Endogenous Demography and the Welfare Gains from Trade: Evidence from British India's Railroads

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[PRELIMINARY: PLEASE DO NOT CITE OR CIRCULATE WITHOUT PERMISSION]

Abstract

A robust implication from the literature on trade is that opening up to trade raises aggregate welfare, as factors reallocate to sectors of comparative advantage. However, for societies characterized by a Malthusian equilibrium, in which fertility and mortality respond to overall living standards, the long-run impact of trade on per-capita incomes is muted by population growth. I study the case of the railroads of British India, which were associated with large aggregate gains in real agricultural income. I develop a simple neo-Ricardian trade model with endogenous population growth absorbing income gains. Employing a dataset of newly-collected and corrected vital statistics, I document dramatic local population responses to the arrival of the railroads: specifically, fertility rose slightly, mortality fell steeply, and mortality became much less responsive to extreme rainfall shocks in the wake of the railroads. The long-run effect of these changes is that districts with railroads are 6% more densely populated than those without. This case illustrates the importance of demography in the theory and measurement of economic change in historical contexts.

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1 Introduction

Economists studying trade, from the classical trade theory of Ricardo to the "new new trade theory" of Eaton and Kortum, have long argued that trade liberalization raises welfare in the long run: in aggregate, real wages rise as workers move to sectors of comparative advantage and some goods are obtained more cheaply from abroad.[1] However, for societies characterized by a Malthusian equilibrium, in which fertility and mortality respond to real wages, the long-run impact of trade liberalization on real wages can be muted if populations expand in response to the gains from trade. Economists have largely neglected the potential endogeneity of demography to income in measuring the welfare gains from trade. For many contemporary policy questions, this is an eminently defensible abstraction; however, given the great strides in domestic and international market integration made before the demographic transitions of the nineteenth century (in Western Europe and its New World offshoots) and the twentieth century (in Asia, the Middle East, Africa, and parts of Latin America), ignoring the population margin may understate the impact of trade on societies in historical contexts.

The Indian subcontinent under British rule provides a valuable case for testing the theoretical predictions of models relating trade and demography for several reasons. First, India's internal and external integration accelerated in the century following the 1857 Rebellion: this process was facilitated by institutional reforms, improvements in transport, and the commercialization of agriculture.[2] By World War I, India had become an important exporter of cotton, wheat, tea, oilseeds, and jute, among other primary commodities. In particular, the British-built railroad network, expanding rapidly between the 1850s and 1920s, represented a major shock to many of India's hinterland regions. Second, uniquely among the developing world, relatively detailed disaggregated demographic data exist for India for much of this period, starting with the introduction of vital registration and decennial censuses in the 1870s. Third, the broad patterns of income and population conform to the essential insight of the Malthusian world. The most recent estimates suggest a slow but steady rate of population growth in the 19th century, about 0.5-1% p.a., but stagnant GDP per capita through Independence in 1947, and in related work, I find evidence for a Malthusian mechanism at work in the

[1] See Eaton and Kortum (2012) for a recent review. Multiple-factor models like Heckscher-Ohlin feature real wage gains only when labor is the relatively abundant factor (Stolper and Samuelson, 1941).

[2] Henceforth, I use the term "India" as shorthand for the subcontinent as a whole as unified under British rule, covering modern-day Pakistan, India, Bangladesh, and Burma.

short-run responsiveness of ferility and mortality to monsoon-rainfall-driven shocks to income.[3]

In this paper, I develop a model of how trade and demography interact by combining the insights from benchmark models of trade (Ricardo) and of demographic responses to economic change (Malthus). The model is in principle rich enough to accommodate structural estimation, but this requires further data collection on agricultural prices and production. I therefore rely on the model primarily to generate a set of predictions that I test in reduced-form, and secondarily for a simple calibration exercise. The predictions I generate are in essence joint tests of the Malthusian and Ricardian hypotheses. I first provide evidence to substantiate my argument that these are both appropriate frameworks for thinking about the colonial Indian economy, and that their synthesis suggests a new way of thinking about the measurement of trade's impact on developing societies.

I test these predictions using a new panel dataset of colonial Indian vital statistics. The raw data on births and deaths in colonial reports have long been mistrusted by demographic historians, who have noted major problems with under-registration and age misstatement: even if they were correct, computing *rates* rather than counts requires an appropriate annual measure of the total population.[4] I digitize archival materials collected in London, Chicago, and Lahore to construct a new dataset on district-level vital rates and populations for British India's largest provinces, corrected for problems of under-registration, age misstatement, and underenumeration. The heart of the adjustment exercise is the reconciliation of age-enumerated populations at the decennial Censuses with annual data on births and deaths-by-age, assuming that under-registration is constant over a decade (but can vary freely by age-group, gender, and district).[5] These data cover a population of 190 million (in 1901) across over 120 British Indian districts.[6] I combine this with data on the district-by-district expansion of the railroad network throughout India, in order to study how fertility, mortality and total populations evolve as the railroads arrive. I rely on a generalized difference-in-difference approach, studying the evolution of these demographic variables within districts before and after the railroads arrive relative to a common trend. The primary endogeneity concern is that railroads were built to target areas that were expected to have faster-growing population growth, falling mortality or rising fertility

[3]Visaria and Visaria, (1983), Broadberry and Gupta (2012), Ahmad (2018).

[4]See Davis (1951), Bhat (1981), and Dyson (2002) for commentary.

[5]Ahmad (2018) contains the details of the reconstruction exercise.

[6]The panel is unbalanced due to boundary changes over time: I can track 100 districts over 1881-1931, an additional 13 from 1891, 11 from 1901, 28 from 1911, and 10 from 1921.

(relative to an aggregate trend). I address these using a series of additional robustness checks, including leads and lags of railroad arrival, province-year fixed effects and the placebo checks employed by Donaldson (2018) in his study of the railroads' impact on agricultural income in British India.

I find that, consistent with the theory I propose, the railroads were associated with population growth, with railroad districts 6% larger than their non-railroad counterparts over 1871-1941. This is a sizable magnitude, accounting for a quarter of population growth. This change is accounted for primarily by a reduction in mortality: in particular, an attenuation of mortality crises associated with scanty rainfall. I also find evidence of a small fertility response, consistent with the Malthusian view that children are normal goods.

Finally, I employ my model to conduct a back-of-the-envelope counterfactual exercise: assuming all gains from trade were reflected in the population change we observe, what counterfactual income growth might India have expected from the railroads if India had undergone a demographic transition a century earlier than it did? The counterfactual real wage gains are about 3% over 1871 to 1941. This is large when compared to the low rates of real wage growth observed over the last 70 years of British rule: for example, Roy's (2005) estimates of real agricultural wages for British India suggest that real wages grew 2.5% between 1873 and 1941.

This paper contributes to the literature on the short- and long-run causal impacts of transport infrastructure on economic development. Railroads in particular have been an enduring subject of study by economic historians[7], and have recently renewed interest from applied microeconomists who have revisited this question in contexts as varied as the United States (Atack et al. 2010, Donaldson and Hornbeck 2015), Europe (Herranz-Loncán 2006, Keller and Shuie 2008), Latin America (Summerhill 2005, Herranz-Loncán 2014), South Asia (Donaldson 2018), and sub-Saharan Africa (Jedwab and Moradi 2015). More broadly, economists have turned to the study of the 20th century expansion of roads and highways in China (Banerjee et al. 2012, Baum-Snow et al. 2015) and in sub-Saharan Africa (Storeygard 2013), among other contexts. Relatively few, however, study economies prior to their demographic transitions, where we expect welfare gains to be reflected in population as well as income-per-capita margins. Donaldson's (2018) closely-related work on the colonial railroads of India suggests the possibility of a Malthusian response in studying the

[7] Fogel's 1964 and Fishlow's 1965 studies on the US railroads and growth spawned a series of classic studies of England (Hawke 1970), Russia (Metzer 1974), Germany (Fremdling 1977), and India (Hurd 1983).

railroads of India, though his measure (a constructed measure of real agricultural income per acre) does not account for population change. Jedwab and Moradi (2015) report increased rural population density in regions of Ghana penetrated by colonial railroads, though their focus is primarily on urban populations. My work on India suggests that we should consider population as a crucial margin for conceptualizing and measuring the gains from trade in the developing world prior to the middle of the 20th century, conditioning appropriately for local differences in demographic regimes to distinguish between changes in fertility, nuptiality, and mortality.

This paper also contributes to the literature on growth theory in a Malthusian world. The seminal work on Malthusian growth theory, beginning with Galor and Weil (1999, 2000), emphasizes the development of a unified framework for the transition of societies from a Malthusian equilibrium (in which all economic change is reflected in population growth, with long-run stagnation in per-capita income) to a modern growth regime (in which persistent per-capita income growth is possible).[8] Galor and Mountford (2006, 2008) put forward the argument that the current distribution of population around the world is partly explained by the historic differences in how gains from trade were absorbed, with post-demographic-transition countries gaining in terms of rising income per capita and pre-transition ones gaining in population. They rely on stylized facts from economic history as evidence, including the divergence between Great Britain and colonial India, as well as a cross-country regression showing that trade-openness correlates with lower fertility and higher education levels in OECD countries but the opposite in non-OECD ones. In this paper, I employ a full-fledged model of trade with the aim of fitting the particular historical setting of colonial India. Empirically, I rely on within-country and cross-time variation in trade costs associated with the railroads to identify the causal effect of trade on demographic outcomes, as well as to identify the margins of demographic adjustment (fertility vs. mortality). My work suggests that mortality declines are an important component of population change in the Indian context, whereas Malthusian growth-theoretic models rely on a fertility mechanism to explain population growth.

Finally, I contribute to the literature on South Asian economic history. A Malthusian interpretation of the colonial period suggests that demography is fundamental to measuring economic development over this period, alongside more standard measures of economic performance (output, factors, and prices). Vital

[8]See Galor (2011) for a systematic book-length treatment of the Malthusian growth literature.

statistics have a number of features that are attractive relative to many other economic measures available for the colonial era: they are high-frequency, locally-disaggregated, and tangibly represent a basic measure of human welfare in a subsistence economy. Historians have been overly cautious in their rejection of the vital statistics data collected by the colonial bureaucracy due to under-registration, relying instead on the Census.[9] Furthermore, demographic historians have only loosely tied demographic history to economic phenomena. In this paper, I employ rich archival sources on under-registered district-level counts of births and age-specific deaths, along with better-enumerated Census populations, to reconstruct vital statistics.[10] This paper therefore opens up a broader research agenda, one that requires revisiting some of the major themes of South Asian economic history using this new way of seeing: examples include the distributional consequences of land-revenue systems, the efficacy of expenditure on public health and irrigation infrastructure, the impact of long-run climate change, and the historical roots of regional differences in gender inequality.

In the remainder of this paper, I set out in Section 2 some brief historical context on colonial India, focusing on economic demography, population change, and the railroads. This motivates the model I present in Section 3 and the empirical strategy laid out in Section 7. I describe my data and empirical strategy in Sections 5 and 4. I discuss results in Section 6, followed by discussion and further steps in Section 7. Section 8 concludes.

2 Historical Context

India spent 190 years under British rule, first under the East India Company from the Battle of Plassey (1757) until the First Uprising (1857), and then under direct British rule until Partition and Independence (1947). See Figure (1) for a timeline. During this time, our best estimates of GDP per capita suggest negligible growth: at Independence, South Asian GDP per head was merely back at par with the Mughal Empire at its zenith under Akbar in 1600. Only the last quarter-century of colonial rule saw growth, and that at the paltry rate of 0.5% p.a. On the other hand, population grew more or less steadily at 0.5% p.a, and accelerated sharply towards the end of colonial rule, tripling its growth-rate to 1.5%: Britain left India

[9]See Bhat (1989), for instance. The literature on famines are a notable exception: Sen (1981), Ravallion (1987), and Maharatna (1996) all make judicious use of vital statistics in understanding short-run vital responses to scarcity and famine.

[10]See Ahmad (2015).

with twice as many people as it found, but just as poor. Consistent per-capita growth is nearly exclusively a post-Independence phenomenon; the trend break in population growth is much earlier, around 1920.

[Figure 1 about here.]

2.1 Population Change in Colonial India in Context

Essentially no reliable estimates exist for India's population before 1870.[11] However, that decade marks a watershed in India's recorded history: the British launched the first (asynchronous) set of provincial censuses in the late 1860s and early 1870s, after which the decennial Census was first begun in 1881. This makes South Asia an exceptional part of the developing world today: it is the only low-income region today for which such highly detailed disaggregated data on local populations are available dating back to the 19th century. Census enumerators collected systematic information on age, gender, religion, marital status, occupation, caste, language, infirmities, literacy, and education, and published it in abstracted cross-tabulations down to the district level.

Moreover, the era of the census saw the launch of a bureaucratic apparatus (through the provincial offices of public health officials called Sanitary Commissioners) to monitor vital statistics.[12] From 1859, early efforts were concerned primarily with the health of the Indian army (both European and native troops) but soon began to report regularly on fertility and mortality in the civilian population (first urban, and then rural) as a means of controlling epidemics. Reporting was standardized by the early 1880s across provinces, with annual publications issued in 1881 by Sanitary Commissioners for Assam, Bengal, Berar, Bombay, the Central Provinces, Coorg, Madras, Punjab, and the United Provinces - notionally covering a population over 200 million, over 90% of British India, and over 80% of the subcontinent as a whole (including the princely states). Each annual report consists of a narrative history of the year in question, occasionally accompanied with charts and summary tables, and concludes with annexed statistical tables. These tables showed several changes in reporting standards (e.g. on disease classifications, age-groupings, and geographic

[11] The estimates above come from Broadberry and Gupta (2010). The earliest set of concrete population estimates are based on revenue figures in Abu Faz'l's statistical atlas of the Mughal empire under Akbar in the late 16th century, about which there has been substantial debate: see Moosvi (1977). See Visaria and Visaria (1982) for further discussion of population estimates in the pre-Census era.

