainly reflects trade with more distant regions, which reduce the potential for bias from local shocks increasing both access to local markets and economic prosperity. Empirically, we first measure the market access to the regions beyond the neighbor grids (About100km, Table B.7), then we measure the market access to more distant regions beyond the neighbor's neighbor grids(About 200km, Table B.8). In both two tables, the positive effects of market access on population density are hold at same significance level compared with the baseline Table 4, although the magnitudes decline to approximately 0.04% (column (4) in Table B.8). The results suggest that, the market access to further regions still accounts for the increase in local population density to a certain extent.

VI A Spatial Model and Counterfactual Analysis

VI.A A model of Trade among grids in ancient China

We set up a trade model follows Eaton and Kortum (2002) and Donaldson and Hornbeck (2016), with the immobile production factor land and the mobile factors labor and capital. The economy consists of many trading districts (grids), where the origin of a trade is indexed by o and the destination by d. Each district produces varieties with a Cobb-Douglas technology using land (T), labor (L), capital (K)[3] , and an exogenous productivity shifter $z_o(j)$ drawn from a Fréchet distribution[4] (Eaton and Kortum (2002)).With perfect competition assmption, price of each variety j equals to its marginal producing cost $p_o(j) = MC_o(j) = \frac{q_o^\alpha w_o^\gamma r_o^{1-\alpha-\gamma}}{z_o(j)}$, where q_o is the land rental rate, w_o is the wage, and r_o

[3] $x_o(j) = z_o(j)(T_o(j))^\alpha (L_o(j))^\gamma (K_o(j))^{1-\alpha-\gamma}$

[4] z_o with CDF $F_o(z) = \Pr[Z_o \leq z] = \exp(-A_o z^{-\theta})$, where $\theta > 1$ captures the standard deviation of productivity, corresponding to the scope of comparative advantage, and A_o is a grid's state of absolute technology advantage.

is the interest rate[5]. The trade model is based on "iceberg" cost, for one unit of a good to reach destination d, $\tau_{od} \geq 1$ units must be shipped from origin o. This implies the price of a good produced at location o and sold at location d should be $p_{od}(j) = \tau_{od} p_{oo}(j)$. Besides, Consumers have CES preferences over a continuum of differentiated goods j in our model [6].

VI.A.1 Consumer Price Index and Trade Flow Gravity Equation

Based on the above model setting, Eaton and Kortum (2002) derives two important equations. One is the consumer CES price index (P_d) in destination location d :

$$P_d^{-\theta} = \kappa_1 \sum_o [A_o(\tau_{od} q_o^\alpha w_o^\gamma)^{-\theta}] \equiv CMA_d \tag{6}$$

Donaldson and Hornbeck (2016) refers this price index as Consumer Market Access (CMA_d), it measures district d's access to cheap goods.

Another one is a gravity equation describing the trade flow X_{od} from o to d,

$$X_{od} = \kappa_1 A_o (q_o^\alpha w_o^\gamma)^{-\theta} Y_d CMA_d^{-1} \tau_{od}^{-\theta} \tag{7}$$

VI.A.2 Market Access and Population

Summing the gravity equation over destinations d and assuming that goods markets clear yields total income of origin o,

$$Y_o = \sum_d X_{od} = \kappa_1 A_o (q_o^\alpha w_o^\gamma)^{-\theta} \sum_d [\tau_{od}^{-\theta} CMA_d^{-1} Y_d] \tag{8}$$

Donaldson and Hornbeck (2016) define "firm market access" of district o as $FMA_o \equiv \sum_d \tau_{od}^{-\theta} CMA_d^{-1} Y_d$. If trade costs are symmetric, FMA and CMA must satisfy $FMA_o = \rho CMA_o = MA_o$ for $\rho > 0$. MA_o is "market access" in district o. Then, we get

$$MA_o = \rho \sum_d \tau_{od}^{-\theta} MA_d^{-1} Y_d \tag{9}$$

[5]Following Donaldson and Hornbeck (2016), we assume the capital is perfectly mobile so that the return to capital is equalized across all grids in the same period (i.e., $r_o = r$)

[6]The indirect utility of a consumer with income y_o and facing prices P_o is$V(P_o, y_o) = \frac{y_o}{P_o}$,where P_o is a CES price index of the form $P_o = \left(\int_j p_o(j)^{1-\sigma} dj\right)^{\frac{1}{1-\sigma}}$.

and Equation (3) for Y_o becomes[7]

$$Y_o = \kappa_1 A_o (q_o^\alpha w_o^\gamma)^{-\theta} MA_o \tag{10}$$

Assuming mobile labor, the real wage and utility are equalized across locations ($\bar{U} = W_o/P_o$). With the income share of Land (α) and Labor (γ) in Cobb-Douglas production function[8], Equation (5) can be written as[9]:

$$\ln L_o = \kappa_2 + \frac{1}{1+\theta\alpha}\ln A_o + \frac{-1-\theta(\alpha+\gamma)}{\theta(1+\theta\alpha)}\ln \bar{U} + \frac{-\theta\alpha}{1+\theta\alpha}\ln T_o + \frac{1+\theta(1+\alpha+\gamma)}{\theta(1+\theta\alpha)}\ln MA_o \tag{11}$$

And Equation (4) derives the relationship between MA_o and MA_d[10] :

$$MA_o = \kappa_3 \sum_d \tau_{od}^{-\theta} MA_d^{-(1+\theta)/\theta} L_d \tag{12}$$

VI.A.3 θ Estimation

As presented in Equation (6), in time t, we have $lnL_{ot} = f(\theta)_{ot} + \epsilon_{ot}$, where $f(\theta)_{ot} = \frac{1+\theta(1+\alpha+\gamma)}{\theta(1+\theta\alpha)} lnMA(\theta)_{ot}$. $MA(\theta)_{ot}$ is decided implicitly by Equation (7) given the trade cost matrix τ_{od},population L_d and θ at time t. This is a NLS problem because $f(\theta)_{ot}$ is nonlinear in the parameter θ. Besides, we assume ϵ_{ot} is orthogonal to $f(\theta)_{ot}$ conditional on a set of control on geographical and agricultural factors as described in Section III. We obtain the NLS best fitted θ using a grid search over θ based on an evenly spaced grid with 300 points. Following the existing papers, we use $\alpha = 0.19$ and $\gamma = 0.60$ as land and labor shares to compute $f(\theta)_{ot}$ (Caselli and Coleman (2001); Donaldson and Hornbeck (2016)). As shown in Figure C.1, the θ with least RSS value is 9.22. And its 95% confidence interval is [8.98-9.64] based on bootstrapping at the grid-level, with 300 replications (the distribution of theta values as shown in Figure C.2) .

VI.A.4 Model-Derived MA vs. Simple Approximation

Table 5 compares the impacts of model-derived and simple approximated market access on population density. In columns (1) and (2), the OLS estimates for the impacts on

[7] $\kappa_1 = \mu^{-\theta}\gamma^{-(1-\alpha-\gamma)\theta}, \mu = \left[\Gamma(\frac{\theta+1-\sigma}{\theta})\right]^{\frac{1}{1-\sigma}}$

[8] $q_o T_o = \alpha Y_o, w_o L_o = \gamma Y_o$

[9] $\kappa_2 = \frac{\theta\alpha}{1+\theta\alpha} ln(\gamma\alpha) + \frac{-1-\theta(\alpha+\gamma)}{\theta^2(1+\theta\alpha)} ln\rho + \frac{1}{1+\theta\alpha} ln\kappa_1$.

[10] $\kappa_3 = \rho^{\frac{1+\theta}{\theta}} \frac{\bar{U}}{\gamma}$.

population density show a significant difference. We first eliminate the discrepancy caused by potential endogeneity bias through the IV estimations. As shown in columns (3) and (4), the estimation difference narrows by approximately 80%. Then we adjust the bias arising from the magnitude incomparability between the model-derived and the simple approximated market access. With standardization, the IV estimated impact of model-derived market access in column (8) is consistent with that of the calculated market access in column (7) , supporting the reliability of the counterfactual estimates derived from model-derived market access.

Table 5: Model-derived MA vs. Simple Approximation

Dependent variable	ln(Population Density)							
	UnStandardized Market Access				Standardized Market Access			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Baseline	Model-derived	Baseline	Model-derived	Baseline	Model-derived	Baseline	Model-derived
	OLS		**2SLS**		**OLS**		**2SLS**	
lnma(rawroute,popu-based)	0.137***	1.541***	0.143***	0.505***	0.309***	1.113***	0.342***	0.378***
	(0.017)	(0.058)	(0.043)	(0.130)	(0.039)	(0.043)	(0.100)	(0.093)
Grid FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl1 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl2 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
AgriControl × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
R-squared	0.891	0.964	0.051	0.377	0.891	0.962	0.047	0.376
Observations	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249

Note: Control variables are same as those listed in Table1. Standard errors displayed in parentheses are clustered at grid level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

VI.B Counterfactual Analysis

As in Donaldson and Hornbeck (2016), the counterfactuals can be solved by either assuming $\bar{U}$ is constant across counterfactuals and the total population adjusts, or the total population is constant and $\bar{U}$ adjusts. We are interested in the impact of market access on population density in our paper, so we focus on the first case, which allows for population mobile and require utility $\bar{U}$ is constant (Specifically, we assume $\bar{U} = 1$). We solve the model for population with different counterfactual Grand Canal as shown in Appendix C.B. Briefly, we first back out the constant unobserved factors including productivity A_o and land T_o. Then we can estimate the new population with counterfactual trade cost and constant terms through our model.

