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Alan Fernihough (Queen's University Belfast)
Ronan C. Lyons (Trinity College Dublin)

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Queen's University Belfast
185 Stranmillis Road
Belfast BT9 5EE

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Agglomeration and Emigration: The Economic Impact of Railways in Post-Famine Ireland*

Alan Fernihough† Ronan C. Lyons‡

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Abstract

Ireland developed one of the world's most intensive railroad networks in the second half of the 19th century. However, the emergence of railroads occurred in tandem with a failure to industrialize and mass depopulation suggesting limited, if any, impact on the island's economy. This paper examines this claim from a trade-based market-access perspective. Matching high-resolution geospatial data for nearly 3,400 districts to existing road and waterway networks as well as Ireland's nascent railroad network, we quantify the extent of market access improvements caused by rail. Additionally, we compute an external market access measure that accounts for improved access to international ports. Our findings reveal that this distinction is vital. Improvements in domestic market access brought about by railroads had a substantial positive influence on both population density and land values, while better access to ports had the opposite, negative, effect. Overall, these conflicting forces largely cancel out, hiding rail's importance. However, a supplementary analysis reveals that the introduction of rail fostered a significant reorientation within the economy across two key domains: emigration and the labour-intensiveness of agriculture. Areas with relatively more access to ports experienced greater levels of emigration and a faster switch from labor-intensive tillage to pastoral farming—with differential access explaining around two-fifths of the observed shift in both variables between the Great Famine and the Great War.

Keywords: Ireland, Railways, Market Access, Emigration.
JEL codes: N14, N94, O18, R12, R4

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†Queen's University Belfast and CEPR; email: a.fernihough@qub.ac.uk.

‡Department of Economics and Centre for Economics, Policy & History (CEPH), Trinity College Dublin, and Spatial & Economics Research Centre, LSE; email: ronan.lyons@tcd.ie.

1 Introduction

The 19th-century introduction of steam trains revolutionised transport. By dramatically reducing transport costs and travel times, railroads altered possibilities for trade and migration, both within and between economies. In making labour more mobile at a time of industrialization, rail also enabled agglomeration and the exploitation of increasing returns in growing urban spaces. The link between infrastructure and local economic outcomes has remained a question of fundamental importance ever since, with numerous examples of countries at all income levels hoping to stem regional population losses with major infrastructural investments.

In this paper, we examine the link between rail and economic outcomes using the example of Ireland between its Great Famine (1845–51) and the Great War (1914–18). Unlike many of its European peers, Ireland experienced limited industrialization and mass migration during this period, even as large investments created an extensive rail network. To examine rail's influence on the Irish economy, we quantify domestic market access both before the railroad and as the rail network was built, using a methodology that incorporates both the time and cost improvements caused by railroads. We add a similar measure reflecting access to major international ports, through which the vast majority of people and goods left. In both measures, we do this at the level of over 3,400 Census 'District Electoral Divisions' (DEDs), for which consistent data exist back to 1841. Our principal outcomes of interest are the change in population density and the change in land values. We also decompose overall changes in population density into two components: agricultural and non-agricultural population density, both of which fell dramatically in Ireland in the half-century following the Great Famine, although this decline was not universal.

Potential endogeneity is addressed in several ways. Our data is longitudinal, meaning can apply a cross-section-in-first-differences approach that allows us to incorporate standard DED-unit and time-fixed effects. Thus, our model results are not driven by either time-invariant factors or a common time trend. Spatial confounding is tackled by including a semiparametric term that accounts for nonlinear latitude-longitude effects. Basic distance-to-line controls help to distinguish the physical railroad infrastructure from the market access gains it generated. We further control for potential endogeneity in the placement of rail by calculating the hypothetical market access gain had the second report of the Irish Railway Commission of 1836–38 (Great Britain, 1838a), a centrally planned network primarily based on economic considerations, been implemented. Additionally, we show that our results are robust, in both Ordinary Least Squares (OLS) or Instrumental Variables (IV) set-ups, to changing the definition of market access to exclude local, and therefore potentially more endogenous, railroad growth.