[12] See Harrison (1994) for more details.

disaggregation), but over the entirety of the 1881-1931 period, total counts of births and deaths (by gender and age) are available. Figure 2 below depicts typical tables from which data were drawn from this project.

[Figure 2 about here.]

Figure 3 shows how low estimates of life expectancy at birth were for colonial India at the dawn of the Census. No other society on record appears to have sustained such low levels of life expectancy for an extended period. The speed of the turnaround is astonishing post-1920, but the rate of mortality decline that sets in does not seem unusual otherwise. Nonetheless, of India's gains in life expectancy over the last 130 years, nearly half the gains arrived during the colonial era, an open puzzle that deserves additional exploration.

[Figure 3 about here.]

2.2 The Railroads

British India saw the creation of a sizable railway network over the late nineteenth century, growing from a single line constructed in 1853 to 65,000 km by 1930. These lines have long been a study of polemic and debate, going back to Marx, who heralded them as agents of social and economic revolution, forerunners of industry and dissolvers of caste, as well as the nationalists of India who decried the system of guaranteed profits and consequent drain of Indian wealth to Great Britain.[13] Economists have been engaged with the colonial railroads at least since the 1970s, when Hurd (1974) documents grain price convergence following railway lines.[14]

These price data have continued to be used in more recent work. Studer (2008) uses this data, extending it backwards to the 18th century where possible, in order to overturn revisionist claims that markets in early modern India may have been comparable to those in contemporary Europe in terms of integration and efficiency. Donaldson (2018) employs them alongside additional data on output, rainfall, and trade flows to estimate trade costs, which he uses to calibrate a general-equilibrium neo-Ricardian trade model and quantify the aggregate welfare gains associated with the railroads, which he estimates at approximately 16%

[13]Marx (1853), Naoroji (1901), Dutt (1904).

[14]See Mukherjee (1980) for a similar approach to the same question, with a narrower focus on Bengal, and additional data on relative trade flows on rivers and railways.

(in terms of real agricultural income per acre). Finally, Andrabi and Kuehlwein (2010), who revisit Hurd's analysis with a reduced-form econometric approach, challenge the claim that the falling spatial dispersion is explained primarily by railroad expansion, and favor instead other contemporaneous institutional changes that facilitated market integration. Donaldson's (2018) work is the most compelling of these trade-focused papers: avoiding the common trap of inferring transport costs from spatial price gaps, he exploits the fact that we observe origin-specific salt prices at different destinations over time to calibrate a structural neo-Ricardian model, accounting for most of his reduced-form estimate of a 16% impact of railroads on real agricultural income. Furthermore, Donaldson and Burgess (2010) document that the railroads had a second important impact: insuring districts against rainfall risk. They find that real income levels are less volatile, as are crude death rates, once the railroad has arrived in a district, a finding that I corroborate in this paper.

Finally, Bogart and Chaudhary (2013) and Bogart et al. (2015) analyze the impact of the railways on the Indian economy in broader perspective, taking on Fogel's (1964) classic social savings methodology: they estimate costs for moving freight and passengers around using pre-railway technology (rivers and carts), account for TFP growth in the railway sector itself, and use these to calculate consumer and producer surplus relative to a no-railway counterfactual. Bogart et al. (2015) estimate that the railways contributed 0.29% per year to GDP per capita growth, a large fraction of overall growth during the 1860-1912 period (0.39% p.a., according to Maddison (2001)).

The literature therefore appears to have reached a consensus that the gains associated with the railways were quantitatively large in magnitude. If this is the case, however, what we know about Malthusian economies suggests we should try to account for the endogeneity of overall population levels to the income gains associated with the railroads: if we do not, we are likely to understate their impact. In particular, this logic suggests that Donaldson's (2018) estimates, restated on a per-capita basis, may underestimate the total welfare gains associated with trade openness to the extent that those welfare gains appear in the form of people rather than income. Similarly, the social-savings estimates of Bogart et al. (2015) may be biased downwards if the counterfactual population they use is too large (that is, if the counterfactual population reflects population growth associated with factual benefits of the railroads).

[Figure 4 about here.]

[Figure 5 about here.]

3 Model

I begin by describing two benchmark models: one that describes how economic change is linked to demographic outcomes, and one that describes how trade is related to economic outcomes. The key link between the two models is the real wage: in the Malthusian model, real wage changes drive changes in fertility and mortality (in the short-run) and population levels (in the long-run), as individuals respond to changes in living standards. In the trade model, opening up from autarky drives changes in the long-run real wage, as factors are reallocated across sectors. The synthesis of the two models is driven entirely by the link.

3.1 Malthus

I begin with a very general model of a Malthusian economy, which consists of three relationships:

1. a production function $F(\cdot, L)$ featuring diminishing returns to labor, $F_L(\cdot) > 0$, $F_{LL}(\cdot) < 0$.
2. a birth-rate function $B(w)$ that is positively related to wages. $B_w(\cdot) > 0$, $\underset{w\to 0}{lim} B(w) = 0$.
3. a death-rate function $D(w)$ that is negatively related to wages. $D_w(\cdot) < 0$, $\underset{w\to\infty}{lim} D(w) = 0$.

The latter relationships define a steady-state wage w^* that is required for demographic equilibrium, $B(w) = D(w)$, where there is no population growth.

Given a declining labor-demand schedule associated with $F(\cdot)$, there is a unique level of the population L^* for which that steady-state wage holds, defined by $L^* = F_L^{-1}(w^*)$. Because $F_{LL}(\cdot) < 0$, it follows that L^* is a declining function of the wage. Demographic systems that give rise to high wage levels feature small populations, *ceteris paribus.*

It is instructive to trace through the transition path of endogenous variables in response to technological improvement (a level shift in labor demand). From steady state, a rise in productivity is reflected initially in increased wages, $w^{'} > w^*$. At these higher wages, births exceed deaths (the natural rate of increase is positive) and the population begins to grow. Along the transition path to a new steady state, the natural rate of increase decreases to its steady state level (zero), as do wages (w^*). This is illustrated in Figure 6.

[Figure 6 about here.]

I present some micro-foundations for these relationships in Appendix A; for our purposes here, it will be sufficient to consider aggregate relationships of the following form:

$$b(w) = \bar{b}(\frac{w}{\bar{w}})^{\beta}$$

$$d(w) = \bar{d}(\frac{w}{\bar{w}})^{\delta}$$

where $\bar{b}$ and $\bar{d}$ represent birth and death rates at the subsistence wage $w = \bar{w}$, and $\beta > 0$, $\delta < 0$ represent the elasticities of fertility and mortality with respect to the wage.[15]

The notion of demographic equilibrium here is a steady-state population where $b = d$. The relationship above tells us the unique wage consistent with a demographic steady-state:

$$w^{*} = \bar{w} \left(\frac{\bar{d}}{\bar{b}} \right)^{\frac{1}{\beta - \delta}} \tag{1}$$

The exponent is strictly positive by assumption ($\beta > 0$ and $\delta < 0$), and the ratio in parentheses is strictly greater than 1 ($\bar{d} > \bar{b}$). The level of consumption in steady-state, relative to subsistence, is therefore a function of:

1. The ratio of subsistence death rates to subsistence birth rates ($\frac{\bar{d}}{\bar{b}}$): higher relative subsistence-mortality is associated with higher consumption levels in steady-state, since the birth-rate (and hence wage) required to maintain zero population-growth is higher.

2. The sum of absolute magnitudes of demographic elasticities ($\beta - \delta$): the smaller this sum, the steeper each relationship is and the higher are steady-state wages. As this sum approaches ∞ and the curves flatten, steady-state wages approach subsistence level $\bar{w}$.

Now consider a standard Cobb-Douglas production function, $Q = AL^{\alpha}T^{1-\alpha}$, which features a declining labor-demand schedule (holding land, T, fixed). Setting wage equal to marginal product:

[15] I assume the subsistence death rate exceeds the birth rate ($\bar{d} < \bar{b}$), which ensures that a steady-state with above-subsistence wages exists.

$$w = MPL = \alpha A \left(\frac{T}{L}\right)^{1-\alpha}$$

Demography pins down $w = w^*$, so this can be rearranged to tell us about population levels:

$$L^* = T\left(\frac{\alpha A}{w^*}\right)^{1/(1-\alpha)} \tag{2}$$

Equation (2) tells us the population levels are rising in TFP (A) and other factors (T) and declining in the level of the real wage. All growth, whether through factor accumulation or productivity growth, is ultimately reflected in population levels.

Now consider the following extension of equation (2), where $\bar{L}$ reflects the initial population size:

$$L = \bar{L}^{\mu} T\left(\frac{\alpha A}{w^*}\right)^{(1-\mu)/(1-\alpha)} \tag{3}$$

The parameter μ here represents the degree of "Malthusian-ness:" when $\mu = 1$, we are in the neoclassical world where economic change is reflected in wages, and $\mu = 0$ simplifies to the limit case of (2), where economic change is reflected in population levels.

There are two natural ways to interpret μ:

- μ represents the dynamics of population growth along the transition path between two static equilibria. Define $\mu_t(w_t) = \left|\frac{B(w_t)-D(w_t)}{L_t}\right|$, that is, as the absolute value of the Crude Rate of Natural Increase (CRNI).[16] In Malthusian steady-state, where births equal deaths, $\mu = 0$.
  - A permanent increase in A at $t = 0$ leads to higher wages, given $\mu = 0$. In the following period, $\mu_1 > \mu_0 = 0$. Along the transition path, population grows ($L_{t+1} > L_t$), real wages fall ($w_{t+1} < w_t$), and the CRNI falls ($\mu_{t+1} < \mu_t$) until demographic equilibrium is reached again at $\mu = 0$. Wages have returned to their original level for which $\mu_t(w_t) = 0$, and population levels fully reflect economic growth.
- μ represents the position of a society along its demographic transition, with $\mu < 1$ corresponding to the

[16]Note that $\mu'(w) > 0$ follows immediately from the signs of $B'(w)$ and $D'(w)$. In terms of the micro-foundations described in Appendix A, μ can be thought of as a function of the preference or cost parameters for children vs. consumption.

pre-demographic-transition (Malthusian) regime, and $\mu = 1$ corresponding to the modern demographic regime. Any positive $\mu < 1$ reflects a situation where economic growth is reflected in the long-run *both* in per-capita welfare *and* in the population margin. In this interpretation, some other unspecified effect prevents population growth from absorbing all welfare gains: for example, a capacity or congestion constraint on population would achieve this.

Together, these interpretations make clear how we should study structural economic change in Malthusian economies:

1. in the short-run: economic change has implications for wages, fertility, and mortality along the transition path;

2. in the long-run: economic change is ultimately reflected in population levels (for $\mu \in [0, 1)$) as well as wages (for $\mu \in (0, 1]$).

3.2 Ricardo

The simplest place to start is with the model of trade put forward by Malthus' contemporary, Ricardo.[17] For Malthusian effects to bite, there must be diminishing returns to labor: I therefore consider a model with land as a fixed factor of production. The intuition for what follows is standard: opening up to trade breaks the link between production and consumption that exists in autarky, allowing countries to allocate factors to sectors of comparative advantage and export those goods in exchange for goods from sectors of comparative disadvantage, thus raising real wages.

I show formally in a general framework, with an arbitrary number of districts and goods, that reductions in trade costs are reflected in only the population dimension in a world where population growth absorbs all per-capita welfare gains. The set-up follows closely the exposition of the canonical neo-Ricardian model, Eaton and Kortum (2002) and Donaldson (2018).

[17] In Ricardo's original formulation, as well as in contemporary neo-Ricardian models, production occurs at constant returns to scale with a single factor (labor), with technological differences reflected in unit labor costs. See Eaton and Kortum (2012) for a survey.

Setup

Consider a country composed of $j = 1, ..., n$ districts, each endowed with two factors of production (land, T, and labor, L), each of which is immobile. The economy features a continuum of goods, indexed $\omega \in [0, 1]$.

Preferences: Each district is composed of an identical measure of households with preferences over goods Ω,

$$U_j = \left(\int_0^1 c_{ij}(\omega)^{\frac{\sigma}{\sigma-1}} d\omega \right)^{\frac{\sigma-1}{\sigma}} \tag{4}$$

where $c_{ij}(\omega)$ denotes the consumption of good ω purchased from district i and $\sigma > 1$ denotes the elasticity of substitution between consumption-goods. District j households face the budget constraint:

$$\int_0^1 p_{ij}(\omega) c_{ij}(\omega) d\omega \leq w_j L_j + r_j T_j \tag{5}$$

Production: Each variety is produced in district i using a Cobb-Douglas production function[18] with associated unit cost:

$$C_i(\omega) = \frac{w_i^{\alpha} r_i^{1-\alpha}}{z_i(\omega)} \tag{6}$$

The productivity of each district i, $z_i(\omega)$ is stochastic, drawn from the Fréchet distribution, $F_i(z) = Pr(Z_i \leq z) = e^{-A_i z^{-\theta}}$, where:

- $A_i > 0$ is a district-specific parameter that governs the location of the distribution (but not its spread): districts with higher values of A_i are more likely to have high productivity draws across goods. This is naturally interpreted as describing district-specific absolute advantage in productivity.