We first assume that there is no Grand Canal. Specifically, we drop the Grand Canal from our transportation network, and estimate the counterfactual population under this assumption. The counterfactual estimates are shown in the "Counterfactual 1" in Table 6. We can see that, without the Grand Canal, the population will aggregately decrease by 4% ~11% in different years. Then we further assume that if there was no Grand Canal, the empire's investment in overland infrastructure would increase, and thus the cost of land transportation would decrease. We first assume that the land cost dropped by 20%, to about 0.772 tons/1,000 kilometers, and the results show that this could only compensate for 4% of the population reduction caused by the removal of the Grand Canal. We further reduce the land cost by 40%, and the counterfactual estimation show that this could compensate for the total population reduction caused by the disappearance of the Grand Canal. The land transportation cost declines 40% indicates that the travelling speed of wagon approximately increases by 59%, from 27.5km per day to 44 km per day. From this perspective, the Grand Canal played an important role in improving transportation efficiency in ancient China.

We then assume the Grand Canal did not change its route after Song dynasty. Specifically, we assign Song's Grand Canal route to other dynasties after Song, while holding the other routes of each dynasty unchanged. As shown in Figure 2, the canal in Song connected more inner regions than the canal in Ming, therefore a larger market access is expected after Song with the counterfactual canal routes. In addition, we consider counterfactual effects in Tang. Because although the canal route of the Tang Dynasty is roughly similar to the canal route of the Song Dynasty, it is simpler and less developed. We wanted to see how the population would have changed if the canals of the Tang Dynasty are as developed as the canals of the Song Dynasty. The "Counterfactual 2" in Table 6 shows estimates of the aggregate counterfactual change in the population under this assumption. The results show that, adopting the Song Dynasty Grand Canal will increase the population density by 2.48% ~4.14% in the Tang, Ming and Qing dynasty, while decrease the population density by 3.09% in the Yuan Dynasty. The negative counterfactual population estimates in Yuan possibly because the Yuan Dynasty relied on maritime transportation, rather than the Grand Canal transportation.

Next, we assume that Tang and Song Dynasties adopted the Grand Canal in the Ming Dynasty, and show the counterfactual estimates of population in the "Counterfactual 3". The estimates indicate that, with all other routes unchanged, changing to Ming Dynasty Grand Canal will reduce the population density by 5.42% ~7.00% in the Tang and Song dynasties. Negative counterfactual estimates of population due to the shortening of the Grand Canal confirm the role of the Grand Canal route in improving market access and population density.

We further perform several other counterfactual estimates under different assumptions. The results are reported in the Table B.9. In "Counterfactual 1", we report the counterfactual estimates of population assuming that the land route cost declines 30% and 50% without the Grand Canal. We can see that, if the land route cost declines by 50%, the population will increase compared with the actual population even if abandoning the Grand Canal in each dynasty. We then report population counterfactual estimates under five other possible transport cost rate assumptions introduced in Table A.1. Besides, we also provide the predicted changes in population without the Grand Canal based on the OLS estimated impact of market access in the baseline estimation . In "Counterfactual 2" and "Counterfactual 3", we first report the counterfactual estimates considering only the waterway transportation. The population counterfactual estimates of the corresponding changes in the Grand Canal are consistent with or smaller than the baseline estimates in Table B.9. We also report the counterfactual estimates under other five transportation cost settings. With the NLS best fitted value of θ, the counterfactual estimates under different sets of cost parameters do not differ much from the corresponding base estimates in Table 6. Summarizing the above results, we can say that the Grand Canal is important for increasing market access and population density in antiquity.

Table 6: Aggregate effects of counterfactual transport networks

	Counterfactual:Percent Increase in Population (%)								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	741	*980*	*1080*	*1102*	*1290*	*1393*	*1580*	*1776*	*1820*
Counterfactual 1: Drop the Grand Canal									
Land Road Cost Unchanged	-9.21	-8.52	-8.91	-8.66	-9.49	-10.40	-10.63	-4.39	-4.37
Land Road Cost Decline 20% (0.772 ton/ton-1000km)	-5.13	-5.04	-5.48	-5.27	-5.74	-6.39	-6.42	0.43	0.41
Land Road Cost Decline 40% (0.579 ton/ton-1000km)	1.57	0.30	-0.20	-0.04	0.04	-0.34	-0.05	7.72	7.63
Counterfactual 2: Adopt Song Dynasty Grand Canal									
	2.56				-3.09	2.50	2.48	4.14	4.07
Counterfactual 3: Adopt Ming Dynasty Grand Canal									
	-5.42	-7.00	-6.83	-6.68					

Note: This table summarizes the aggregate effects of counterfactual networks with different canal routes and land route costs.

VII Conclusions

In historical China, the Grand Canal plays a central role in connecting the China north and the prosperous south, linking the capital to the key regions of the nation and solidifying the central governance. During the Sui, Tang and the Northern Song dynasties, the Grand Canal passed through the national capitals located in the central, the Henan Province today, and flowed to the south to connect Hangzhou, and to the north to connect Beijing in China. From the Yuan dynasty, the national capital was relocated to Beijing, and the Grand Canal was re-constructed to connect Beijing and Hangzhou directly, bypassing the central until it gradually fell into disuse by the late Qing dynasty. With the redefinition of the Grand Canal, the Central Plain experienced its prosperity and decline in economy and population.

By examining the historical case of China's Grand Canal redefinition in the context of the national capital relocations during 8th-19th centuries, this paper explores two key effects of political-motivated transportation networks, the benefits of enhanced market access and the potential resource misallocation. We first investigate whether the relocation of national capitals led to the shortening of the Grand Canal. We calculate the geographical optimal canal routes that connect the national capitals and the north starting point and the south end point (Hangzhou), and show that, the optimal route can predict the actual canal route effectively, that 1km increase in the optimal route lead to 0.87 km increase in the actual route. We also find that the market access based on the optimal route is significantly correlated with the market access based on the actual transportation networks.

We second examine the impact of this political-driven market access on economic development measured by population density. Our results show that, 1% increase in market access lead to 0.14% significant increase in population density. Then we use the market access based on optimal routes and CSI, which is relatively exogenous to artificial route selection and population changes , as the instrumental variable for market access. The 2SLS estimation shows the impact changes trivially. We further define the "market access shock" as the difference in market access between the Song and Yuan dynasties, and find that the abrupt change in market access triggered by the rerouting of the Grand Canal had a significant permanent negative impact on the population. The magnitude of this negative effect still persisted at approximately -0.15% by 1820.

We finally conduct a set of counterfactual analysis to examine the potential welfare misallocation of this political driven infrastructure. There are two important findings. One is the Grand Canal improved the aggregate welfare- removing all canals will lead to total population decrease by 4%-11% in different years. Another finding is, the Grand Canal redefinition due to the national capital relocations caused welfare misallocation. If Ming and Qing dynasties adopted the Song canal, which traverses the central, the total population could increase by 2.5%-4%. Conversely, if we assume the Tang and Song dynasties adopted the Ming canal which bypasses the central, the total population would decrease by 4%-7%. This paper employs market-access approach in spatial economics, allowing us to examine how politics determine the economic geography and the potential welfare misallocations.

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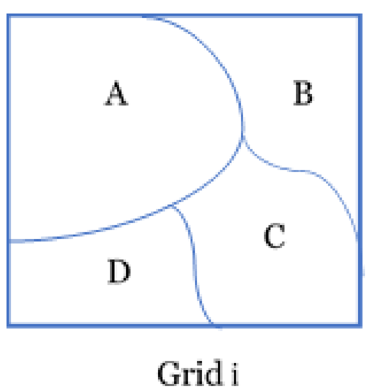
ONLINE APPENDIX

Appendix A Data Construction

A.A Grid-Level Population Density

The raw dataset is the data on prefecture's population (or household number) and area in each sample year. The population data is collected from Ge (2000) and Liang (2008). Since there are only records of prefecture's household number in Song dynasty, we simulate the prefecture's population by five times the number of households in the year 980, 1080 and 1102. The area of each prefecture is calculated based on the polygon information provided by digital maps. Some prefectures have missing population data, we fill it in with the average population density of neighboring prefectures. We repeat this process until there is no missing population density. Now we have population density and area data for each prefecture. Then we overlay the grid map with the prefecture map in each dynasty and extract the overlapping area of prefectures in each grid. For example, as the following figure shows, the grid i overlaps with four prefectures A, B, C and D. Let the overlapped area of each prefecture be $S_{i,A}$, $S_{i,B}$, $S_{i,C}$, $S_{i,D}$. The population of grid i is the sum of population of each overlapping region, that is $Popu_i = \sum_j S_{i,j} PopDensity_j$. Finally, we divide the grid population ($Popu_i$) by the grid area to get the grid population density.

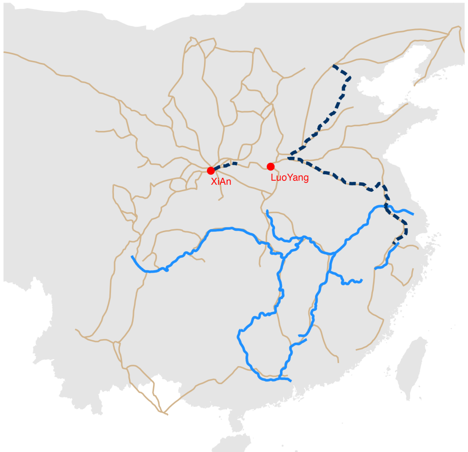
Figure A.1: Grid's Population



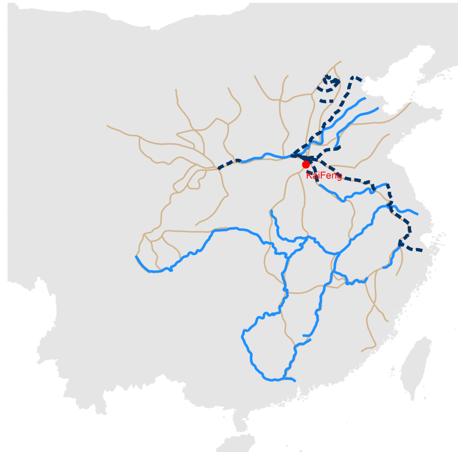
A.B Measuring Market Access

Based on the Historical Maps of China (*ZhongGuoLiShiDiTu*) (Cheng and Xu (1980)), we digitalize the maps with waterway and land routes in the Tang, Song, Yuan, Ming and Qing dynasties during 741 to 1820 into ArcGIS files. The transportation networks during these five dynasties are presented in Figure A.2.