We document that the competing effects of improved access to domestic markets and access to external markets via ports had a significant impact on population density. Improved access to domestic markets increased population density, while access to external markets via ports contributed to depopulation. Approximately 28 per cent of the depopulation can be attributed to access to ports, but this is mostly offset by the market access channel, which increased population by 20 per cent. A similar pattern emerges when examining land values as the outcome of interest. Our preferred estimates suggest that 44 per cent of the appreciation in land values before the Great War was caused by improved market access, although this appreciation was restrained by improved access to ports, as values would have been 39 per cent higher if railways had maintained constant access to ports.

When we decompose population density into economic sectors, agricultural and non-agricultural, we find both similarities and differences. On the one hand, we see the same opposing forces at play: a positive effect of market access and a compensating negative effect of port access. On the other hand, the estimated effects are greater in magnitude for both agricultural and non-agricultural population density. These findings are consistent with rail transport fostering agglomeration while also facilitating rural population loss as Ireland switched from tillage to pasture in the later 19th century. They also align with existing international evidence, which has generally found large domestic market access effects, and help us understand why, overall, railroads did not have a dramatic boost on the Irish economy in the second half of the 19th century.

Understanding the influence of railroads on economic growth has long been a contentious topic in economic history. Fogel (1964), who pioneered the use of the "social savings" methodology, challenged the traditional consensus of the rail-growth link in America. According to Fogel, late 19th century America would have been marginally worse off in a counterfactual world without railroads because alternative transport methods (canals and roads) were only slightly inferior. At most, railroads contributed 4.7 per cent to US GNP by 1890 (Fogel, 1964, p. 223). However, the social savings methodology has not been immune to criticism (Leunig, 2010). Furthermore, alternative social savings estimates from various historical economies, compiled in Leunig (2010), are heterogeneous—ranging from 0.5 per cent (China in 1933) to 38.5 per cent (Mexico in 1910).

Recent research, aided by advances in geographic information systems (GIS), uses longitudinal data to measure the historic influence of rail and other transport networks. In this framework, the emergence of railways can be viewed as a "natural experiment" that created treated and control units based on network access. Whilst railroad placement and economic outcomes are endogenous, quasi-experimental empirical methods, such as difference-in-differences (DiD) and instrumental variables (IV), offer potential solutions. Typically, research in this literature has estimated causal effects by blending both approaches. Rail access IVs—variables measuring exogenous variation in access—rely on the fact that most areas only gain rail access because they lie between two major population centres on a trunk route. This approach assumes that the distance to hypothetical trunk routes, formed based on a straight line or a least-cost path (i.e. accounting for geographical concerns such as elevation), should only influence economic outcomes through a railroad effect. Empirical papers of this nature tend to find large and economically relevant railroad effects, in a variety of historical contexts. Examples include: the American Midwest (Atack et al., 2010; Atack & Margo, 2011), Prussia (Hornung, 2015), Sweden (Berger & Enflo, 2017), Switzerland (Büchel & Kyburz, 2020), colonial Sub-Saharan Africa (Jedwab & Moradi, 2016), and Japan (Yamasaki, 2017). In setting, the most closely related research to ours is Bogart, You, et al. (2022), who examined the case of England and Wales during the 19th century. They combine a least-cost path approach with a rich new database on nearly 10,000 spatial units including parishes and villages and find that having stations increased annual population growth by 0.87 per cent.