- $\theta > 1$ is a generic parameter, common to all districts, that primarily governs the spread of the distribution of productivities across goods: with lower values of θ, productivity is less variable across goods. This is naturally interpreted as describing the importance of comparative advantage, since the gains

[18] This corresponds to the production function $F_\omega(L, T) = \hat{\alpha} z(\omega) L^{\alpha} T^{1-\alpha}$, where $\hat{\alpha} = \alpha^{\alpha}(1-\alpha)^{(1-\alpha)}$ is a normalizing constant that makes the unit cost function more approachable.

from trade are higher the more districts differ in their relative efficiency.

Figure 7 presents some examples. Think of the three lines (red, green, blue) as representing three different districts of increasing absolute advantage. Consider the dashed lines (corresponding to $\theta = 10$), where each district has a tightly-clustered distribution of productivities across goods. There are always gains from trade in terms of comparative advantage, but they are offset in this world against trade costs: *ceteris paribus*, when the red district is capped at drawing its best technology ($z \approx 1.5$), it may still be hard for it to export in a frictional world. Turning to the solid lines (corresponding to $\theta = 2.5$), each district now has a wide spread of productivities. The red district is now likely to draw some varieties well (in which it may specialize) and the blue one may draw some poorly (which it may stop producing). Holding trade costs fixed, the forces of comparative advantage are stronger here.

[Figure 7 about here.]

Trade: Goods can be moved from district i to district j at a variable cost of the standard iceberg form: $\tau_{ij} \geq 1$ units must be shipped from i for 1 unit to arrive in j. These are good-invariant. I assume that goods are costless to distribute within districts ($\tau_{ii} = 1$) and that transport arbitrage ensures that no indirect routes are cheaper than the direct route ($\tau_{ik}\tau_{kj} \geq \tau_{ij}\ \forall i, j, k$). I assume that factors (labor and land) cannot move across districts.

Prices: Let w_i and r_i denote the wage for labor and rental rate for land in district i, respectively. Let p_i be the consumer price index for district i.

Market-clearing: Local markets in factors clear in each district, as does the global market for each good $\omega \in \Omega$. In addition, trade balance requires that total expenditures for each district equal total income.

Solution

The cost to a household in district j of good ω bought from district j is:

$$p_{ji}(\omega) = \frac{\tau_{ij} w_j^{\alpha} r_j^{1-\alpha}}{z_j(\omega)} \tag{7}$$

The Fréchet assumption on productivities tells us that the probability that district i faces the following prices from district j:

$$G_{ji}(p) = 1 - exp\left[-A_i\left(\frac{p}{\tau_{ij}w_j^{\alpha}r_j^{1-\alpha}}\right)^{\theta}\right] \tag{8}$$

Since each individual good is homogeneous, the representative consumer in i sources each good from the lowest-cost supplier (accounting for trade costs):

$$p_i(\omega) = min\left\{p_{i1}(\omega), p_{i2}(\omega), ..., p_{iN}(\omega)\right\} \tag{9}$$

Together, equations (7), (8), (9) and the fact that productivity-draws are independent imply that district i faces the following distribution of prices:

$$G_i(p) \quad = \quad 1 - \Pi_{j=1}^{N}\left[1 - G_{ij}(p)\right] = 1 - exp(-\Phi_i p^{\theta}) \tag{10}$$

where $\Phi_i = \sum_j A_j(\tau_{ij}w_j^{\alpha}r_j^{\alpha})^{-\theta}$. Note that this expression aggregates information on expected unit costs from all districts, as well as those districts' economic distance from i.

Given the CES form of the utility function and expression (10), we can derive the CES price index as:

$$p_i = \mathbb{E}\left[G_i(p)\right] = \gamma\Phi_i^{-1/\theta} \tag{11}$$

where $\gamma = \left[\Gamma(\frac{\theta+1-\sigma}{\theta})\right]^{1/(1-\sigma)}$ and Γ is the Gamma function.[19]

A convenient consequence of this framework is that the expenditure of district i on goods from any district j, X_{ij}, is a constant fraction of total expenditure in district i, X_i:

$$\frac{X_{ij}}{X_i} \equiv \lambda_{ij} = \frac{A_j(\tau_{ij}w_j^{\alpha}r_j^{1-\alpha})^{-\theta}}{\Phi_i} \tag{12}$$

where it is clear from the definition of Φ_i that $\sum_j \lambda_{ij} = 1$, $\forall i$.

I now rearrange the term representing unit costs in terms of the unit wage, using the fact that production is at constant returns to scale (so factor payments equal total output, Y_i):

[19] For the price-index to be well-defined, we require $\sigma - 1 < \theta$.

$$r_i T_i = (1-\alpha) Y_i = \frac{(1-\alpha)}{\alpha} w_i L_i \tag{13}$$

and therefore:

$$w_i^{\alpha} r_i^{1-\alpha} = w_i \left(\frac{1-\alpha}{\alpha} \right)^{1-\alpha} \left(\frac{L_i}{T_i} \right)^{1-\alpha}$$

Substituting this into (12), and solving for the real wage (w_i/p_i) in the case of $i = j$:

$$W_i \equiv \frac{w_i}{p_i} = \frac{1}{\gamma} \left(\frac{\alpha}{1-\alpha} \right)^{1/\alpha} \left(\frac{A_i}{\lambda_{ii}} \right)^{1/\theta} l_i^{\alpha-1} \tag{14}$$

where l_i is the population-land ratio, L_i/T_i. Consider the case of autarky, when the home trade-share λ_{ii} is one: in this case, it is easy to see that real wages are increasing in a district's overall level of productivity (A_i) and decreasing in its population-land ratio (l_i).

To close the model, notice that total expenditure in each district must equal total earnings, so we have a set of N trade-balance conditions:

$$w_i L_i + r_i T_i = \sum_j \lambda_{ij} (w_j L_j + r_j T_j) \tag{15}$$

Recalling from equation (13) that we can write r_i as a function of w_i, this means we have N equations in N unknowns (w_i), since all other variables in this expression are exogenous $\left\{ A_i, T_i, L_i, \{\tau_{ij}\}_{j=1}^{N} \right\}_{i=1}^{N}$. Therefore, given parameters, the equilibrium of this model is defined as the (N-1)-vector of wages implicitly given by (15), (up to a normalization). Alvarez and Lucas (2007) provide proofs of existence and uniqueness of equilibrium for this standard set-up, as well as numerical methods for solving for $N-1$ equilibrium wages.

3.3 Synthesis: Malthus and Ricardo

Recall that real wages in a Malthusian world are fixed by demographic parameters in equilibrium: economic fundamentals therefore determine population levels (and not real wages). We can simply invert Equation (14) and solve for population density as a function of economic and demographic fundamentals.

$$l_i = \left[\gamma \left(\frac{1-\alpha}{\alpha} \right)^{1/\alpha} \left(\frac{\lambda_{ii}}{A_i} \right)^{1/\theta} \bar{W}_i \right]^{1/(\alpha-1)} \tag{16}$$

This says that equilibrium population density is an increasing function of absolute advantage (A_i), and a decreasing function of the (demographically-determined) real wage, $\bar{W}_i$, and the home-trade share λ_{ii} (recall that this is endogenous, since it is a function of all district-level populations). More simply, we can express $\hat{l}_i$, the change in l_i resulting from a change in trade costs from $\{\tau_{ij}\}_{i,j \in N}$ to $\{\tau'_{ij}\}_{i,j \in N}$, as:

$$\hat{l}_i = \frac{l'_i}{l_i} = \left(\frac{\lambda'_{ii}}{\lambda_{ii}} \right)^{\frac{1}{\theta(\alpha-1)}} = \left(\hat{\lambda}_{ii} \right)^{\frac{1}{\theta(\alpha-1)}}$$

This resembles a standard elasticity result in a broad range of neo-Ricardian trade models: the more a district engages in trade (the lower λ_{ii}), the larger its equilibrium population. [20]

For the generic intermediate case, population increases only partially absorb income increases. Recall the introduction above of the parameter $\mu \in [0, 1]$, which I call "Malthusian-ness." A lower μ denotes a greater elasticity of long-run population to income. In this case, population density can be written as:

$$l_i = [\bar{l}_i]^{\mu} \left[\gamma \left(\frac{1-\alpha}{\alpha} \right)^{1/\alpha} \left(\frac{\lambda_{ii}}{A_i} \right)^{1/\theta} \bar{W}_i \right]^{(1-\mu)/(\alpha-1)} \tag{17}$$

where $\bar{l}$ and $\left(\bar{W}_i\right)$ represent the population and real wage associated with autarky.

Analogously, one can write real wages as:

$$W_i = [\bar{W}_i]^{1-\mu} \left[\frac{1}{\gamma} \left(\frac{\alpha}{1-\alpha} \right)^{1/\alpha} \left(\frac{A_i}{\lambda_{ii}} \right)^{1/\theta} \bar{l}_i^{\alpha-1} \right]^{\mu}$$

For any $\mu \in (0, 1)$, both real wages and population shift in response to changes in trade costs, with the extreme cases of $\mu = 0$ corresponding to the pure Malthusian case where population growth absorbs all welfare gains, and $\mu = 1$ corresponding to the modern demographic regime where welfare gains are reflected purely in factor rewards.[21]

[20] See Arkolakis et al. (2012) for a review.

[21] As before, another way to interpret μ is as an index of transition from one equilibrium $(L_0, W_0)_{i=1}^N$ to another $(L_T, W_T)_{i=1}^N$, as population gradually adjusts, i.e. where $\mu_0 = 1$ and $\mu_T = 0$.

3.4 Rainfall Shocks

I extend the model to incorporate an additional set of predictions about the welfare consequences of harvest shocks.[22] Consider rewriting $A_i = \phi_{it}\tilde{A}_i$, where ϕ_{it} represents a unit-mean district-specific productivity shifter (potentially correlated across districts) and $\tilde{A}_i$ represents permanent district-specific productivity. Holding population fixed (as is appropriate in the short run) and considering the autarkic case ($\lambda_{ii} = 1$), it is clear that real wages co-move with idiosyncratic rainfall shocks; the Malthusian component of the model therefore suggests that fertility will rise and mortality will fall.

$$\frac{w_{it}}{p_{it}} = \frac{1}{\gamma}\left(\frac{\alpha}{1-\alpha}\right)^{1/\alpha}\left(\frac{\phi_{it}\tilde{A}_i}{\lambda_{ii,t}}\right)^{1/\theta} l_{i,t}^{\alpha-1} \tag{18}$$

What does trade do in this context ($\lambda_{ii} < 1$)? Consider a shock to district i alone (i.e. $\phi_{it} \neq 1$, $\phi_{jt} = 1$ $\forall j \neq i$), as an extreme example of an idiosyncratic shock. λ_{ii} will co-move with ϕ_{it}: with a negative shock, imports rise and home-consumption falls, and with a positive shock, exports and home-consumption rise. Trade therefore smooths real incomes, and hence dampens demographic responses.

4 Empirical Strategy

Equation (16) represents a set of N equations (one for each district) in which the population l_i is a function of parameters, the home trade-share, productivity, and the (Malthus-determined) real wage. In principle, given data on the proportion of district agricultural output that is produced domestically and district-specific real wages, one could estimate the parameters of this model (the labor share of income α and the comparative-advantage parameter θ). In this paper, I use the model to generate three predictions about the consequences of trade cost reductions for demographic change, and test for these responses using the railroads as a proxy for trade costs. I then calibrate the model using estimates in the literature to estimate counterfactual changes in real wages in the absence of Malthusian effects.

Prediction 1: After the railroad arrives in a district, the welfare gains associated with trade should be reflected in higher fertility and lower mortality.

[22] This exercise follows Donaldson and Burgess (2012), who document *inter alia* attenuated mortality responses to rainfall in the wake of the railroads.

Prediction 2: In the long run, districts with railroads should have larger populations.

Prediction 3: After the railroad arrives in a district, fertility and mortality should be less responsive to rainfall shocks than they were before.

In all cases, I employ fixed effects regressions with district and year dummies throughout, with robust standard errors clustered at the district level. Coefficients of interest are therefore identified by changes in outcome variables before and after the arrival of the railroad, *relative* to aggregate time-patterns in those outcome variables. The principal threats to identification are the targeting of districts that are trending (relative to the aggregate) upwards in population or fertility, or downward in mortality. Donaldson (2018) presents complementary evidence that is reassuring in one important respect: his estimate of the impact of railroads on real agricultural income (relying on a similar two-way fixed effects specification) is robust to a variety of placebo tests, suggesting that British rail planners were not (successfully) targeting regions that were about to see increases in agricultural income in the absence of railroads. I employ his placebo tests, which I describe in more detail below, check for leading/lagging effects of the railroads in a dynamic specification. My results throughout are robust to the inclusion of province-year fixed effects, ruling out that my findings are driven by regional differences in demographic trends.

4.1 Prediction 1

I run regressions of the following form, for outcomes y_{it} at the level of district i and year t:

$$y_{it} = \mu_i + \nu_t + \beta rail_{it} + \epsilon_{it}$$

My dependent variables are my corrected measures of the (logs of) the crude birth rate (CBR) and the crude death rate (CDR) per thousand. These measures can be constructed both from the raw data (using interpolated intercensal population counts as denominators, and raw measures as enumerators), as well as from my corrected data; I present both sets of results and comment on differences where salient.