Figure A.2: National Captial Relocation and Transportation Networks



(a) Tang



(b) Song

(c) Yuan

(d) Ming

(e) Qing

Notes: The brown lines are land routes, the blue lines are waterways, the dashed lines are the Grand Canal. The red points are national capitals in each dynasty.

A.B.1 Transportation Cost (τ_{od})

We measure the cost of trade using a simple iceberg cost (τ_{od}). Assuming that varieties produced in grid o and sold in grid o have price $p_{oo}(j)$, and varieties produced in grid o and shipped to grid d for sale have price $p_{od}(j)$, they will satisfy $p_{od}(j) = \tau_{od}p_{oo}(j)$, and $\tau_{od} \geq 1$. Specifically, we calculate our trade cost between origin o and destination d as $\tau_{od} = 1 + RouteCost_{od}$.

$RouteCost_{od}$ is the transport cost for shipping 1 unit variety from origin o to destination d, and $RouteCost_{od} \geq 0$. For the variety produced in grid o and sold in grid o, $RouteCost_{od} = 0$. We calculate $RouteCost_{od}$ by multiplying the baseline route cost rate (per ton-1000 km), with the exact distance travelled.

We take the least transportation cost routes between origin o and destination d to calculate the $RouteCost_{od}$. The routes may include different transportation modes (natural waterways, canal routes, land routes, and trails), and the route cost is the sum of the costs of the different transportation modes included.

(i) Modes of transportation As Figure A.2 shows, there are three types of routes, namley natural rivers, canals, and land routes. Moreover, we also need to connect the individual grids to the transportation routes to complete the network. Then, we additionally create the shortest straight-line paths from the centroid of each grid to the nearby waterway or land routes and treat the paths as trail routes. According to the Fogel (1964)'s adjustment factor, the mile travelled is about 1.4 times the shortest straight-line distance. Then, we have four modes of routes. Given the transportation network database, we need to break the routes into segments to permit turns at each intersection, including the intersection of water and land routes, to ensure the connectivity throughout the network. It is worthy to mention that we do not specify where the Grand Canal can switch to other land or natural waterways. In fact, Grand Canal is for tribute grain transportation, and governed by central authority. There are designated trans-shipment warehouses along the canal, such as Suzhou, Huai'an, Yangzhou, Dezhou, Linqing, etc. Grain was transported from various places to transfer warehouses, and then transported along the canal to Beijing by the transport soldiers. So actual canal shipping may be less flexible.

(ii) Trade cost rate parameter for canals According to *DaMingHuiDian* and the book *QingDaiCaoYun* Li and Jiang (1995) , we take the baseline cost rate parameter of the Grand Canal to be 0.249, which means that to transport 1 ton of grain 1,000 kilometers, 0.249 tons of grain will be consumed on the way. The specific reference are as follows.

We use Suzhou and Yangzhou—two major sources of tribute grain during the Ming and Qing dynasties—as reference points for cost calculations. We focuses on the rice consumed during transit, which primarily consists of rations for laborers and animals, and exclude the portion of surplus rice converted into silver (*YuMiZheYin*). We examine the costs associated with *DuiYun*, the method of transporting rice to Beijing's warehouses. We find that transport one ton of rice from Suzhou to Beijing (1,500 km) via the Grand Canal incurred an additional 0.4 tons of rice as transit costs. Similarly, shipping one ton from Yangzhou to Beijing (1,300 km) required an extra 0.3 tons. These costs are comparable to those of *GaiDui*, an alternative method that delivered rice only to Tongzhou's warehouses rather than Beijing's. Notably, our calculations account solely for in-transit rice consumption.

By conversion, the baseline cost parameters based on Suzhou and Yangzhou are 0.267 (0.4/1.5) and 0.231 (0.3/1.3), respectively. We take the average value 0.249 (tons per ton-1000km) as the final parameter of the baseline cost rate for Grand Canal.

(iii) Trade cost rate parameter for natural rivers The book "Mid-Ching Rice Markets and Trade: an essay in price history" Quan and Kraus (1975) records the rice price of different places along the Yangtze River during the period 1723 -1735 . The places along the Yangtze rivers shipped their rice production to Suzhou, where the rice was then transported to Beijing along the Grand Canal by officials. The book provides the distance and relative prices between each place and Suzhou, so we can estimate the transport cost along natural Yangtze River using the "Price Difference Method". The specific referred material is as follows.

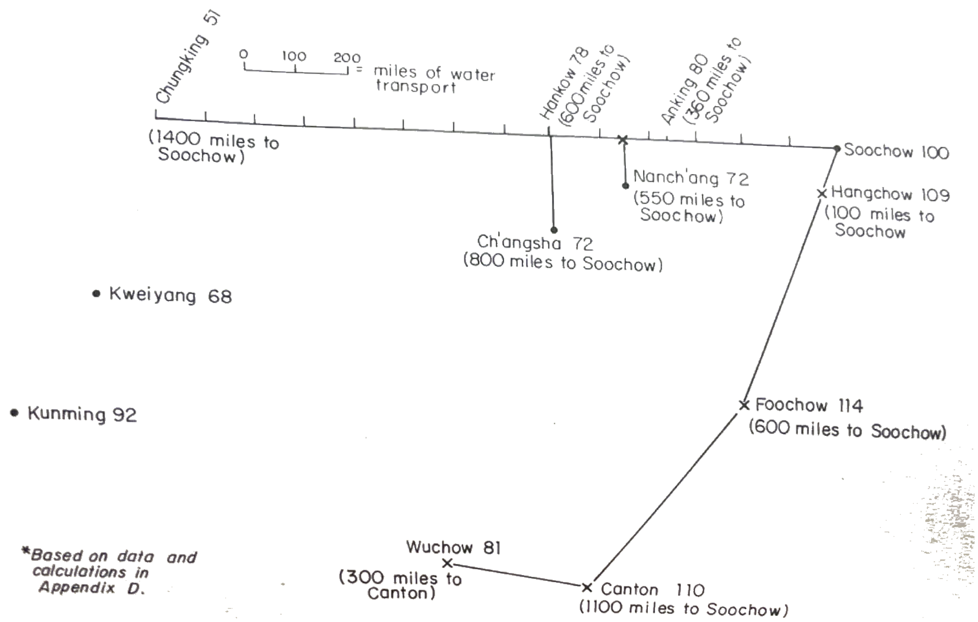


Figure 5 Estimated rice price levels in China, 1723-1735*
(100 = Soochow price level)

The places along the Yangtze River in this figure includes Chongqing, Changsha, Hankou, Nanchang, Anqing and Suzhou. The author also says, "the data for Changsha, Hankou and Suzhou are much more dense, internally consistent, and reliable than the data for Nanchang and Anqing". For accuracy, we exclude Nanchang and Anqing, only take Chongqing, Changsha and Hankou for cost rate calculation. The specific estimation formula is sliver $costrate_{od} = \frac{P_d - P_o}{P_o \times Distance_{od}}$. We calculate the sliver cost rate for each pair of cities among Suzhou, Chongqing, Changsha and Hankou, and the average value is 0.353 per ton-1000km. However, the sliver cost rate derived from price difference method includes not only the cost of grain in transit, but also all the other costs, such as loading costs, as well as the contingency and risk costs. We only care about the rice consumed during transportation, which is cost of grain in transit. We note that the figure also shows the price of rice in Hangzhou, and the Grand Canal is the main mode of grain transportation between Hangzhou and Suzhou. We can derive the cost rate of grain in transit for natural waterways by comparing the silver cost rate of natural waterway and that of canal transport between Suzhou and Hangzhou. The silver cost rate between Suzhou and Hangzhou along the Grand Canal is 0.559 per ton-1000km. Therefore, after conversion, the grain cost for natural waterway transportation is 0.249*(0.353/0.559) =0.157 tons per ton-1000 km.

(iv) Trade cost rate parameter for land routes In ancient times, most grain transport vehicles were four-wheeled or two-wheeled carriages, and the food consumed by humans and animals during transportation were carried with them. The estimation of the cost of overland transportation needs information on three parts, daily food consumption of humans and horses, daily travel distance and the load capacity. According to "*MengXiBiTan*", a person eats about 0.02 dan rice per day , which is equivalent to 1.18 kg nowadays. Besides, the book "Horse Breeding"(*YangMaXue*Husbandry and School (1979)) records that, a horse with a medium workload needs about 2kg of grain (usually beans) and 8 kg of fodder per day. In addition, a wooden-wheeled carriage with a load of 300-450 kilograms can travel 25-30 kilometers a day on ordinary mountain roads and sandy roads (*ZhongGuoMaLvPinZhongZhi*Zheng et al. (1987)) . Since the configuration of this carriage and road conditions are similar to ancient grain transportation (wooden wheels and dirt roads), we use this as a reference and assume that an ancient wooden wheel carriage with a load of 375 kg can travel 27.5 kilometers per day (average values are taken).