One drawback associated with the empirical studies above is that they rely on categorical indicators of rail access which, in practice, overlook the fact that it is the destination of the railroad, not the track itself, that is of economic importance. This market/rail access difference was highlighted by Redding and Turner

(2015), who recommended a market access approach more consistent with economic theory and therefore better equipped to understand general equilibrium effects. This approach was further developed by Donaldson and Hornbeck (2016). Similar to Atack and Margo (2011), they examine the impact of railroads on American agriculture but use the travel-cost-weighted sum of other county populations as a measure of market access derived from general equilibrium trade theory. Methodologically, this market-access approach is the most similar to ours. Using this measure, they find that land values increased substantially with market access from 1870–90 and that removing all railroads in 1890 would have decreased the total value of U.S. agricultural land by 60 per cent. More recently, Hornbeck and Rotemberg (2019) found that railroad-inspired market access also increased U.S. manufacturing productivity during this period.

Our contribution extends beyond being the first to rigorously estimate the causal impact of rail in Ireland. We are the first to combine the use of spatially granular data, as in Bogart, You, et al. (2022), with the market-access approach of Donaldson and Hornbeck (2016) in a historical setting. While U.S. counties had an average size above 3,000km^2, Irish Census DEDs were on average 25km^2, similar to English and Welsh parishes. Unlike Donaldson and Hornbeck, our market access measure incorporates speed as well as cost improvements in the spirit of Jaworski and Kitchens (2019). We are also the first to distinguish between domestic and foreign (port) market access, allowing us to examine the link between railroads and the external flow of people and goods. Given the broader historical forces at play in the second half of the 19th century—an era of intense globalization manifesting in increased international movements of labour and capital—this seems pertinent. Further, unique to the literature, we present comparable results for the same economy across measures of population, land value and employment structure, pioneering a new measure of agricultural and non-agricultural population density, rather than using shares, to compare elasticities across all outcome measures.

The rest of this paper is structured as follows. In Section 2, we outline the context for the Irish economy in this period. We describe firstly the economic and political setting, including the importance of the Corn Laws to Ireland's agricultural sector, secondly the roll-out of Ireland's rail network and the 1834 Drummond Report, which attempted to introduce a planned network, and thirdly, the

1840s famine and subsequent patterns of migration. In Section 3, we describe our data, including the digitization of Ireland's transport network, including rail, canals and roads, as well as consistent census data over time. We detail the market access methodology and discuss our identification strategy given the relevant endogeneity concerns. Section 4 presents the results of our analysis, while the final section concludes.

2 Historical Context

Ireland entered a full political and economic union with Britain between 1801, when the Acts of Union took force, and 1826, when all trade between the two islands was treated as coasting trade. This union, which lasted until 1921 when Ireland was partitioned, was central to the island's economic development. It fostered substantial economic integration between the two islands, with the free movement of goods, people, and capital. Ireland had been an emerging textile producer in the 18th century, in particular of linens, although it also exported significant amounts of food, especially salted beef and butter (Bogart, Kling, et al., 2022). Britain's industrialization at a time of economic integration between the two helped reorient Ireland's exports away from manufactured products (textiles) to agricultural goods.

This transition was supported by the Corn Laws, which gave domestic (i.e. Irish and British) producers preferential access to the large and growing consumer market for oats and wheat in particular. High prices for tillage goods combined with the suitability of the Irish climate for the potato, saw the widespread adoption of the potato as a subsistence crop for poorer rural Irish households, as they grew tillage goods for export to pay for, among other things, rents—often to absentee landlords—as well as imported colonial goods such as tea and sugar. This economic model was hugely influential in the early 19th century, albeit at the extensive margin: while average living standards remained perhaps roughly 40 per cent lower than in Britain, the population of Ireland grew rapidly, almost doubling in the half-century to 1841, from 4.4 million to 8.2 million. In this regard, Irish population growth kept pace with Britain's during this period, which also nearly doubled from 1791–1841. Indeed, Thomas and Dimsdale (2017) estimate that Ireland's GDP, adjusted for inflation, grew faster in 1780–1845 than Britain's: by a factor of 3.3, compared to 3.1 for Britain.