The model predicts $\beta > 0$ for fertility and $\beta < 0$ for mortality.

I also run specifications of the form:

$$y_{it} = \mu_i + \nu_t + \sum_k \beta_k railyears_{ikt} + \epsilon_{it}$$

where $railyears_{ikt}$ is a dummy for whether district i in year t is in its k'th period of having the railroad. I define k in quinquennial periods (that is, 10-6 years before arrival, 5-1 years before arrival, 0-4 years after arrival, and so on) from 10 years before to 20 years after the railroads' arrival, with an additional dummy for all years after 20. The β_k here therefore reflects the impact of railroads by period relative to their average 10 years before the railroads' arrival.

4.2 Prediction 2

For prediction 2 (regarding long-run change), I can extend my panel backward and forward a decade to examine long-run changes in population density as a function of the railroads. This covers a period of 70 years, from 1871 to 1941 (six years before Independence in 1947), where the railway network is mostly complete by 1921. This is a conservative (lower-bound) measure of the long run to the extent that population growth trajectories continued to diverge across railroad and non-railroad districts through to the modern day.[23]

The specification is as above, using (logged) Census population totals for each district over 1871-1941.

$$pop_{it} = \mu_i + \nu_t + \beta rail_{it} + \epsilon_{it}$$

The model predicts $\beta > 0$.

I also employ my corrected demographic data (which allow the construction of an annual district-level population series that is consistent with the Censuses by construction), though it covers a shorter time-span (1881-1931) and a smaller set of districts.

[23] Other factors may have driven population trajectories to converge (e.g. agricultural productivity improvements associated with the Green Revolution, targeted infrastructural policies for non-railroad districts). Testing long-run patterns of population growth at the district level from the colonial era to today requires more careful matching of pre-Independence to post-Independence district boundaries, as well as an accounting for the amalgamation of the princely states into the Indian Union and migratory flows associated with partition of Pakistan. This work is in progress.

4.3 Prediction 3

For prediction 3, regarding harvest shocks, I regress crude vital rates on dummies for railroad status, a rainfall shock, and the interaction between the two:

$$y_{it} = \mu_i + \nu_t + \beta rail_{it} + \gamma shock_{it} + \xi \left[rail_{it} \times shock_{it} \right] + \epsilon_{it}$$

I define rainfall in year t as the sum of rainfall over the *preceding* southwest monsoon (July-September) and the northeast monsoon (October-December), that is, at $t-1$.[24] Given the patterns of responsiveness of fertility and mortality by deviations from district-specific means (see Figure 8), there is no evidence of a monotonic relationship between rainfall and vital rates - at high levels of rainfall (over 50% of the mean), mortality appears to rise and fertility appears to fall. I therefore define a negative shock as rainfall that is 50% or more below the district-specific mean.

The model predicts $\beta < 0$, $\gamma > 0$, and $\xi < 0$ for mortality, and the opposite signs for fertility.

[Figure 8 about here.]

5 Data

For prediction 1, I employ a new dataset of corrected birth rates and death rates I have developed for colonial India over this period (1881-1931) for the rural districts of the five major British India provinces of:

- Bengal (including Bihar and Orissa),
- Bombay (including Sindh),
- the Central Provinces (including Berar),
- Madras, and
- the United Provinces of Agra and Oudh.

[24] Contemporaneous rainfall appears to have no systematic correlation with births, which makes sense given a gestation period of nine months. For deaths, a qualitatively similar but statistically weaker relationship exists with contemporaneous rainfall: when both current and lagged rainfall are included, only lagged rainfall is significant.

Together, these provinces account for a population of 190 million in 1901, across 626,000 square miles and 167 districts. This represents four-fifths of British India by population, or two-thirds by area/districts.

[Figure 9 about here.]

The raw vital registration data that provides district-level statistics on births and deaths are notoriously under-registered, differentially across time and districts, and have rarely been used in the quantitative study of South Asian economic history; I employ matched district-level data on age distributions in the Census, and reconcile these figures with each other using tools from empirical demography, some mild assumptions about the nature and levels of underregistration, and computationally-intensive simulation techniques.

Figure 10 illustrates one high-level output from this exercise: corrected crude birth and death rates, compared to reported rates. The vertical gap between the two lines corresponds to the degree of underregistration in a given year: a function of district-specific age- and gender-composition in the case of deaths, and simply district- and gender-specific underregistration in the case of births. In aggregate, the raw counts suggest that there were 204 million deaths and 237 million births over this period: my corresponding corrected counts are 301 million and 384 million, suggesting that only about two-thirds of vital events were registered. I refer the interested reader to Ahmad (2018) for technical details, as well as a descriptive exploration of other outputs of this exercise, including crude vital rates, age-specific mortality rates, and life-expectancy measures.[25]

[Figure 10 about here.]

I construct a dataset on railway arrivals by district using the publication *History of Indian Railways Constructed and In Progress* (1918, 1946). I code a district rail dummy as positive from the year of arrival onwards. Some districts have lines that run through them many years before their headquarters are reached by rail (if ever): depending on how these are described in provincial administrative reports and imperial gazetteers (e.g. "carrying important produce from the district"), I code the district as connected from that branch-line forward. I cross-checking my coding with that of Donaldson (2018) for consistency, and employ

[25]My preferred specifications involve the use of district and year fixed effects: these absorb much of the (substantial) cross-district variation in registration levels and the cross-year changes in overall registration levels that I report in Ahmad (2018). Differences in my corrected estimates relative to that of the raw data should be interpreted as arising from a combination of district-specific deviations from aggregate trends in overall underregistration and aggregate age/gender-composition (since I find that under-registration is heavily influenced by the age and gender structure of the population).

his data for placebo checks, which draw on colonial Indian railway planning documents and two mid-19th century plans for railways published by colonial authorities in 1848 (the Kennedy Plan) and 1868 (the Lawrence Plan).

For prediction 2, I rely only on reported Census counts of the total population, which is less vulnerable to problems around inconsistent interannual flows. In Ahmad (2018), I document substantial underenumeration of under-five year-olds: as above, in this setting, district and year fixed-effects absorb much of this variation, and results based on my estimates of Census counts are similar to those for reported counts.

For prediction 3, I employ rainfall data collected from:

1. 1870-1900: John Eliot's (1902) Meteorological Memoirs of India contains monthly station-level rainfall data for 446 stations across India, reaching back as far as the 1810s for some districts. This source covers British India (Pakistan, India, and Bangladesh) as well as some native states.

2. 1900-1930: The Global Historical Climatology Network (GHCN) Daily dataset on rainfall (Menne et al. (2012)) provides daily station-level rainfall data from January 1, 1900 onwards, which I aggregate up to the monthly level. For the 1900-1930 period, only stations now in modern-day India are included.

3. 1900-1930: For stations now in Pakistan and Bangladesh, I use the Rainfall of India series (1891-1914) and Daily Rainfall of India series (1915-1930), which includes provincial summaries of monthly rainfall by recording station.

I match across these sources when necessary using station names, cross-checking with station-specific latitude/longitude/elevation data when provided (in Eliot (1902) and Menne et al. (2012)), and through overlaps (Rainfall of India and Eliot (1902)). I use each district headquarters' rainfall as my measure of district-specific rainfall; for the handful of cases where this is not available, I use the closest matching station (within 50 km of the district headquarters).[26]

[26]For example, Anantapur, eponymous headquarters of a newly-created district in the Madras Presidency as of 1882, has no reported rainfall data, but Gooty, 50 km away, is reported consistently in Eliot (1902) and Menne et al. (2012).

6 Results

6.1 Prediction 1: Vital Rates and the Railroads

Tables 1 and Table 2 show the average effect of railroads on mortality and fertility, respectively: I find that crude death rates fall by about 11%, and crude birth rates rise by 5%, following the arrival of the railroad in a district.

I include in columns (2)-(4) Donaldson's (2018) placebo checks for planned (but unbuilt) railroads: in his own study, he finds that these do not predict agricultural income growth (whereas the railroads themselves do). We should therefore have good reason to believe they are unlikely to predict demographic outcomes that are mediated by that agricultural income. The first column is a set of dummy variables drawn from colonial railway planning reports on railroads abandoned after being planned, reconnoitered, or surveyed in district i at time t. Each railway ultimately built passed through these four stages successfully: to the extent that passing through these stages suggest foresight or expectations of the railway planners, we would expect them to predict (successively better with each stage) demographic outcomes. The second placebo check draws on Viceroy John Lawrence's 1868 plan, which presents over six five-year phases (from 1868 to 1898) a framework for rolling out the railways across India from the initial branch lines built by his predecessor. Lawrence's plan was never followed after his successor, in a cost-saving measure, decided to slow down the rate of railway expansion. To the extent that Lawrence's plan was based on an anticipation demographic trends, we would expect to find a systematic pattern of growth synchronized to his plan. I do not, although his plan does appear to "predict" a mortality fall in 1884-9 and a fertility rise in 1889-1893. This suggests less foresight, perhaps, than the extreme idiosyncratic volatility of vital rates given harvest shocks. Finally, an 1848 plan drawn up by India's chief engineer, Major Kennedy, may plausibly have targeted areas expected to grow faster than average. As in Donaldson (2018), I interact Kennedy's identified "high-" and "low-priority" districts with a time-trend, and find no evidence that these predict demographic outcomes. In all cases, the coefficient on the direct railroad connection variable itself remain stable.

Figures 11 and 12 show the dynamic effects of railroad arrival on fertility and mortality, from 15 years before to 20 years after, in quinquennial periods. These suggest the possibility of an anticipatory effect only in the years just before the railroad arrives, though it is statistically insignificant in both cases. One reason for this may be a spillover from the arrival of the railroads in neighboring districts, increasing market access before a district is "treated" with its own railroad connection (a similar though insignificant anticipatory increase in agricultural income is apparent in Donaldson's dataset).[27]

[Table 1 about here.]

[Table 2 about here.]

[Figure 11 about here.]

[Figure 12 about here.]

6.2 Prediction 2: Population Counts and the Railroads

Table 3 shows the results of three regressions of railroads on district population density measured at Census intervals: OLS, FE (district dummies only), and two-way (year and district dummies). The final column suggests that the effect of railroads on long-run population levels (over this seventy year period, 1871-1941) is around 5.6%.[28]

[Table 3 about here.]

I also examine the shorter period (1881-1931) over which I have annual population figures from my demographic correction exercise. These suggest an even larger increase (8%, within the confidence interval of my first estimate), and is robust to the inclusion of Donaldson's (2018) placebo checks. The differences stem partly from the shorter horizon (as population growth accelerates in 1930s across early, late-, and non-railroad districts), as well as the smaller unbalanced sample for which I can reconstruct annual population measures. I use 6% going forward as a conservative measure of population's long-run responsiveness to the railroad.

[Table 4 about here.]

[27] Another potential mechanism for an anticipatory effect is the boost in local labor demand during the construction phase before a new line opens, discussed qualitatively in colonial reports about railroad construction but not apparent in the wage data for this period.

[28] This is robust to the use of my simulated Census counts (corrected for underenumeration), as well as to the restricted time period used in the vital rates regressions of Predictions 1 and 3 (1881-1931).

I also check that increases in population density are not explained by differential migration across railroad qand non-railroad districts, using data from each Census on the proportion of the population enumerated in each district that was born in that district and year (1891, 1901, 1911, 1921 and 1931) on the left-hand side. The coefficient on the railroad dummy is extremely small and statistically insignificant (p-value: 0.54), implying that areas receiving railroads saw a 0.05% *increase* in the share of home-born population. This suggests that the main drivers of the population increase we observe are in fact differential changes in fertility and mortality (discussed above), rather than differential migration.

6.3 Prediction 3: Rainfall, Railroads, and the Attenuation of Vital Rate Responsiveness

Table 5 presents the results of a regression of crude death rates on a lagged negative rainfall shock (defined as one that is 50% below the mean), the railroad, and an interaction between the two. For both the corrected and raw data, the shock and the rail coefficients have the correct sign, but the data corrections result in a much larger magnitude and a clear sign on the interaction coefficient. The sum of the coefficients is not significantly different from zero ($F = 1.08$).

For fertility (Table 6), the negative effect of rainfall on fertility is clearly identifed - note that the coefficient here (6%) is much smaller in magnitude than that for mortality (46%). However, the railroad and interaction terms cannot be distinguished statistically from zero.

[Table 5 about here.]

[Table 6 about here.]

7 Discussion

So far, I have established that the railroads appear to have had a causal impact on demographic outcomes at the local level in a manner consistent with the Malthusian-augmented trade model I derived: mortality fell and fertility rose, and populations are larger in railroad districts. I now conduct a simple calibration exercise to back out a counterfactual estimate of real wages foregone if the population growth I estimate represents total Malthusian absorption of those gains. I also discuss the interpretation of my findings, in particular their consistency with a Malthusian mechanism, and further steps.

7.1 A Calibration

I undertake a simple calibration exercise, taking my model above seriously in order to estimate how much higher real wages would have been if India had undergone its demographic transition a century earlier. Specifically, what would real wages have been if India had counterfactually received the railroads around the time in its demographic history as continental Europe had, such that the welfare gains from trade were reflected purely in higher incomes rather than in higher populations?[29]

My starting point is that $\hat{l}_i = (\lambda_{ii})^{\frac{(1-\mu)}{\theta(\alpha-1)}}$ implies $\lambda_{ii} = \hat{l}^{\frac{\theta(\alpha-1)}{(1-\mu)}}$.