To assess the efficiency of ancient overland transportation, we propose the following model: Consider a 1,000-kilometer journey with post stations or markets every 100 kilometers for resupply. Under this system, carriages only need to carry provisions sufficient for 100 kilometers of travel, reducing unnecessary load.We examine a horse-drawn carriage with a load capacity of 375 kg which can cover approximately 27.5 km per day on standard dirt roads. The daily consumption rates are as follows: Horse: 2 kg of grain + 8 kg of fodder, Human (one attendant): 1.18 kg of grain. Thus, transporting goods over 100 km requires 11.56kg grain consumption (human+horse) and 29 kg fodder consumption (horse). After deducting these provisions from the initial load, 344.44 kg of grain (375 kg – 11.56 kg – 29 kg) remain for delivery at the 100 km destination. The team then replenishes 11.56 kg of grain and 29 kg of fodder at the next market to continue the journey. According to the*DaMingHuiDian*, during the *JiaJing* period of the Ming Dynasty, 1 unit of beans could be exchanged for approximately 5.74 units of fodder, providing a reference for relative food costs.

Based on the consumption rates established earlier, we compute the total grain expenditure for a 1,000-kilometer journey is (11.56+29/5.74) *1000/100 = 166.12 kg. Assuming identical consumption for the return journey, the total round-trip expenditure is 166.12*2=332.24 kilograms of grain. Meanwhile, the net delivered grain per trip remains 344.44 kg.The land route's transportation cost parameter is derived as 332.24/344.44=0.965.

(v) Trade cost rate parameter for trails For routes inaccessible to wheeled vehicles, pack animals (horses/mules) served as the primary mode of goods transport. Historical records (*MengXiBiTan*) indicate each horse/mule carried 1.5 dan (88.8 kg) of grain, moving 25 km/day (slower than a carriage). With daily consumption of 1.18 kg (human) and 4 kg of beans (pack animals, double rations due to absent fodder), a 100-km segment (4 days) required 20.72 kg of provisions. A 1,000-km round trip consumed 414.4 kg (20.72 kg $\times$ 10 segments $\times$ 2), delivering only 68.08 kg (88.8 kg initial - 20.72 kg outbound), yielding a cost ratio of 6.087 (414.4 kg/68.08 kg) - meaning 6.087 kg were expended per 1 kg delivered.

(vi) A summary of trade cost rate parameter We then determine the trade cost rate parameters for each mode of transport. There are four modes of transportation in our model, water transportation includes the Grand Canal and natural waterways, over land transportation includes land roads shown on the map and manually created straight-line trails. Based on the historical documents on relevant transportation information, we set the cost rate for natural waterway is 0.157 ton of grains per ton per 1000 km and for Grand Canal is 0.249 ton per ton-1000 km. As for land transportation, we set the cost rate for the land road is 0.965 ton per ton-1000 km, and for trails is 6.087 ton per ton-1000 km . The cost rate of natural waterways is much lower than that of the Grand Canal, since the natural waterway transport is dominated by the tides and wind power while the Grand Canal transport mainly relies on human power. At the same time, the land road transportation is dominated by horse-drawn carriages, while trail transportation relies on people and pack animals, so the cost rate of trail transportation is significantly higher than that of land road transportation. The details on the reference materials and applied methods to determine these cost rates are shown in the appendix of route cost parameters.

Table A.1: The value of τ

	Type	Route cost	Alternative route cost				
			1	2	3	4	5
1	Natural Waterway	0.157*length	0.157*l	0.157*l	0.157*l	0.157*l	0.353*l
2	Grand Canal	0.249*length	0.249*l	0.249*l	0.249*l	0.249*l	0.559*l
3	Land Routes	0.965*length	0.157*11*l	0.157*5*l	0.157*11*l	0.157*5*l	0.965*(0.559/0.249)*l
4	Trails	6.087*length	0.157*30*l	0.157*30*l	0.249*30*l	0.249*30*l	6.087*(0.559/0.249)*l

Note: Length (l) in 1000 km.

(vii) Minimum cost route We calculate the minimum transportation cost for every pair of grids by year. We first calculate the least transport cost between two grids along the transportation network using the baseline set of cost rates. But it is unreasonable to directly take this cost as the final minimum cost, because the transport cost along the network may be greater than the cost of a straight-line trail between two grids, especially for adjacent grids that are far away from the transportation network. Hence we estimate the cost of the straight-line trail between two grids, and take the smaller one of the two costs as the final cost. Finally we obtain a transportation cost matrix for each sample year.

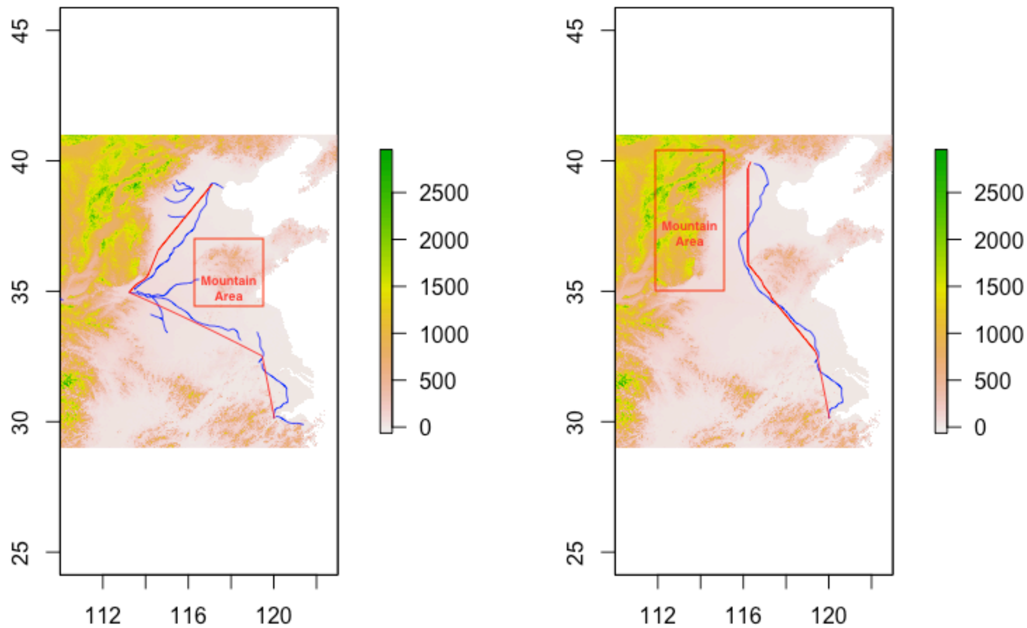
(viii) Alternative cost rates Additionally, we propose five alternative cost rates for robustness checks. Based on other relevant literature, the cost of the normal land roads is possibly to be 5 times or 11 times the cost of the Yangtze River (Quan and Kraus (1975)), and the cost rate of trails is possibly to be 30 times the cost rates of smooth water transport (Evans (1984)). Therefore, we have four other possible sets of land transportation cost. First we set the cost rates of land and trail are 11 and 30 times the cost of natural waterways, i.e., 1.727 tons/ ton-1000km and 4.710 tons/ton-1000km respectively. We then take the minimum possible values, set the cost rates of land and trail are 5.5 (0.864 tons/ ton-1000km) and 30 times (4.710 tons/ ton-1000km) the cost of natural waterways. Thirdly, We assume the cost of land roads is 11 times (1.727 tons/ ton-1000km) the cost of natural waterways, and the cost of trails is 30 times (7.47 tons/ ton-1000km) the cost of Grand Canal, that is the maximum possible cost rates of land and trail transport. The final set is assuming the cost of land roads is 5.5 times (0.864 tons/ ton-1000km) the cost of natural waterways, and the cost of trails is 30 times (7.47 tons/ ton-1000km) the cost of Grand Canal. Our estimated road and trail cost rates fall within the range of the alternative parameters, which supports the reliability of our cost rate estimates . On the other hand, we take the estimated cost rates derived from "Price Difference Method" as the one that contains all potential transport costs. Specifically, according to the record on rice prices along the Yangtze River (Quan and Kraus (1975)), we calculate the cost of canal and natural waterway are 0.559 and 0.353 per ton-1000km respectively. Due to the lack of accurate overland rice price records, we simply prorate the cost rates to 2.166 and 13.665/ton-1000 km for overland and trail transport, respectively. We verify the robustness of our results to these five sets of alternative transportation cost rates in the Appendix tables B.1 and B.2 .

A.C Optimal Grand Canal Routes Based on DEM

In the Tang and Song dynasties, the mountainous regions of eastern Shanxi may affect the alignment of the Beijing-Kaifeng Canal. Thus, we use a 500m*500m resolution DEM map to calculate the highest elevation (196 m) the Beijing-Kaifeng Canal pass through, then drop the area on the map that are higher 196m, and use the remaining part to estimate the shortest canal route for the Beijing-Kaifeng section. For Kaifeng-Yangzhou section, the straight-line canal route is taken as IV route (the highest elevation the straight-line route passes is less than 196 m). The first graph shown below is for the Optimal Canal routes in Song Dynasty. The red lines are optimal canal routes, while the blue lines are the actual Grand Canal.

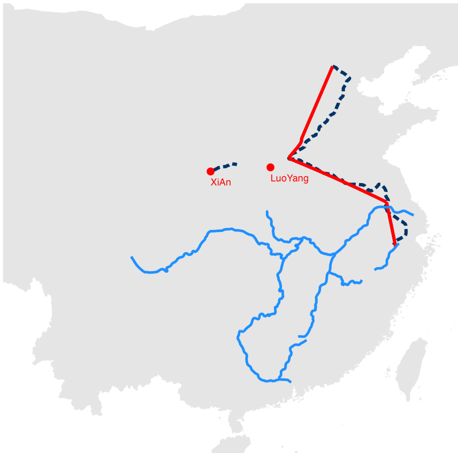
Considering that the mountainous areas in central Shandong may have an impact on the canal alignment during the Yuan, Ming and Qing Dynasties, for the Beijing-Yangzhou section, we take the shortest canal path that bypasses the mountainous areas in Shandong as the IV route after 1290. Similarly, we calculate the highest elevation (95m) that the canal passes through in Shandong, and then drop the area in Shandong higher than 95m on the map, and utilize the remaining portion to estimate the shortest canal path of the Beijing-Yangzhou section. The second graph shown below takes Ming Dynasty as example, shows the Optimal Canal routes based on DEM. The red lines are optimal canal routes, and the blue lines are the actual Grand Canal.

Figure A.3: Constructing Optimal Routes to the National Capital



Notes: The blue lines are natural waterways, the dashed lines are original Grand Canal, the red lines are Optimal Grand Canal(Based on DEM). The red points are national capital in each dynasty.

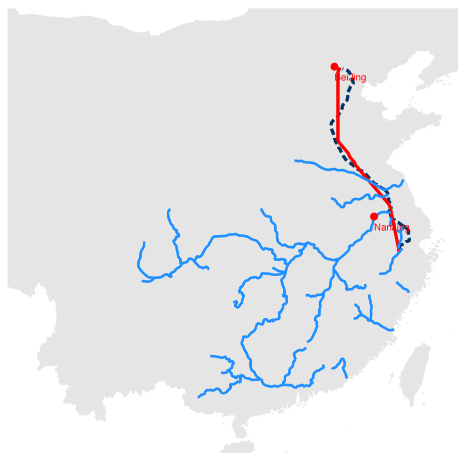
Figure A.4: Optimal Routes to the National Capital and Actual Grand Canal



(a) Tang

(b) Song

(c) Yuan



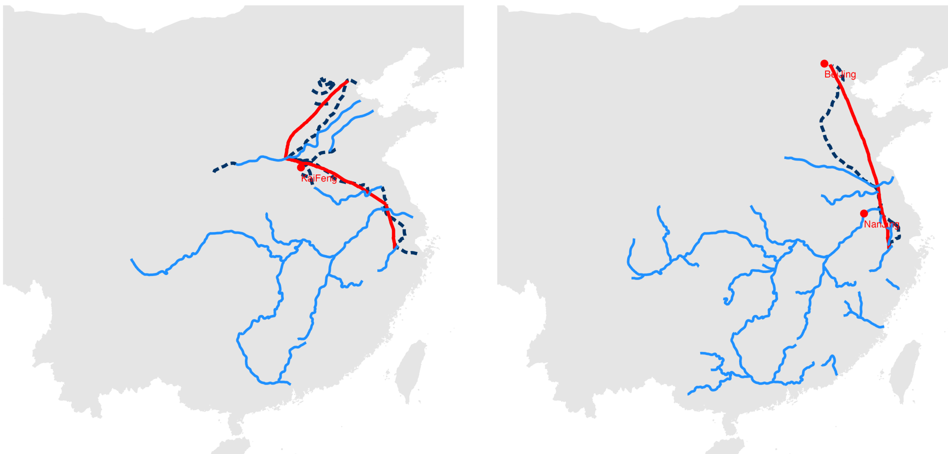
(d) Ming

(e) Qing

Notes: The blue lines are waterways, the dashed lines are the actual Grand Canal, the red lines are optimal routes to national capital. The red points are national capitals in each dynasty.

A.D Alternative Optimal Grand Canal Routes

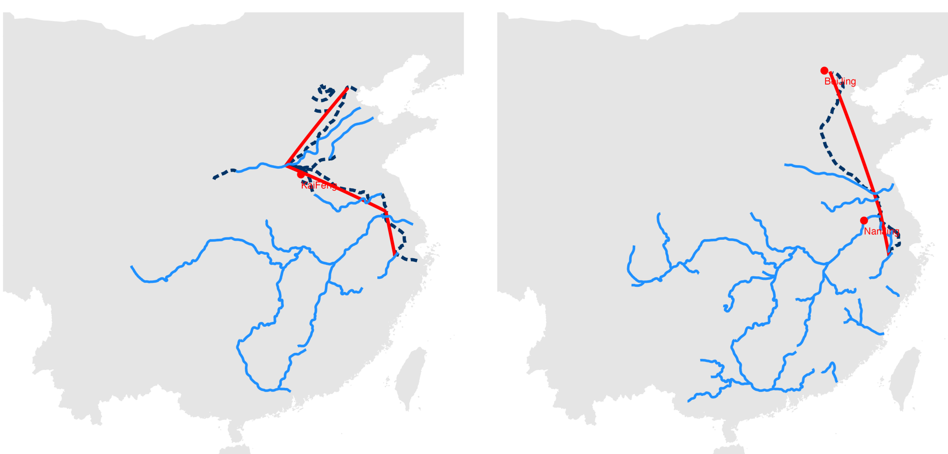
Figure A.5: Optimal Routes to the National Capital (Human Mobility Index)



(a) Song (b) Ming

Notes: The blue lines are waterways, the dashed lines are the actual Grand Canal, the red lines are optimal routes to national capital. The red points are national capitals in each dynasty.

Figure A.6: Optimal Routes to the National Capital (Shortest Straight-Line)



(a) Song (b) Ming

Notes: The blue lines are waterways, the dashed lines are the actual Grand Canal, the red lines are optimal routes to national capital. The red points are national capitals in each dynasty.

A.E Summary Statistics and Data Sources

Table A.2: Summary Statistics

Variable	Obs.	Mean	S.D.	Sources
1.Economic Outcome				
ln (Population Density)	3249	2.750	1.525	A
2. Market Access				
lnma(Rawroute, Popu-based)	3249	11.193	2.542	A,B
lnma(Rawroute, CSI-based)	3249	12.604	1.982	B,C
lnma(Waterway,DEMcanal,CSI-based)	3429	11.392	2.157	B,C
Market Access Shocks	361	-0.240	2.003	A,B
3. Waterway Cross Condition				
Waterway Length (km)	1805	28.244	55.215	B,C
Waterway Cross	1805	0.299	0.458	B,C
Waterway Length (DEM Canal, km)	1805	26.861	52.999	B,C
Waterway Cross (DEM Canal)	1805	0.285	0.452	B,C
4.War Shocks				
Death Tolls	361	0.839	1.904	A
Number of Wars	361	0.806	1.601	D
5. Geographical Control Variables				
Plain	361	0.651	0.477	E
Major river	361	0.488	0.501	E
Coastal	361	0.13	0.337	E
Slope	361	3.077	2.491	E
Elevation	361	5.932	1.558	E
Area	361	9.163	0.332	E
Longitude	361	110.996	5.855	E
Latitude	361	30.692	5.390	E
Macro region 1	361	0.025	0.125	E
Macro region 2	361	0.207	0.390	E
Macro region 3	361	0.127	0.317	E
Macro region 4	361	0.106	0.286	E
Macro region 5	361	0.179	0.358	E
Macro region 6	361	0.057	0.218	E
Macro region 7	361	0.057	0.221	E
Macro region 8	361	0.118	0.307	E
Macro region 9	361	0.124	0.315	E
6. Agricultural Control Variables				
Suitability of wheat	361	3.969	1.075	F
Suitability of rice	361	2.865	1.126	F
Suitability of maize	361	3.708	1.001	F
Suitability of sweet potato	361	3.833	1.471	F
Suitability of fox millet	361	4.53	1.078	F

Note: A: Ge (2000) & Liang (2008); B: Cheng and Xu (1980); C: Galor and Özak (2016); D:Committee (2003); E: CHGIS(2007); F: GAEZ (FAO's Global AgroEcological Zones) (2012).

Appendix B Additional Results

B.A Changing Parameters

Table B.1: Market Access Based on Optimal Route and Market Access: Changing Parameters

Dependent variable	lnma(raw route,popu-based,Different Theta)						lnma(raw route,popu-based,Different Route Cost)				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	$\theta = 1$	$\theta = 3.6$	$\theta = 8.22$	$\theta = 8.98$	$\theta = 9.64$	$\theta = 12.86$	OtherCost1	OtherCost2	OtherCost3	OtherCost4	OtherCost5
	Route Cost Unchange						**Theta Value Unchange (8.92)**				
lnma(Waterway,DEMcanal,CSI-based)	0.511***	0.518***	0.520***	0.518***	0.517***	0.514***	0.664***	0.533***	0.579***	0.485***	0.516***
	(0.042)	(0.042)	(0.049)	(0.049)	(0.049)	(0.050)	(0.044)	(0.049)	(0.046)	(0.051)	(0.049)
Grid FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl1 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl2 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
AgriControl × Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
R-squared	0.990	0.949	0.908	0.905	0.902	0.893	0.940	0.915	0.917	0.888	0.894
Observations	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249

Note: Control variables are same as those listed in Table1. Standard errors displayed in parentheses are clustered at grid level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table B.2: Impact of Market access on population density: Changing Parameters