I calibrate the parameters and $\bar{\hat{l}}$ to recover $\bar{\hat{\lambda}}$ under the assumption that $\mu = 0$ (that is, that population increases fully absorb workers' gains from trade), and then reverse the operation to determine the counterfactual real wage in the case that $\mu = 1$ (that is, that population levels are fixed and all gains from trade are reflected in factor income).

- $\bar{\hat{l}} = 1.056$: long-run elasticity of population density to the railroads (estimated above in Section 6.2), range: +/- 1 SE (0.021)
- $\mu = 0$: assumes that all gains from trade are reflected in population, range 0-0.2
- $\theta = 3.2$ from Donaldson (2012), average across crops. 1 SD range: 2.6-5.0
- $\alpha = 0.5$ from Evenson et al. (1999) for India in the 1950s. Range 0.4-0.6.

Altogether, these imply $\bar{\hat{\lambda}} \in [0.70, 0.94]$ with 0.89 as the central estimate. That is, a district with a railroad typically sees a reduction of around 11% in the fraction of consumption that is produced domestically.

Therefore, the counterfactual real wage (with $\mu = 1$) is $\hat{W} = \bar{\hat{\lambda}}^{-1/\theta}$. This means that real wage gains

[29]The comparison of *welfare* across the factual and counterfactual is not straightforward: indeed, the standard utilitarian view leads to the Repugnant Conclusion that for any population and level of welfare, there exists some sufficiently larger but much poorer population that has higher aggregate welfare by simple virtue of summing up utilities. See Parfit (1984). Golosov et al. (2007) provide a theoretical exploration of welfare theory in the context of endogenous populations, where one must contend with valuing the welfare of unborn agents.

(counterfactually) would have been in the range of 1.4 to 5.7%, with a central estimate of 2.8%.[30] In the context of what we know about wage growth under British rule, these counterfactual gains are substantial: Roy's (2005) time-series of real agricultural wages in India show that they grew only 2.5% between 1873 and 1941.

7.2 Further Steps

The fact that demographic responses appear to *lead* the arrival of the railroads by several years may reflect in part the reduction in trade costs associated with the approach of the railroads. This suggests that a better measure of trade costs would be the distance of a district's headquarters from the nearest railroad (rather than a dummy for the railroads' arrival in a district, as I use here). Constructing such a measure requires creating GIS maps of the expansion of the railroad network branch by branch; I leave this for future work.

Donaldson (2018) has shown that it is possible to construct meaningful data on real agricultural output from colonial data on yields, acreage, and prices. This is important for validating the mechanisms for the findings of this paper, as a means of estimating changes in income, the degree of crop specialization, and distinguishing between the population growth on the extensive and intensive margins of cultivation. I have begun preliminary work to gather these data for 1900-1930 for all districts, and am extending my coverage backwards as reports allow.

The model here, in common with the literature on Malthusian growth theory, features a single representative household. The distribution of income within districts (and in particular, the distribution of the gains from trade) should have implications for the demographic responses to the railroad. The demographic responses I find suggest that some of the gains from trade did in fact feed through to small peasant households and laborers, who constitute the largest share of the population, but the strength of these responses across districts ought to vary systematically with the degree to which these gains were shared with other groups in society.

Three other groups are important to consider: landlords, the colonial state (as a recipient of taxes levied on gross agricultural output), and commercial intermediaries (who, with some degree of market power, may

[30]Mechanically, note that the comparative-advantage parameter θ does not matter for the counterfactual wage estimate: as θ rises, the same estimated population increase $\bar{\hat{l}}$ is associated with larger reductions in the home trade share $\bar{\hat{\lambda}}$, but this is offset exactly by the decreased responsiveness of wages to the home-trade share $(-1/\theta)$.

have commanded some of the surplus associated with the gains from trade). There is some cross-district variation in the degree of landholding inequality and in tax rates that could be exploited here, though quantitative data on intermediaries is scarcer. Direct evidence from wages are also potentially informative about distributional effects: I have collected data on district-level nominal wages 1873-1906 from the *Prices and Wages* series, and plan to supplement it with data from the quinquennial provincial wage surveys through the early 1930s. The land-revenue data are more difficult to collect systematically across provinces and time, though I have begun to assemble sources to do so for two of the five major provinces in my study (the Presidencies of Madras and Bombay).

8 Conclusion

In this paper, I argue that demography is an important means of understanding economic change in colonial India. I present a model in which I combine the Malthusian insight that population increases absorb all income gains associated with growth with the Ricardian insight that opening up to trade brings income growth. This model suggests that vital rates respond to changes in trade costs in the short run, and hence that population levels respond to trade costs in the long run.

Using the case of the British-built railroads of India, I document that mortality responses are consistent with the notion that populations are responsive to economic change. Mortality falls in the aftermath of the arrival of the railroads, by about 9% on average, fertility rises about 4%, and districts ultimately end up being about 6% denser. I consider explicitly the counterfactual of the railroads in the absence of Malthusian responses, which suggests real wage gains on the order of 3%.

This exercise suggests we may need to revisit our understanding of the weak link between trade and growth in the preindustrial developing world. For developing colonies and nation-states drawn into global trading networks during the first globalization of the late 19th century, it appears likely that some of the gains from trade may also have appeared in the form of people rather than per-capita incomes. Further research on economic demography outside of Western Europe utilizing local archival sources may be able to validate this mechanism in other contexts. More broadly, this work underlines the importance of accounting for endogenous population change when constructing economic counterfactuals for pre-demographic-transition societies.

Appendix A: Microfounding Malthus

In the paper, I work primarily with aggregate relationships that relate vital rates (births and deaths) to real wages to simplify the exposition. In this appendix, I sketch some standard micro-foundations for these relationships. This treatment of fertility is standard in a broad range of Malthusian growth models, which treat children as a normal good.[31] The mortality relationship here is similar to that used in Jones (2001) or Voigtlander and Voth (2013).

Consider a household with a utility function of the Stone-Geary class:

$$U(F,C,B) = (F - \bar{F})^{\gamma_1} C^{\gamma_2} B^{\gamma_3} \tag{19}$$

where F represents food, C a composite good (called clothing for convenience), and B births.[32] A subsistence level of food $\bar{F}$ imposes a lower-bound on food demand as income falls. An alternative way of interpreting B is as the number of children who survive to some age, conditional on exogenous mortality under that age.

The positive relationship between fertility and income follows immediately: the household allocates the first $p_F\bar{F}$ of their income y to subsistence consumption, and the remaining supernumerary income is divided according to the Cobb-Douglas preference weights. Therefore, equilibrium fertility is given by:

$$B^*(\vec{p}, y) = \gamma_3 \frac{y - p_F\bar{F}}{p_B} \tag{20}$$

The negative relationship between mortality and income requires additional structure. Consider the following function for mortality as a function of food consumption F:

$$D(F) = \bar{D}(\frac{F}{\bar{F}})^{-\delta} \tag{21}$$

When $F = \bar{F}$, the death rate is $\bar{D}$, which we can think of as representing subsistence mortality. As food consumption deviates from that level, the mortality-consumption relationship is governed by a constant

[31] Several models, e.g. Galor and Weil (2000), emphasize the Becker (1960) notion of the quality-quantity trade-off.

[32] One can think of F and C here as composites of a continuum of Dixit-Stiglitz varieties, the kind used in the neo-Ricardian model I set out above.

elasticity parameter $\delta > 0$. As δ grows, mortality is more responsive to changes in food consumption.

Plugging in optimal food consumption, $F^*(\vec{p}) = \bar{F} + \gamma_1 \frac{y - p_F \bar{F}}{p_F}$, I derive mortality as a function of prices and income:

$$\bar{D}(\vec{p}, y) = \bar{D}\left(1 + \frac{\gamma_1(y - p_F\bar{F})}{\bar{F}p_F}\right)^{-\delta} \tag{22}$$

It is straightforward to see that demographic elasticities with respect to income are signed correctly:

$$\frac{\partial B^*}{\partial y} = \frac{\gamma_3}{p_B} > 0$$

$$\frac{\partial D^*}{\partial y} = -\frac{\delta\gamma_1\bar{D}}{\bar{F}p_F}\left(1 + \frac{\gamma_1 y}{\bar{F}p_F}\right)^{-\delta-1} < 0$$

Demographic equilibrium (no growth) requires that births balance deaths: i.e. that (20) equals (22): the y^* at which this is true defines the equilibrium level of income consistent with no growth.

$$\gamma_3\frac{y^* - p_F\bar{F}}{p_B} = \bar{D}\left(1 + \frac{\gamma_1(y^* - p_F\bar{F})}{\bar{F}p_F}\right)^{-\delta}$$

What can we say about it? Comparative statics results are obtained by implicit differentiation, and are intuitive:

- a stronger preference for births (γ_3) or a lower price (p_F) results in a higher y^*.
- higher baseline mortality ($\bar{D}$), taste for food (γ_1), or δ (food-death elasticity) results in a higher y^*.

Note that the existence of the clothing sector makes clear that real wage changes are possible without driving demographic change. If the price of clothing falls, $p_C \downarrow$, then y rises in real terms but birth and death rates are unchanged.[33] This does not pose a generic problem for the existence of Malthusian steady-states or the properties of short-run Malthusian dynamics: if the demography-relevant good (here, F) has a large enough weight in consumption baskets, as we expect for a settled agrarian economy near subsistence levels

[33] This is the insight of Wu (2013) and Wu et al. (2014) that the existence of such a "luxury" sector renders the iron law of wages less than iron-clad.

of consumption, then changes in the prices of non-essentials will only drive a small wedge between the real income and the demography-relevant real income.

References

Ahmad, Shameel. 2015. "Midnight's Elders: Reconstructing District-Level Populations for British India." *Working Paper.*

Alvarez, F, and R E Lucas. 2007. "General equilibrium analysis of the Eaton–Kortum model of international trade." *Journal of Monetary Economics.*

Andrabi, Tahir, and Michael Kuehlwein. 2010. "Railways and Price Convergence in British India." *The Journal of Economic History*, 70(02): 351–377.

Banerjee, Abhijit V, Esther Duflo, and Nancy Qian. 2012. "On the road : access to transportation infrastructure and economic growth in China."

Bhat, PN Mari. 1989. "Mortality and Fertility in India, 1881-1961: A Reassessment." In *Indias historical demography studies in famine, disease and society.* , ed. Tim Dyson, 73–118. London:London : Curzon.

Bogart, Dan, and Latika Chaudhary. 2013. "Engines of growth: the productivity advance of Indian railways, 1874–1912." *The Journal of Economic History.*

Bogart, Dan, Latika Chaudhary, and Alfonso Herranz-Loncan. 2015. "The Growth Contribution of Colonial Indian Railways in Comparative Perspective." *SSRN Electronic Journal.*

Broadberry, Stephen, and Bishnupriya Gupta. 2012. "India And The Great Divergence: An Anglo-Indian Comparison Of GDP Per Capita, 1600-1871."

Burgess, R, and Dave Donaldson. 2010. "Can openness mitigate the effects of weather shocks? Evidence from India's famine era." *The American Economic Review*, 100(2): 449–453.

Davis, Kingsley. 1951. *The population of India and Pakistan.* Princeton:Princeton University Press.

Donaldson, Dave. 2010. "Railroads of the Raj: Estimating the Impact of Transportation Infrastructure."

Dyson, Tim, and Cormac O'Grada, ed. 2002. *Famine demography: perspectives from the past and present.* Oxford, UK:Oxford University Press.

Eaton, Jonathan, and Samuel Kortum. 2012. "Putting Ricardo to Work." *Journal of Economic Perspectives*, 26(2): 65–90.

Eaton, Jonathan, and S Kortum. 2002. "Technology, geography, and trade." *Econometrica.*

Esteves, R, and A Herranz Loncán. 2015. "Big push or big grab? Railways, government activism, and export growth in Latin America, 1865–1913." *The Economic History ....*

Fishlow, Albert. 1965. *American railroads and the transformation of the antebellum economy.* Cambridge:Harvard Univ Press.

Fogel, Robert William. 1962. "A quantitative approach to the study of railroads in American economic growth: a report of some preliminary findings." *The Journal of Economic History.*

Fogel, Robert William. 1964. "Railroads and American economic growth: essays in econometric history."

Galor, Oded. 2011. *Unified Growth Theory.* Princeton:Princeton University Press.

Galor, Oded, and Andrew Mountford. 2006. "Trade and the great divergence: the family connection."

Galor, Oded, and Andrew Mountford. 2008. "Trading Population for Productivity: Theory and Evidence." *Review of Economic Studies*, 75(4): 1143–1179.

Galor, Oded, and D N Weil. 1999. "From Malthusian stagnation to modern growth." *American economic review.*

Galor, Oded, and D N Weil. 2000. "Population, technology, and growth: From Malthusian stagnation to the demographic transition and beyond." *American economic review.*

Golosov, M, L E Jones, and M Tertilt. 2007. "Efficiency with endogenous population growth." *Econometrica.*

Hawke, Gary Richard. 1970. *Railways and economic growth in England and Wales, 1840-1870.* Clarendon Press.