Dependent variable	ln(population density)										
	Route Cost Unchange						**Theta Value Unchange (9.22)**				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	$\theta = 1$	$\theta = 3.6$	$\theta = 8.22$	$\theta = 8.98$	$\theta = 9.64$	$\theta = 12.86$	OtherCost1	OtherCost2	OtherCost3	OtherCost4	OtherCost5
lnma											
lnma(rawroute,popu-based)	0.841***	0.269***	0.148***	0.139***	0.133***	0.109***	0.210***	0.167***	0.139***	0.110***	0.102***
	(0.164)	(0.043)	(0.019)	(0.017)	(0.016)	(0.013)	(0.022)	(0.020)	(0.016)	(0.015)	(0.012)
R-squared	0.888	0.889	0.891	0.891	0.891	0.891	0.893	0.891	0.892	0.890	0.891
Observations	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249
lnma (Standardization)											
lnma(rawroute,popu-based)	0.228***	0.263***	0.306***	0.308***	0.310***	0.312***	0.439***	0.335***	0.347***	0.272***	0.306***
	(0.043)	(0.042)	(0.040)	(0.039)	(0.039)	(0.037)	(0.046)	(0.041)	(0.041)	(0.037)	(0.037)
R-squared	0.888	0.888	0.890	0.891	0.891	0.891	0.893	0.891	0.891	0.890	0.891
Observations	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249
Grid FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl1 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl2 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
AgriControl × Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Note: Control variables are same as those listed in Table1. Standard errors displayed in parentheses are clustered at grid level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

B.B CSI Based on Market Access

Table B.3: The Role of CSI-based Market Access

Dependent variable	ln(Population Density)							
	OLS				IV:2SLS			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
lnma(raw route,CSI)	0.103***	0.102***	0.068***	0.068***	0.158***	0.159***	0.133***	0.132***
	(0.019)	(0.019)	(0.019)	(0.019)	(0.049)	(0.049)	(0.044)	(0.044)
post1102 × number of wars		-0.029		0.009		-0.027		0.009
		(0.021)		(0.019)		(0.021)		(0.019)
post1102 × death tolls			-0.230***	-0.232***			-0.219***	-0.221***
			(0.035)	(0.036)			(0.035)	(0.036)
Grid FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl1 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl2 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
AgriControl × Dynasty FE	Y	Y	Y	Y	Y	Y	Y	Y
R-squared	0.888	0.888	0.898	0.898	0.015	0.016	0.106	0.106
Observations	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249

Note: Control variables are same as those listed in Table1. Standard errors displayed in parentheses are clustered at grid level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

B.C More Control Variables

Table B.4: The Role of Provincial Capital

Dependent variable	ln(Population Density)							
	OLS				IV:2SLS			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
lnma(raw route,popu)	0.163***	0.163***	0.117***	0.118***	0.102**	0.102**	0.085**	0.083*
	(0.023)	(0.023)	(0.022)	(0.022)	(0.046)	(0.046)	(0.042)	(0.042)
Provincial Capital	0.270***	0.271***	0.239***	0.248***	0.292***	0.292***	0.247***	0.257***
	(0.059)	(0.061)	(0.056)	(0.058)	(0.067)	(0.068)	(0.061)	(0.062)
post1102 × number of wars		0.004		0.028		0.000		0.028
		(0.020)		(0.022)		(0.021)		(0.021)
post1102 × death tolls			-0.171***	-0.176***			-0.182***	-0.188***
			(0.037)	(0.038)			(0.039)	(0.039)
Grid FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl1 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl2 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
AgriControl × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
R-squared	0.919	0.919	0.925	0.926	0.116	0.116	0.190	0.191
Observations	2,527	2,527	2,527	2,527	2,527	2,527	2,527	2,527

Note: Control variables are same as those listed in Table1. Standard errors displayed in parentheses are clustered at grid level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table B.5: Control for Length of Land routes

Dependent variable	ln(Population Density)							
	OLS				IV:2SLS			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
lnma(rawroute,popu-based)	0.094***	0.090***	0.083***	0.081***	0.122***	0.123***	0.122***	0.121***
	(0.017)	(0.018)	(0.018)	(0.019)	(0.039)	(0.042)	(0.042)	(0.042)
post1102 × number of wars	0.008	0.008	0.008	0.009	0.007	0.007	0.007	0.007
	(0.019)	(0.019)	(0.018)	(0.018)	(0.019)	(0.019)	(0.019)	(0.019)
post1102 × death tolls	-0.214***	-0.215***	-0.210***	-0.205***	-0.206***	-0.207***	-0.202***	-0.197***
	(0.036)	(0.036)	(0.036)	(0.036)	(0.036)	(0.036)	(0.036)	(0.036)
LandLength		Y	Y	Y		Y	Y	Y
LandLength(Nbr)			Y	Y			Y	Y
LandLength(Nbr2)				Y				Y
Grid FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl1 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl2 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
AgriControl × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
R-squared	0.900	0.900	0.900	0.900	0.126	0.126	0.127	0.128
Observations	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249

Note: Control variables are same as those listed in Table1. Standard errors displayed in parentheses are clustered at grid level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

B.D Alternative Instrumental Variables

Table B.6: IV Based on Alternative Definition of Optimal Route

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	IV Estimation:Dependent Variable: ln(population density)							
	HMIcanal				**STLcanal**			
lnma(raw route,popu)	0.168***	0.171***	0.153***	0.152***	0.174***	0.177***	0.156***	0.155***
	(0.051)	(0.051)	(0.047)	(0.047)	(0.050)	(0.050)	(0.046)	(0.046)
post1102 × number of wars		-0.025		0.007		-0.025		0.007
		(0.021)		(0.019)		(0.021)		(0.019)
post1102 × death tolls			-0.195***	-0.196***			-0.194***	-0.195***
			(0.035)	(0.036)			(0.035)	(0.036)
R-squared	0.048	0.049	0.119	0.119	0.047	0.048	0.118	0.118
Observations	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249
	First-Stage:Dependent Variable: lnma(raw route,popu-based)							
lnma(waterway,HMI canal,CSI-based)	0.436***	0.439***	0.427***	0.427***				
	(0.057)	(0.056)	(0.054)	(0.054)				
lnma(waterway,STL canal,CSI-Based)					0.443***	0.445***	0.431***	0.431***
					(0.054)	(0.054)	(0.051)	(0.051)
post1290 × number of wars		-0.055		-0.006		-0.051		-0.002
		(0.034)		(0.032)		(0.034)		(0.031)
post1290 × popushock			-0.294***	-0.293***			-0.290***	-0.290***
			(0.042)	(0.044)			(0.042)	(0.043)
Grid FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl1 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl2 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
AgriControl × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
R-squared	0.901	0.901	0.907	0.907	0.901	0.901	0.907	0.907
Observations	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249

Note: Control variables are same as those listed in Table1. Standard errors displayed in parentheses are clustered at grid level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

B.E Exclude Adjacent Grids

Table B.7: Excluding Neighbor Grids

Dependent variable	ln(Population Density)							
	OLS				IV:2SLS			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
lnma(nbr1)	0.093***	0.092***	0.051***	0.051***	0.188***	0.188***	0.138***	0.137***
	(0.015)	(0.015)	(0.015)	(0.015)	(0.038)	(0.038)	(0.038)	(0.038)
post1102 × number of wars		-0.027		0.008		-0.023		0.007
		(0.021)		(0.019)		(0.021)		(0.019)
post1102 × death tolls			-0.224***	-0.225***			-0.194***	-0.195***
			(0.036)	(0.037)			(0.036)	(0.037)
Grid FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl1 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl2 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
AgriControl × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
R-squared	0.888	0.889	0.898	0.898	-0.001	-0.000	0.090	0.090
Observations	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249

Note: Control variables are same as those listed in Table1. Standard errors displayed in parentheses are clustered at grid level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table B.8: Excluding Neighbor and Neighbor's Neighbor

Dependent variable	ln(Population Density)							
	OLS				IV:2SLS			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
lnma(nbr2)	0.080***	0.080***	0.040***	0.040***	0.214***	0.214***	0.147***	0.147***
	(0.016)	(0.016)	(0.015)	(0.015)	(0.037)	(0.037)	(0.037)	(0.037)
post1102 × number of wars		-0.028		0.008		-0.023		0.007
		(0.022)		(0.019)		(0.021)		(0.019)
post1102 × death tolls			-0.228***	-0.230***			-0.193***	-0.194***
			(0.036)	(0.037)			(0.036)	(0.038)
Grid FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl1 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
GeoControl2 × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
AgriControl × Year FE	Y	Y	Y	Y	Y	Y	Y	Y
R-squared	0.888	0.888	0.898	0.898	-0.039	-0.038	0.074	0.074
Observations	3,249	3,249	3,249	3,249	3,249	3,249	3,249	3,249

Note: Control variables are same as those listed in Table1. Standard errors displayed in parentheses are clustered at grid level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

B.F Alternative Counterfactual Estimates

Table B.9: Other Counterfactual Estimates (Different Assumptions)