Herranz-Loncan, Alfonso. 2006. "Railroad impact in backward economies: Spain, 1850–1913." *The Journal of Economic History.*

Herranz-Loncan, Alfonso. 2007. "Infrastructure investment and Spanish economic growth, 1850–1935." *Explorations in Economic History.*

Hurd, John. 1983. "Railways." In *The Cambridge economic history of India.* Cambridge:Cambridge University Press.

Jedwab, R, and A Moradi. 2015. "The Permanent Effects of Transportation Revolutions in Poor Countries: Evidence from Africa." *Review of Economics and Statistics.*

Maddison, Angus. 2007. *Contours of the World Economy 1-2030 AD: Essays in Macro-Economic History.* OUP Oxford.

Maharatna, Arup. 1996. *The demography of famines: an Indian historical perspective.* Delhi; Bombay:Oxford University Press.

Menne, M J, I Durre, S Korzeniewski, K McNeal, K Thomas, X Yin, S Anthony, R Ray, R S Vose, B E Gleason, and T G Houston. 2015. "Global Historical Climatology Network - Daily (GHCN-Daily), Version 3.22 NOAA National Climatic Data Center."

Metzer, J. 1974. "Railroad development and market integration: the case of Tsarist Russia." *The Journal of Economic History*, 34(03): 529–550.

Mukherjee, Mukul. 1980. *Railways and Their Impact on Bengal's Economy, 1870-1920.* Indian Economic & Social History Review.

Parfit, Derek. 1984. *Reasons and Persons.* Oxford University Press.

Ravallion, Martin. 1987. *Markets and famines.* Oxford; New York:Oxford University Press.

Roy, Tirthankar. 2005. "Agricultural Labor and Economic Transition in Colonial India: Lessons from Wage Data." *Working Paper.*

Sen, A. 1981. "Ingredients of famine analysis: availability and entitlements." *The quarterly journal of economics*, 96(3): 433.

Stolper, W F, and Paul A Samuelson. 1941. "Protection and real wages." *Review of Economic Studies*.

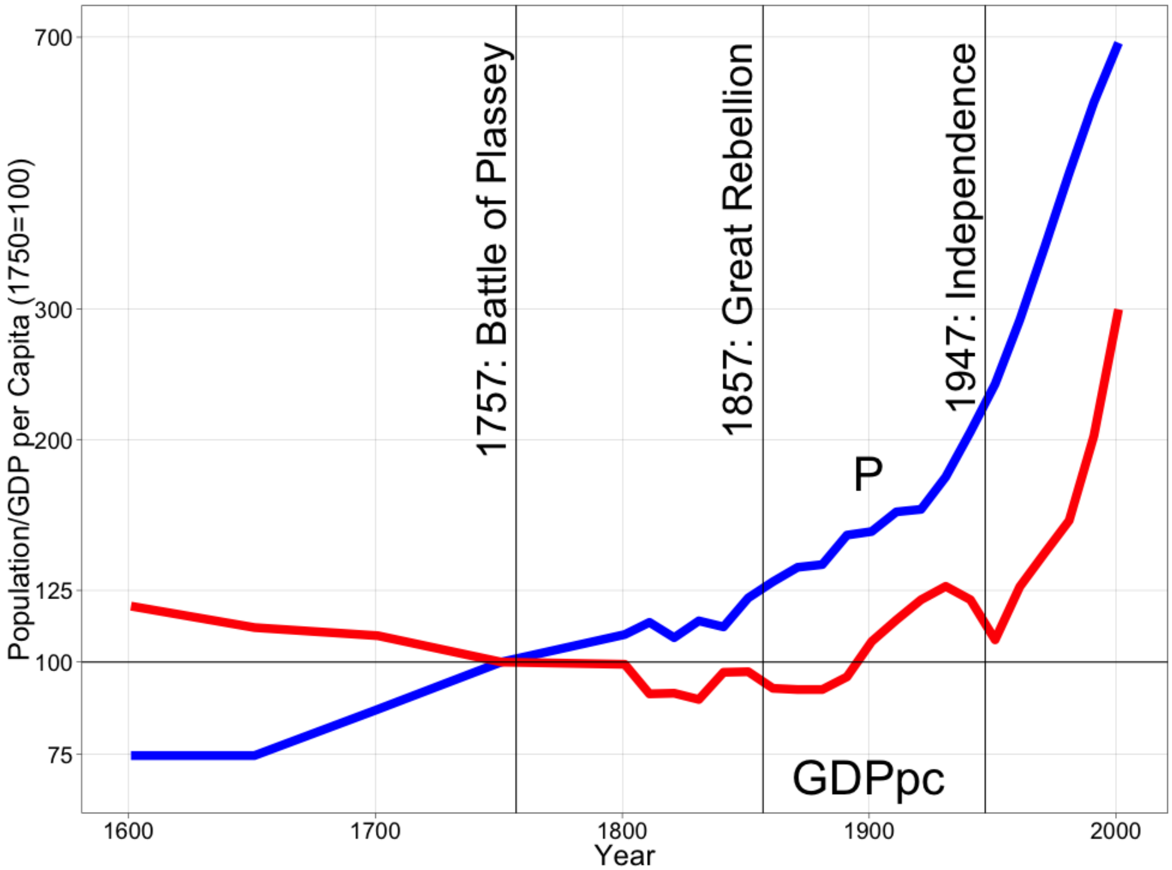
Storeygard, A. 2013. "Farther on down the road: transport costs, trade and urban growth in sub-Saharan Africa." *World Bank Policy Research Working Paper*.

Summerhill, W R. 2005. "Big social savings in a small laggard economy: railroad-led growth in Brazil." *The Journal of Economic History*.

Visaria, Leela, and Pravin Visaria. 1983. "Population (1757-1947)." In *The Cambridge economic history of India*. 463–532. Cambridge:Cambridge University Press.

List of Figures

Figure 1: Components of South Asian Economic Growth, 1600-2000



Source: Heston (1982), Maddison (2003), Broadberry and Gupta (2010)

Figure 2: Excerpted Sources

Births Registered in the Districts of the Madras Presidency during the Year 1876.

1	2			3	4			5			6			7	8	9
Number.	Population according to the Census of 1871.			Districts.	Population for which Returns were received.			Number of Births Registered.			Ratio of Births per 1,000 of Population.			Number of Males born to every 100 Females born.	Excess of Births over Deaths per 1,000 of Population.	Excess of Deaths over Births per 1,000 of Population.
	Males.	Females.	Total.		Males.	Females.	Total.	Males.	Females.	Total.	M.	F.	Total.			
1	695,090	693,529	1,388,619	Ganjam	608,101	602,155	1,210,256	14,179	12,696	26,875	23·3	21·1	22·2	115·9	1·9	...
2	490,515	902,988	1,843,503	Vizagapatam	814,728	783,779	1,598,507	13,349	13,392	26,741	16·3	17·1	16·7	99·6	2·8	...
3	803,149	788,954	1,592,103	Godavery	803,149	788,954	1,592,103	16,466	15,805	32,271	20·4	20·03	20·2	104·1	...	5·4
4	737,319	714,747	1,452,066	Kistna	737,319	714,747	1,452,066	14,037	13,509	27,546	19·03	18·9	18·9	103·9	...	1·2

(a) Births

Deaths Registered according to Age in the Districts of the Madras Presidency during the Year 1876.

1	2	3		4		5		6		7		8		9		10		11	
Number.	Districts.	Under 1 year.		1 year and under 6.		6 years and under 12.		12 years and under 20.		20 years and under 30.		30 years and under 40.		40 years and under 50.		50 years and under 60.		60 years and upwards.	
		Males.	Females.	Males.	Females.	Males.	Females.	Males.	Females.	Males.	Females.	Males.	Females.	Males.	Females.	Males.	Females.	Males.	Females.
1	Ganjam	2,061	1,765	2,223	2,194	1,290	1,018	949	948	1,402	1,321	1,810	827	1,165	744	1,155	941	1,656	1,646
2	Vizagapatam	1,423	1,356	1,618	1,549	977	836	980	1,009	1,278	1,266	1,334	1,105	1,259	1,034	1,440	1,234	1,247	1,311
3	Godavery	2,308	1,993	2,778	2,548	1,929	1,524	1,687	1,867	2,616	2,606	2,295	1,724	2,087	1,331	2,075	1,735	3,734	4,014
4	Kistna	1,664	1,431	2,301	2,119	1,357	1,144	1,115	1,272	1,522	1,791	1,184	1,030	1,225	831	1,648	1,138	3,513	2,931
5	Nellore	1,089	896	1,679	1,526	1,189	949	918	1,097	1,428	1,207	1,817	1,011	1,299	874	1,516	1,026	2,901	2,860

(b) Deaths by Age

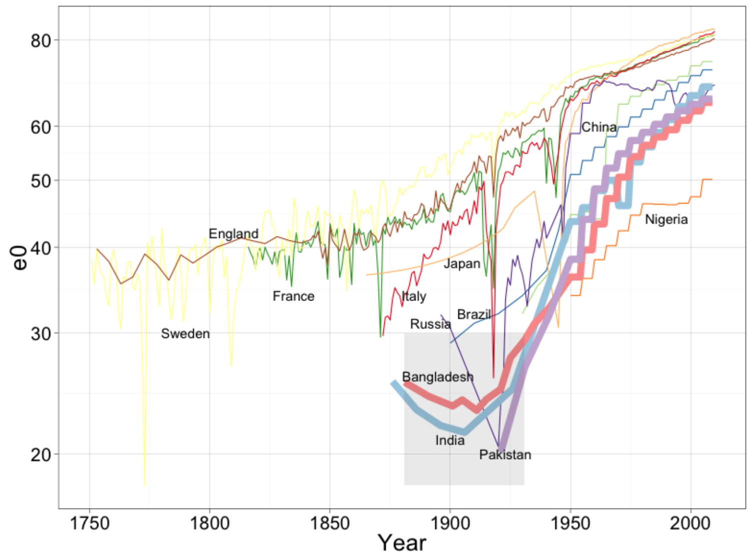
Age, sex and civil condition. Part I.—Districts and States—*continued.*

RELIGIONS.	AGE.	POPULATION.			UNMARRIED.			MARRIED.			WIDOWED.		
		Persons.	Males.	Females.	Persons.	Males.	Females.	Persons.	Males.	Females.	Persons.	Males.	Females.
1	2	3	4	5	6	7	8	9	10	11	12	13	14
	KISTNA—*concluded.*												
HINDU ...	TOTAL...	*1,964,325*	*977,591*	*986,734*	*829,280*	*490,330*	*338,950*	*899,611*	*441,591*	*458,020*	*235,434*	*45,670*	*189,764*
	0-1 ...	54,998	27,551	27,447	54,970	27,539	27,431	28	12	16	...	...	...
	1-5 ...	183,959	90,495	93,464	183,426	90,344	93,082	501	148	353	32	3	29
	5-10 ...	257,931	123,988	133,943	251,428	123,192	128,236	6,226	75[illegible]	5,476	277	46	231
	10-15 ...	250,280	127,687	122,593	200,214	123,500	76,714	48,150	4,007	44,143	1,916	180	1,736
	15-20 ...	179,959	96,704	83,255	74,672	67,900	6,772	100,636	28,427	72,209	4,651	377	4,274
	20-30 ...	343,928	163,729	180,199	48,899	45,312	3,587	270,641	115,413	155,228	24,388	3,004	21,384
	30-40 ...	248,831	125,458	123,373	8,487	7,092	1,395	204,204	112,311	91,893	36,140	6,055	30,085
	40-50 ...	186,533	95,398	91,135	3,700	2,894	806	135,907	83,921	51,986	46,926	8,583	38,343
	50-60 ...	123,684	61,661	62,023	1,832	1,425	407	74,028	50,359	23,669	47,824	9,877	37,947
	60 and over.	134,222	64,920	69,302	1,652	1,132	520	59,290	46,243	13,047	73,280	17,545	55,735

(c) Census

Source: (a), (b) *Annual Report of the Sanitary Commissioner of Madras, 1876, p. 136, p. 139* (c) *Census of India, 1921 Madras Presidency, Imperial Tables, p. 39*

Figure 3: Life Expectancy at Birth around the World, 1750-2000



Source: CLIO-Infra (2010)