	Counterfactual:Percent Increase in Population (%)								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	741	*980*	*1080*	*1102*	*1290*	*1393*	*1580*	*1776*	*1820*
Counterfactual 1: Drop the Grand Canal									
Land Road Cost Decline 30% (0.6755 ton/ton-1000km)	-2.23	-2.68	-3.15	-2.96	-3.19	-3.70	-3.59	3.66	3.61
Land Road Cost Decline 50% (0.4825 ton/ton-1000km)	6.64	4.23	3.73	3.83	4.23	3.96	4.49	12.95	12.81
OtherCost1 (NLS Theta=9.4)	-9.68	-9.41	-9.57	-9.29	-10.14	-11.88	-12.27	-5.57	-5.55
OtherCost2 (NLS Theta=10.42)	-8.02	-7.17	-7.37	-7.15	-8.22	-9.08	-9.25	-3.72	-3.70
OtherCost3 (NLS Theta=8.08)	-10.54	-10.55	-10.93	-10.61	-11.31	-12.83	-13.26	-5.98	-5.96
OtherCost4 (NLS Theta=8.8)	-8.94	-8.47	-9.37	-9.13	-8.98	-9.89	-10.06	-4.06	-4.04
OtherCost5 (NLS Theta=6.1)	-8.81	-8.48	-8.91	-8.64	-9.55	-11.12	-11.37	-4.79	-4.78
Estimation Predicted	-9.08	-5.87	-5.81	-5.26	-7.56	-8.44	-8.37	-3.36	-3.34
Counterfactual 2: Adopt Song Dynasty Grand Canal									
Waterway Only	3.52				0.01	2.26	2.65	3.66	3.60
OtherCost1 (NLS Theta=9.4)	3.22				-4.31	3.34	3.29	5.14	5.07
OtherCost2 (NLS Theta=10.42)	2.26				-2.77	2.18	2.17	3.44	3.38
OtherCost3 (NLS Theta=8.08)	3.03				-4.36	3.44	3.40	5.63	5.56
OtherCost4 (NLS Theta=8.8)	2.28				-2.68	2.34	2.35	3.80	3.73
OtherCost5 (NLS Theta=6.1)	2.23				-3.41	2.56	2.59	3.84	3.79
Estimation Predicted	2.39				-2.62	1.12	0.98	2.35	2.29
Counterfactual 3: Adopt Ming Dynasty Grand Canal									
Waterway Only	-1.52	-2.71	-1.73	-1.87					
OtherCost1 (NLS Theta=9.4)	-4.57	-7.17	-6.55	-6.40					
OtherCost2 (NLS Theta=10.42)	-4.76	-5.91	-5.59	-5.46					
OtherCost3 (NLS Theta=8.08)	-5.42	-8.25	-7.82	-7.65					
OtherCost4 (NLS Theta=8.8)	-5.46	-7.06	-7.49	-7.35					
OtherCost5 (NLS Theta=6.1)	-5.03	-6.79	-6.64	-6.49					
Estimation Predicted	-5.21	-4.96	-4.70	-4.66					

Note: This table summarizes the aggregate effects of counterfactual networks with other assumptions, including different land cost, other five possible route cost settings, and OLS estimation effects.

Appendix C Model and Counterfactual Analysis

C.A Model

This section provides a detailed discussion of the model. The framework is based on Donaldson and Hornbeck (2016) and Eaton and Kortum (2002). The basic setup is a trade model as in Eaton and Kortum (2002) with the immobile production factor land and the mobile factors labor and capital. The economy consists of many trading regions (grids), where the origin of a trade is indexed by o and the destination by d.

Consumers have CES preferences over a continuum of differentiated goods indexed by j, and the indirect utility of a consumer with income y_o and facing prices P_o is,

$$V(P_o, y_o) = \frac{y_o}{P_o} \tag{1}$$

where P_o is a CES price index of the form $P_o = \left(\int_j p_o(j)^{1-\sigma} dj\right)^{\frac{1}{1-\sigma}}$. Each district produces varieties with a Cobb-Douglas technology using land (T), labor (L), and capital (K),

$$x_o(j) = z_o(j)(T_o(j))^{\alpha}(L_o(j))^{\gamma}(K_o(j))^{1-\alpha-\gamma} \tag{2}$$

The production function implies the marginal cost is

$$MC_o(j) = \frac{q_o^{\alpha} w_o^{\gamma} r_o^{1-\alpha-\gamma}}{z_o(j)} \tag{3}$$

where q_o is the land rental rate, w_o is the wage, and r_o is the interest rate. Following Eaton and Kortum (2002), $z_o(j)$ is an exogenous productivity shifter drawn from a Fréchet distribution with CDF $F_o(z) = \Pr[Z_o \leq z] = \exp(-A_o z^{-\theta})$, where $\theta > 1$ captures the standard deviation of productivity, corresponding to the scope of comparative advantage, and A_o is a grid's state of absolute technology advantage. Following Donaldson and Hornbeck (2016), we assume the capital is perfectly mobile so that the return to capital is equalized across all grids in the same period (i.e., $r_o = r$).

Trade costs between locations o and d are modeled based on "iceberg" cost. For one unit of a good to reach destination d, $\tau_{od} \geq 1$ units must be shipped from origin o. This implies that if a good is produced in location o and sold at the price $p_{oo}(j)$, then it is sold in location d at the price $p_{od}(j) = \tau_{od} p_{oo}(j)$. Due to perfect competition, prices equal the marginal costs of producing each variety.

Eaton and Kortum (2002) derive two important results for our model. The first is that the consumer price index in destination location d takes the form

$$P_d^{-\theta} = \kappa_1 \sum_o [A_o(\tau_{od} q_o^{\alpha} w_o^{\gamma})^{-\theta}] \equiv CMA_d \tag{4}$$

We follow Donaldson and Hornbeck (2016) in referring to this price index as CMA_d (Consumer Market Access); it measures district d's access to cheap goods (i.e., low production costs in supplying district and low trade costs).

The second important result drawn from Eaton and Kortum (2002) describes the value of total export X_{od} from o to d, as

$$X_{od} = \kappa_1 A_o (q_o^{\alpha} w_o^{\gamma})^{-\theta} (\tau_{od})^{-\theta} P_d^{\theta} Y_d \tag{5}$$

which can also be written as

$$X_{od} = \kappa_1 A_o (q_o^{\alpha} w_o^{\gamma})^{-\theta} Y_d CMA_d^{-1} \tau_{od}^{-\theta} \tag{6}$$

Solving the Model

Equation 6 is a gravity equation with the standard features that trade increases in income of the destination and in productivity of the origin, while trade decreases in production costs, trade costs, and in consumer market access of the destination. Summing the gravity equation over destinations d and assuming that goods markets clear yields total income of origin o,

$$Y_o = \sum_d X_{od} = \kappa_1 A_o (q_o^\alpha w_o^\gamma)^{-\theta} \sum_d [\tau_{od}^{-\theta} CMA_d^{-1} Y_d] \tag{7}$$

Donaldson and Hornbeck define "firm market access" of district o as

$$FMA_o \equiv \sum_d \tau_{od}^{-\theta} CMA_d^{-1} Y_d \tag{8}$$

Using Equation 7 and 8 into the definition of CMA_d in Equation 4 yields that

$$CMA_d = \sum_o \tau_{od}^{-\theta} FMA_o^{-1} Y_o \tag{9}$$

Following Donaldson and Hornbeck (2016), if trade costs are symmetric, the solution to Equations (7) and (9) must satisfy $FMA_o = \rho CMA_o = MA_o$ for $\rho > 0$ and they refer to MA_o as "market access" in district o. Therefore, we get

$$MA_o = \rho \sum_d \tau_{od}^{-\theta} MA_d^{-1} Y_d \tag{10}$$

We also derive the relationship between Price Index and market access from Equation 4 that

$$P_o^{-\theta} = \rho^{-1} MA_o \tag{11}$$

In the next step, we solve for the relationship between labor and market access. The equations (7) and (8) give us,

$$Y_o = \kappa_1 A_o (q_o^\alpha w_o^\gamma)^{-\theta} MA_o \tag{12}$$

Assuming mobile labor, the real wage and utility are equalized across locations. Nominal wages are given by

$$w_o = \bar{U} \times P_o \tag{13}$$

where $\bar{U}$ is the utility level. According to the Cobb-Douglas production function, the rental rate of land and the nominal wage of labor are related to their income share, such that

$$q_o T_o = \alpha Y_o \tag{14}$$

$$w_o L_o = \gamma Y_o \tag{15}$$

Using equations 11, 13, 14, and 15 in Equation 12, solving for labor yields:

$$\ln L_o = \kappa_2 + \frac{1}{1+\theta\alpha} \ln A_o + \frac{-1-\theta(\alpha+\gamma)}{\theta(1+\theta\alpha)} \ln \bar{U} + \frac{-\theta\alpha}{1+\theta\alpha} \ln T_o + \frac{1+\theta(1+\alpha+\gamma)}{\theta(1+\theta\alpha)} \ln MA_o \tag{16}$$

Besides, using equation 11, 13, and 15, the equation 10 implies:

$$MA_o = \kappa_3 \sum_d \tau_{od}^{-\theta} MA_d^{-(1+\theta)/\theta} L_d \tag{17}$$

C.B Counterfactual Analysis

As in Donaldson and Hornbeck (2016), the counterfactuals can be solved by either assuming $\bar{U}$ is constant across counterfactuals and the total population adjusts, or the total population is constant and $\bar{U}$ adjusts. We are interested in the impact of market access on population density in our paper, so we focus on the first case, which allows for population mobile and require utility $\bar{U}$ is constant (Specifically, we assume $\bar{U} = 1$).

Our goal is to solve for new equilibrium of population distribution and aggregated population in each dynasty assuming that the route of Grand Canal remains unchanged after Song dynasty. This counterfactual exercise depends on the changing matrix of trade cost τ_{od} in the model, while holding the productivity term A_o and the exogenous land area T_o for each grid fixed at their actual level in each dynasty. The first problem is that A_o and T_o are unobserved in our study. We therefore show the procedure to estimate the unknown terms through our model, from the available data on population and actual matrix of τ_{od} in each dynasty.

We begin with estimating the price index using the Equation (7). With $P_o^{-\theta} = \rho^{-1} MA_o$ derived from Equation (1), the Equation (7) can be re-written as

$$P_o^{-\theta} = \sum_d \frac{\tau_{od}^{-\theta} P_d L_d}{\sum_i \tau_{di}^{-\theta} P_i^{1+\theta} L_i}. \tag{A1}$$

Given the actual population L_o of each grid and the actual matrix of trade cost τ_{od} in each period, we can first estimate the actual price index P_o for each grid in each year.