Figure 4: Histogram: Districts by Year of Railroad Arrival

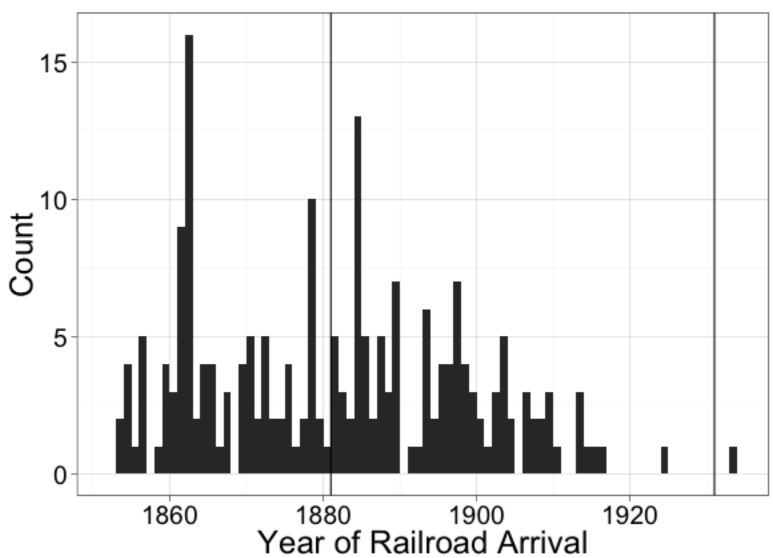
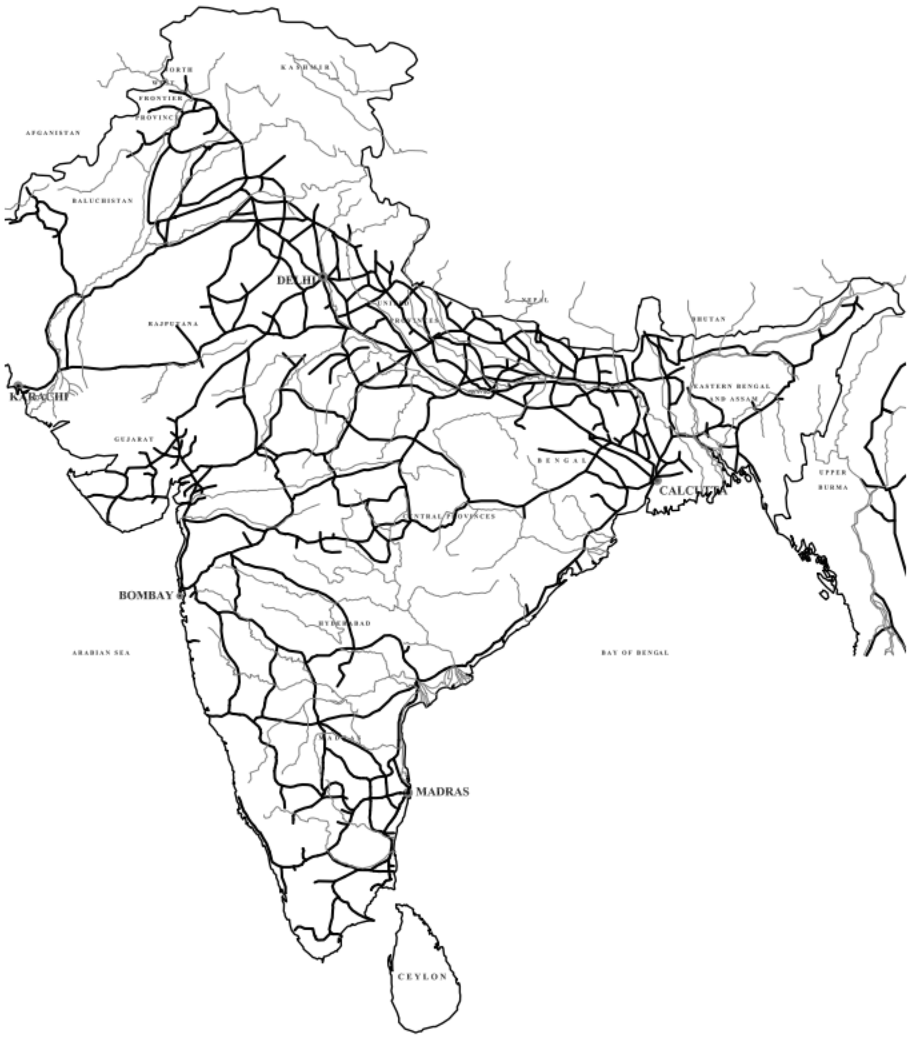


Figure 5: Railways of British India, 1909



Source: Bogart and Chaudhary (2012)

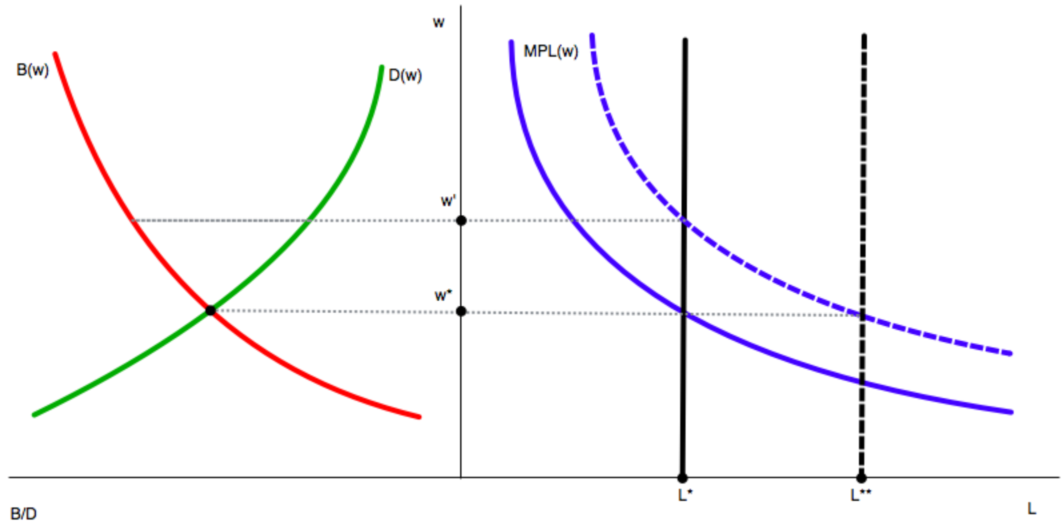


Figure 6: A Malthusian Equilibrium

Figure 7: Fréchet Distribution: Examples

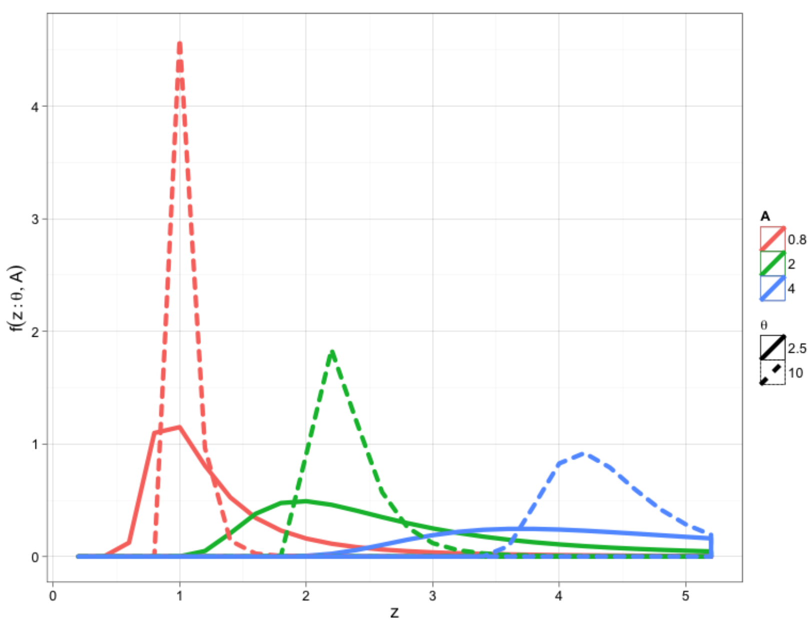
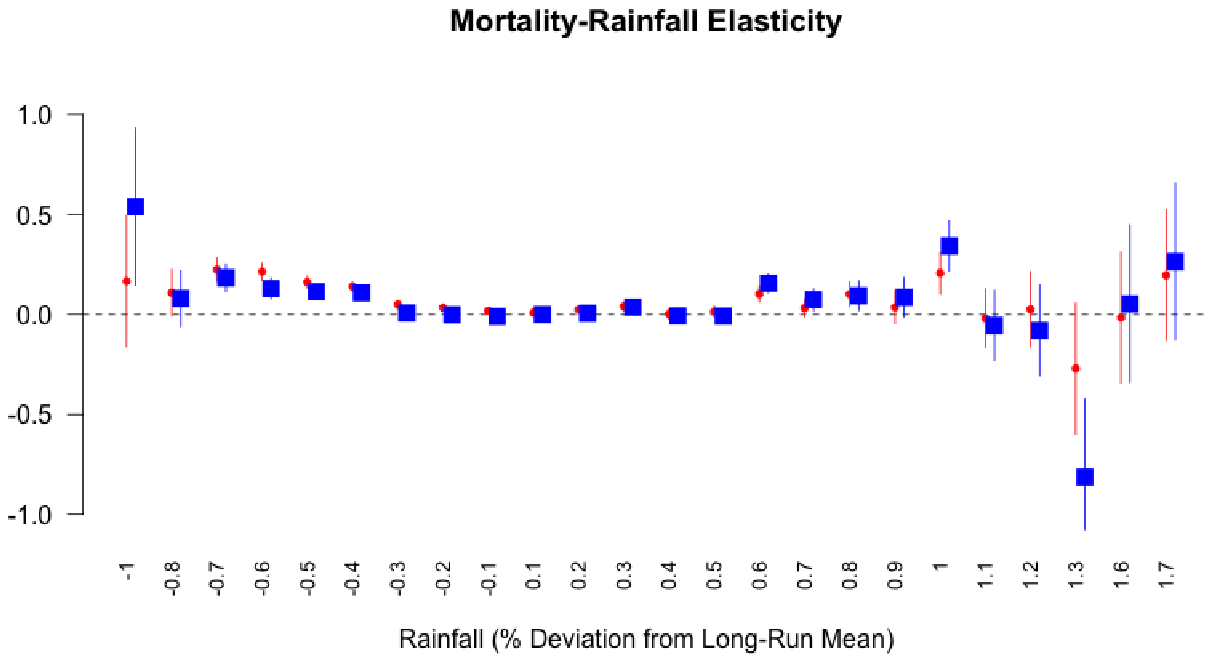


Figure 8: Demographic Elasticities with Respect to Rainfall



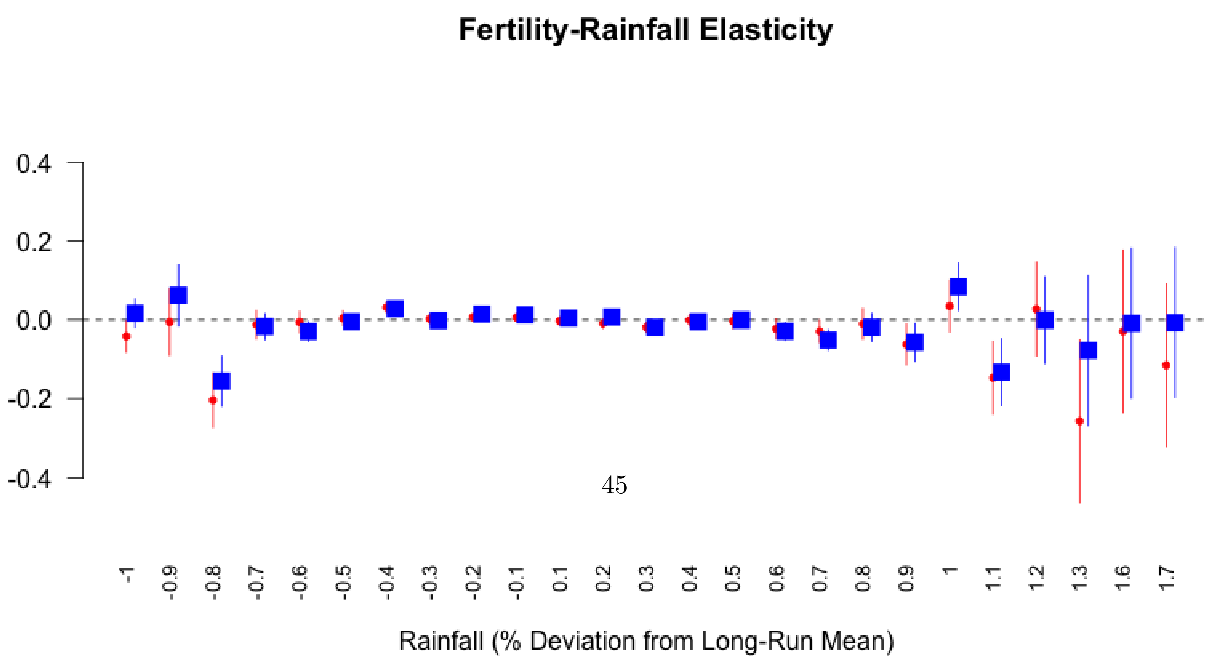
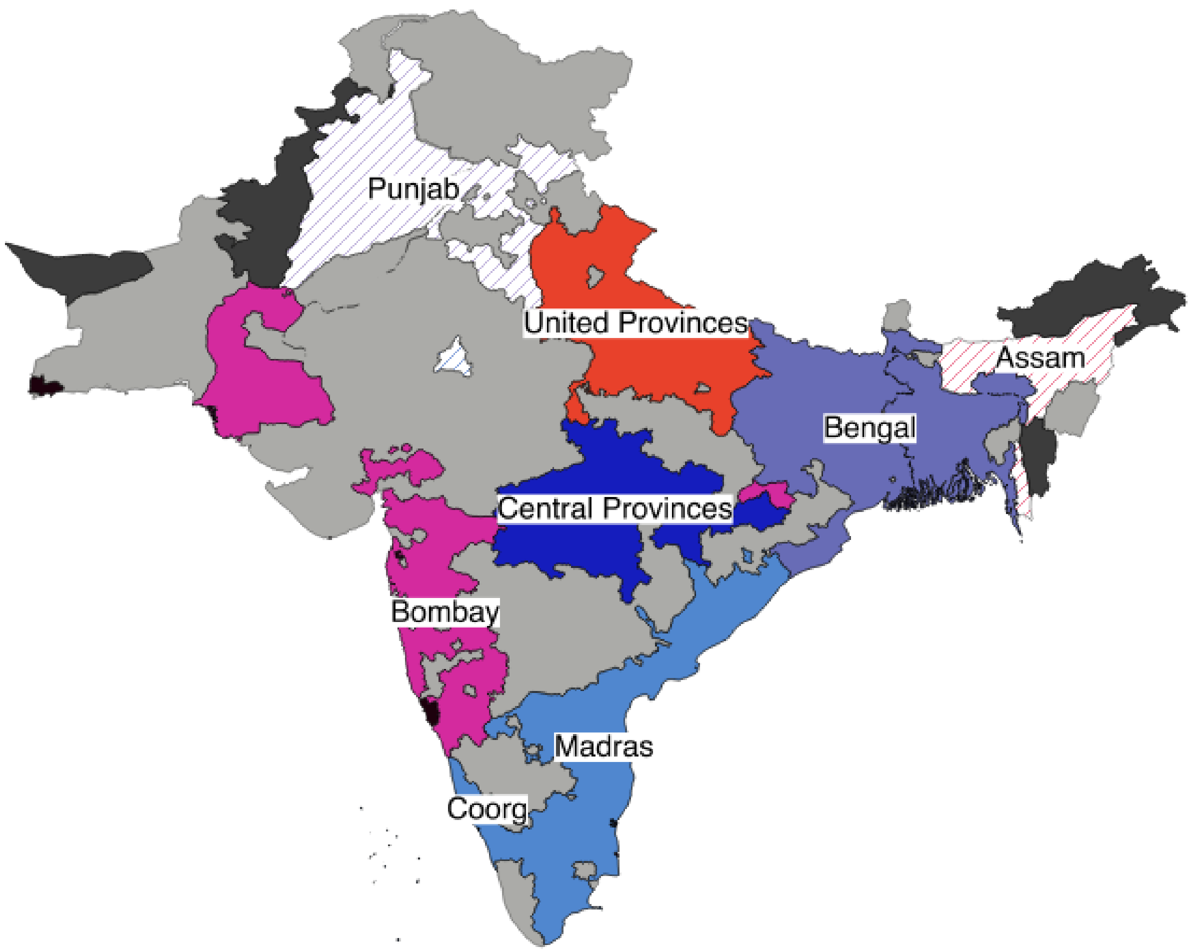
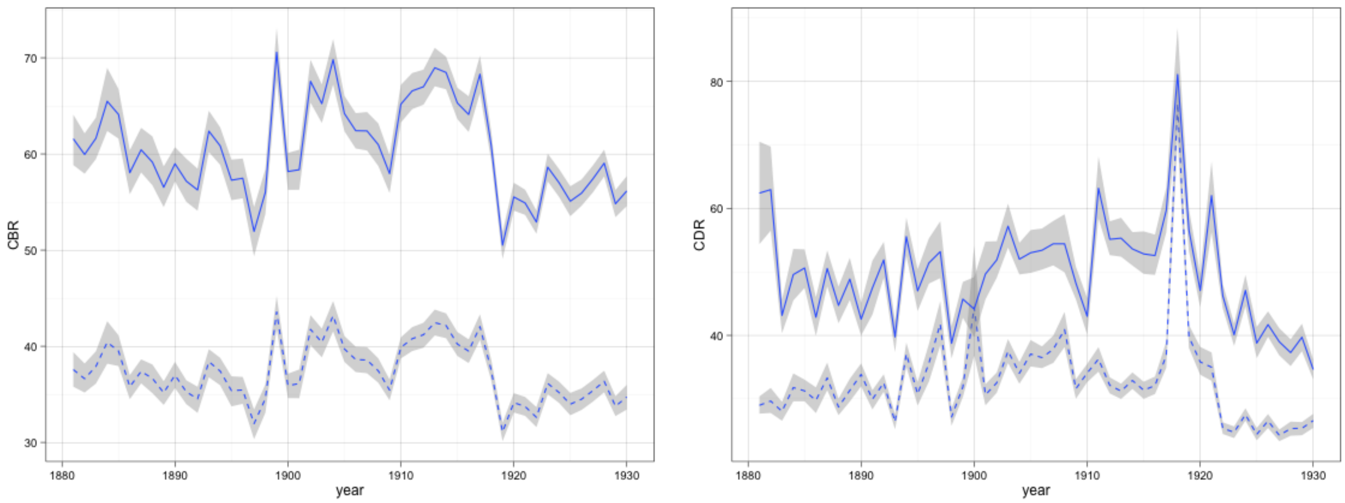


Figure 9: British Indian Provinces (1881)



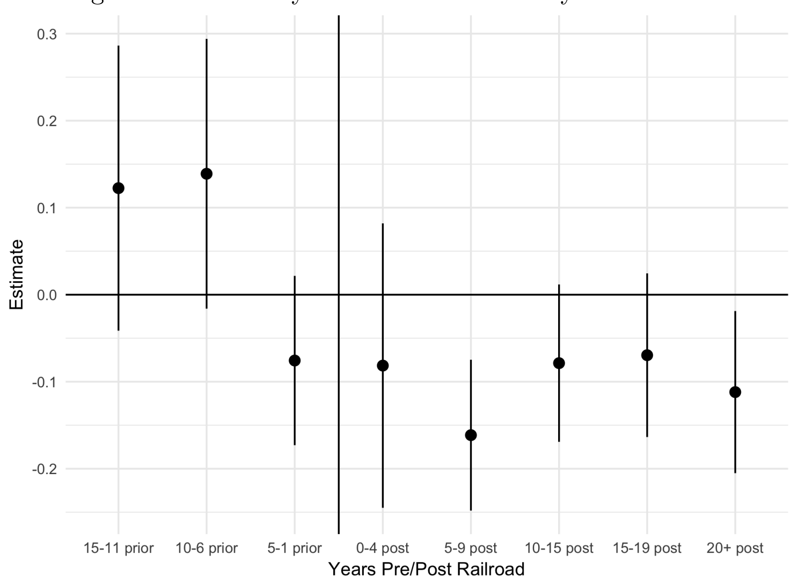
Notes: striped areas correspond to provinces of British India excluded from my study, light gray areas correspond to native states not under district British rule, and dark areas denote tribal/frontier regions not under direct British rule.

Figure 10: Raw and Corrected Crude Vital Rates



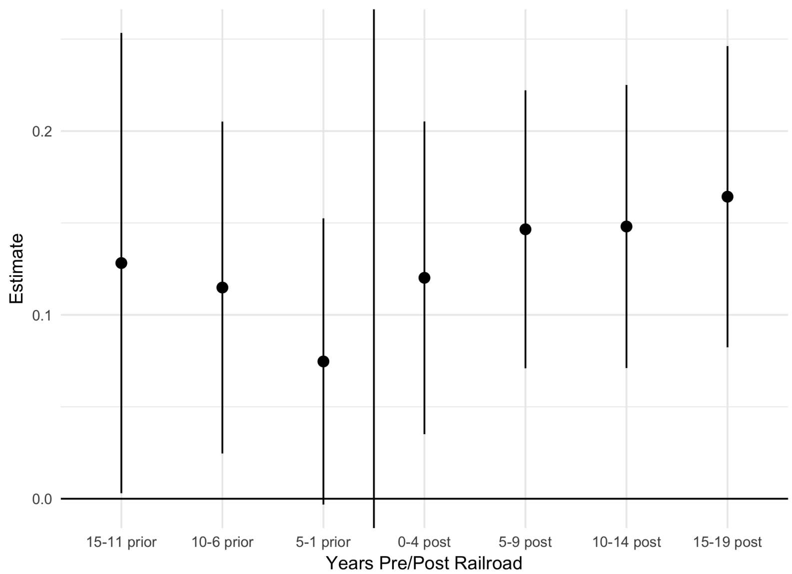
Source: Ahmad (2015). Solid lines represent corrected figures, dashed lines represent crude rates (reported counts divided by interpolated Census counts)

Figure 11: Mortality and the Railroads: Dynamic Effects



Notes: Coefficients plotted (with 95% CI) from fixed-effect regressions of leads and lags of railroads as described above.

Figure 12: Fertility and the Railroads: Dynamic Effects



Notes: Coefficients plotted (with 95% CI) from fixed-effect regressions of leads and lags of railroads as described above.

List of Tables

Table 1: Railroads and Mortality, 1881-1931

	log(Corrected Crude Death Rate)			
	(1)	(2)	(3)	(4)
Railroad	-0.114**	-0.116**	-0.114**	-0.123***
	(0.045)	(0.046)	(0.045)	(0.046)
Unbuilt Railroad (Proposed)		-0.025		
		(0.055)		
Unbuilt Railroad (Reconnoitred)		0.098		
		(0.109)		
Unbuilt Railroad (Surveyed)		0.027		
		(0.031)		
Unbuilt Railroad (Lawrence, Phase IV)			-0.441*	
			(0.245)	
Unbuilt Railroad (Lawrence, Phase V)			-0.028	
			(0.073)	
Unbuilt Railroad (Lawrence, Phase VI)			0.074	
			(0.082)	
Unbuilt Railroad (Kennedy, High Priority)				-0.002
				(0.001)
Unbuilt Railroad (Kennedy, Low Priority)				-0.002
				(0.002)
District FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Observations	3,884	3,884	3,884	3,884
Adjusted R^2	0.269	0.269	0.270	0.270
Note:			$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$	

Table 2: Railroads and Fertility, 1881-1931

	log(Corrected Crude Birth Rate)			
	(1)	(2)	(3)	(4)
Railroad	0.054***	0.050***	0.062***	0.043**
	(0.017)	(0.018)	(0.017)	(0.018)
Unbuilt Railroad (Proposed)		-0.003		
		(0.021)		
Unbuilt Railroad (Reconnoitred)		-0.022		
		(0.044)		
Unbuilt Railroad (Surveyed)		-0.029**		
		(0.012)		
Unbuilt Railroad (Lawrence, Phase IV)			-0.119	
			(0.094)	
Unbuilt Railroad (Lawrence, Phase V)			-0.146***	
			(0.028)	
Unbuilt Railroad (Lawrence, Phase VI)			-0.042	
			(0.032)	
Unbuilt Railroad (Kennedy, High Priority)				0.002
				(0.004)
Unbuilt Railroad (Kennedy, Low Priority)				0.00003
				(0.001)
District FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Observations	3,875	3,875	3,875	3,875
Adjusted R^2	0.538	0.539	0.541	0.541

Note: *p<0.1; **p<0.05; ***p<0.01

Table 3: Railroads and Population Counts (1871-1941)

	Dependent variable:		
	log(PopDen)		
	(1)	(2)	(3)
Rail	0.318***	0.184***	0.056***
	(0.052)	(0.012)	(0.021)
Constant	5.465***		
	(0.046)		
Observations	1,082	1,082	1,082
District FE	N	Y	Y
Year FE	N	N	Y
R^2	0.033	0.207	0.980
Adjusted R^2	0.033	0.176	0.976
Residual Std. Error			0.114 (df = 911)
F Statistic	36.825*** (df = 1; 1080)	239.898*** (df = 1; 917)	

*p<0.1; **p<0.05; ***p<0.01

Table 4: Railroads and Population Counts (1881-1931)

	log(Population Density)			
	(1)	(2)	(3)	(4)
Railroad	0.078***	0.078**	0.079***	0.080**
	(0.030)	(0.032)	(0.030)	(0.032)
Unbuilt Railroad (Proposed)		-0.048		
		(0.027)		
Unbuilt Railroad (Reconnoitred)		0.019		
		(0.014)		
Unbuilt Railroad (Surveyed)		0.011		
		(0.016)		
Unbuilt Railroad (Lawrence, Phase IV)			0.035	
			(0.021)	
Unbuilt Railroad (Lawrence, Phase V)			-0.002	
			(0.026)	
Unbuilt Railroad (Lawrence, Phase VI)			0.048	
			(0.022)	
Unbuilt Railroad (Kennedy, High Priority)				0.001
				(0.001)
Unbuilt Railroad (Kennedy, Low Priority)				0.002
				(0.001)
District FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Observations	4,020	4,020	4,020	4,020
Adjusted R^2	0.990	0.990	0.990	0.990
Note:	*p<0.1; **p<0.05; ***p<0.01			

Table 5: Rainfall, Railroads, and Mortality-Responsiveness Attenuation

	Dependent variable:	
	log(simCDR)	log(CDR)
	(1)	(2)
NegRainShock	0.463***	0.132***
	(0.053)	(0.034)
Rail	−0.088	−0.063**
	(0.053)	(0.031)
NegRainShock*Rail	−0.308***	0.099
	(0.068)	(0.068)
Observations	5,262	5,262
District FE	Y	Y
Year FE	Y	Y
R^2	0.301	0.598
Adjusted R^2	0.273	0.582
Residual Std. Error (df = 5056)	0.341	0.213
	*p<0.1; **p<0.05; ***p<0.01	

Table 6: Rainfall, Railroads, and Fertility Responsiveness Attenuation

	Dependent variable:	
	log(simCBR)	log(CBR)
	(1)	(2)
NegRainShock	−0.062***	−0.066***
	(0.019)	(0.018)
Rail	0.058	0.007
	(0.037)	(0.028)
NegRainShock*Rail	−0.062	0.120
	(0.149)	(0.129)
Observations	5,250	5,250
District/Year FE	Y	Y
R^2	0.543	0.604
Adjusted R^2	0.524	0.588
Residual Std. Error (df = 5045)	0.132	0.133
Note:	*p<0.1; **p<0.05; ***p<0.01	