Then, substituting $w_o = \bar{U} \times P_o, q_o T_o = \alpha Y_o$, and $w_o L_o = \gamma Y_o$ into the Equation(2) and assuming the good markets clear yields that,

$$\kappa_1 \alpha^{-\alpha\theta} A_o T_o^{\theta\alpha} = P_o^{1+\theta(\alpha+\gamma)} \times \left(\frac{L_o}{\gamma}\right)^{1+\alpha\theta} \times \left(\sum_i \tau_{oi}^{-\theta} P_i^{1+\theta} \frac{L_i}{\gamma}\right)^{-1} \times \bar{U}^{1+\theta(\alpha+\gamma)}. \tag{A2}$$

We define the unknown term as $C_o \equiv A_o T_o^{\theta\alpha}$. Holding $\bar{U} = 1$, we have,

$$C_o \kappa_1 \alpha^{-\alpha\theta} \sum_i \tau_{oi}^{-\theta} P_i^{1+\theta} \frac{L_i}{\gamma} = P_o^{1+\theta(\alpha+\gamma)} \left(\frac{L_o}{\gamma}\right)^{1+\alpha\theta}. \tag{A3}$$

Given the price index P_o estimated from equation A1, actual population distribution L_o and the given parameters (θ, α and γ), we can back out the unknown term C_o , which is fixed in each year in the counterfactual exercise.

Then we show the procedure for solving the counterfactual labor distribution. Following Hornbeck and Rotemberg (2024), we use the Perron-Frobenius theorem to show the uniqueness of the counterfactual solutions. The main idea of Perron-Frobenius theorem is that, for any matrix M, with all its elements positive, the equation $\hat{\phi}\lambda = M\hat{\phi}$ has a unique eigenvalue λ and a unique (up to proportionality) eigenvector $\hat{\phi}$ with all its elements positive.

With the assumption $\bar{U} = 1$, and $w_o = \bar{U} \times P_o, q_o T_o = \alpha Y_o$, Equation (1) derives

$$(P_o)^{-\theta} = \kappa_1 \alpha^{-\alpha\theta} \sum_i C_i P_i^{-\theta(\alpha+\gamma)} \left(\frac{L_i}{\gamma}\right)^{-\alpha\theta} (\tau_{oi})^{-\theta}. \tag{A4}$$

Then we solve the equation system of Equations A3 and A4.

We first define a term ϕ_o,

$$\phi_o \equiv \frac{{P_o}^{-\theta} C_o \kappa_1 \alpha^{-\alpha\theta}}{P_o^{1+\theta(\alpha+\gamma)} \left(\frac{L_o}{\gamma}\right)^{1+\alpha\theta}}. \tag{A5}$$

Taking equation A4 into A5, we have,

$$\phi_o = \frac{(\kappa_1 \alpha^{-\alpha\theta})^2 C_o}{P_o^{1+\theta(\alpha+\gamma)} \left(\frac{L_o}{\gamma}\right)^{1+\alpha\theta}} \times \sum_i C_i P_i^{-\theta(\alpha+\gamma)} \left(\frac{L_i}{\gamma}\right)^{-\alpha\theta} (\tau_{oi})^{-\theta} \tag{A6}$$

Since $\phi_i \equiv \frac{\kappa_1 \alpha^{-\alpha\theta} P_i{}^{-\theta} C_i}{P_i^{1+\theta(\alpha+\gamma)} (\frac{L_i}{\gamma})^{1+\alpha\theta}}$, the equation A6 can be re-written as,

$$\phi_o = \frac{\kappa_1 \alpha^{-\alpha\theta} C_o}{P_o^{1+\theta(\alpha+\gamma)} \left(\frac{L_o}{\gamma}\right)^{1+\alpha\theta}} \times \sum_i \phi_i P_i^{1+\theta} (\tau_{oi})^{-\theta} \frac{L_i}{\gamma} \tag{A7}$$

The equation A3 can be written as,

$$1 = \frac{\kappa_1 \alpha^{-\alpha\theta} \sum_i C_o \tau_{oi}^{-\theta} P_i^{1+\theta} \frac{L_i}{\gamma}}{P_o^{1+\theta(\alpha+\gamma)} \left(\frac{L_o}{\gamma}\right)^{1+\alpha\theta}} \tag{A8}$$

We define a matrix A with elements $[A_{od}] = [\frac{\kappa_1 \alpha^{-\alpha\theta} C_o \tau_{od}^{-\theta} P_d^{1+\theta} L_d}{P_o^{1+\theta(\alpha+\gamma)} (\frac{L_o}{\gamma})^{1+\alpha\theta} \gamma}]$. All of the elements in matrix A are positive. According to the Perron-Frobenius theorem, if the equation system A7 and A8 holds, we have two eigenvectors $[\phi_o]$ and [1] that are proportional. Therefore,$\phi_o = \phi^{-1} \times 1$, for some constant ϕ^{-1}.

Then, the equation A5 turns into:

$$P_o^{1+\theta(1+\alpha+\gamma)} = \kappa_1 \alpha^{-\alpha\theta} C_o \left(\frac{L_o}{\gamma}\right)^{-1-\alpha\theta} \phi \tag{A9}$$

Substituting equation A9 into equation A3, and let $g = 1 + \theta(1 + \alpha + \gamma)$, we have:

$(\kappa_1 \alpha^{-\alpha\theta})^{\frac{2\theta+1}{g}} C_o \sum_i \tau_{oi}^{-\theta} (C_i (\frac{L_i}{\gamma})^{-1-\alpha\theta} \phi)^{\frac{\theta+1}{g}} \times \frac{L_i}{\gamma} = (C_o (\frac{L_o}{\gamma})^{-1-\alpha\theta} \phi)^{\frac{\theta(\alpha+\gamma)+1}{g}} \times (\frac{L_o}{\gamma})^{1+\theta\alpha}$

After rearranging, we have the final equation on the counterfactual population distribution as follows,

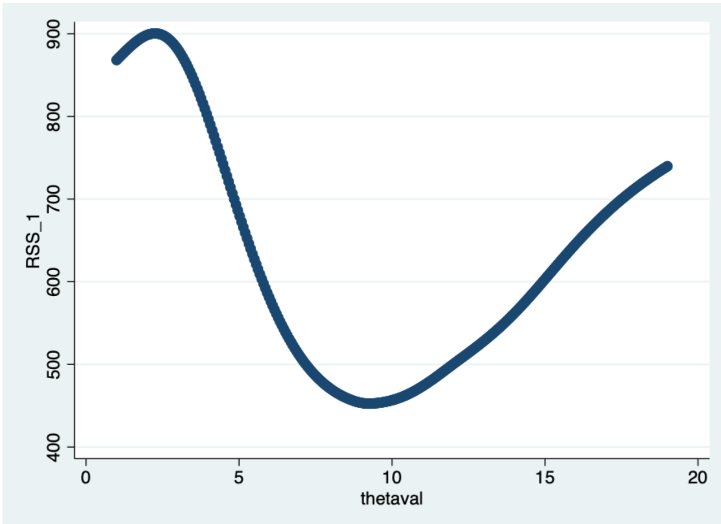
$$\phi^{\frac{\theta(1-\alpha-\gamma)}{g}} \gamma^{\left(\frac{(\theta\alpha+1)(1+2\theta)}{g} - 1\right)} (\kappa_1 \alpha^{-\alpha\theta})^{\frac{2\theta+1}{g}} \times C_o^{\frac{\theta}{g}} \sum_i \tau_{oi}^{-\theta} C_i^{\frac{1+\theta}{g}} L_i^{1-\frac{(1+\theta)(1+\theta\alpha)}{g}} = L_o^{\frac{\theta(1+\theta\alpha)}{g}} \tag{A10}$$

Based on equation A10[11], given counterfactual matrix $[\tau_{od}]$ and unchanged term C_o,we

[11] Following Donaldson and Hornbeck (2016), we assume $\frac{r}{f(P)} = \bar{r}$, where$\bar{r}$ is exogenous foreign real

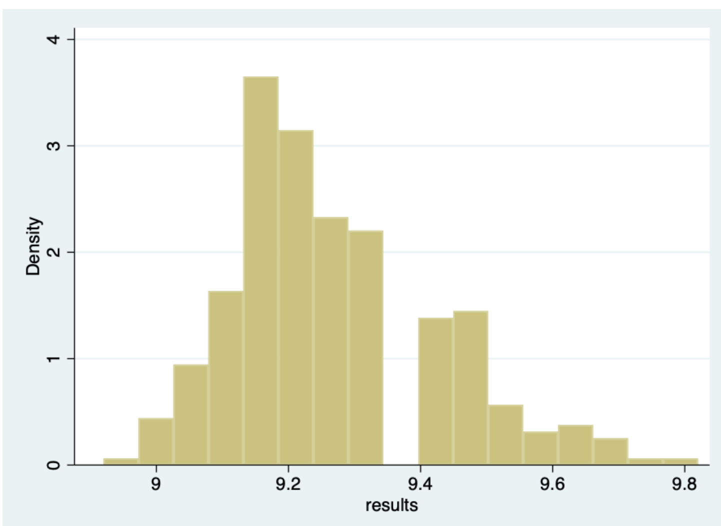
can derive the counterfactual population distribution L_o for each grid in different periods.

Figure C.1: NLS Theta Selection Plot



Notes: Theta with least RSS is selected ($\theta = 9.22$).

Figure C.2: Distribution of NLS Selected Theta



Notes: 95% Confidence Interval is [8.98-9.64] around the estimated theta value 9.22.

interest rate and $f(P)$ is the population-weighted price index of the goods that are implicitly traded for foreign capital. $f(P)$ is equal to $\sum_d \frac{L_d P_d}{\sum_d L_d}$ in our model. Although the interest rate r changes with price indices P_i, it is equalized across grids. So, it does not affect the counterfactual population distribution across grids based on equation A10.