A significant factor in Ireland's early 19th-century economic growth was its developing transportation network (Ó Gráda, 1995). This included a canal network, in particular the Grand (1756–1804) and Royal (1790–1817) Canals, that eventually connected Dublin city in the east to Limerick city and several market towns in the west. Road travel times, aided by new and better-maintained roads and more robust coaches, decreased markedly in the first half of the 19th century (Ó Gráda, 1993, pp.35–36). Reduced travel times mirrored simultaneous increases in service frequency as well as increases in carts carrying commercial freight. The volume of trade meant that Irish-British routes were also pioneers for steam-shipping, including Dublin-Liverpool from 1823 with the launch of the City of Dublin Steam Packet Company. The emergence of steam-powered rail as a new form of overland transport in the 1820s and 1830s resulted in policymaker attempts to introduce a planned network, with the Irish Railway Commission of the mid-1830s and its subsequent report, known as the Drummond Report (Great Britain, 1838a). The goal of the Drummond Report was to set out a unified rail network reflecting economic considerations; the proposed network is shown in Figure 1. Instead, the railway network in Ireland was allowed to develop along similar lines as in Britain (Quinn & Turner, 2020), with private companies being granted authority by Acts of Parliament to construct lines, often with assistance from the Board of Works. In this sense, Ireland partook in the 1840s "railway mania" with over one hundred new schemes—many of which were imprudent and only one-quarter were eventually authorized—proposed during the speculative period of 1844–46 and over 200 miles across six lines completed by 1848 (Ó Gráda, 1995, p.137).

As Murland (1849, p.13) noted contemporaneously, while much public opinion had by the late 1840s come to regard railway construction as "little better than bubble speculations", there was already evidence that "railways already in operation in Ireland ...greatly increased the intercourse in those districts which it traverses". For example, he observed the significant level of growth in passenger numbers for the Dublin & Kingstown railway, effectively a commuter railway from Dublin city to its new port, which increased from 1.28 million in 1840 to 2.35m by 1846. This conclusion was notwithstanding both the short number of years for which most of the railways were then in operation and also the disruption caused by the Great Famine.

The impact of the Great Famine of 1845–51 on Ireland's economic, social, and political development cannot be overstated, particularly given the strong growth in the island's population in the half-century that preceded the Great Famine. A combination of death and extraordinary rates of migration meant that by 1851, the population had fallen 20 per cent from its pre-Famine peak. As Hatton & Williamson have shown both for Ireland (Hatton & Williamson, 1993) and for the "Old World" more generally (Hatton & Williamson, 1998), migration in the late 19th century was subject to stock or "family and friends" effects. This meant that the sudden establishment of large communities of Irish emigrants, particularly in Britain and on the east coast of the United States, acted as a pull factor for later emigrants from Ireland, who had access to current labour market information and, in many cases, informal credit from family members to pay for passage. Consequently, Ireland's population continued to fall for decades and was estimated at just 4.4 million in 1911, approximately half the pre-Famine peak.

One of the policy responses to the Great Famine was the abolition of the Corn Laws, a measure that dramatically reduced the cost of relief for the UK government (Read, 2016) and has been subsequently seen as the definitive shift by the UK to free trade during *Pax Britannica*. However, as noted above, Ireland's pre-Famine economic model had included a reliance on those tariffs, with Ireland exporting vast quantities of oats and wheat to Britain. When combined with the observed shift in activity from labour-intensive tillage to land-intensive pastoral agriculture after the famine, one interpretation of Ireland's economic development from 1850–1910 has been that UK policy—in particular, the Corn Law repeal—contributed to Ireland's population loss. Indeed, nationalist economic historian George O'Brien described repeal as "another calculated aid" in reducing Ireland's population, while Karl Marx wrote that "the Irishman, banished by the sheep and ox, reappears on the other side of the Atlantic as a Fenian" (both cited in O'Rourke, 1994). O'Rourke (1994) finds evidence that lower grain prices did lower agricultural employment by the 1870s but also, in O'Rourke (1991), that it was the collapse of the potato-based system, which had sustained labour-intensive agriculture in Ireland, that underpinned responses to changes in relative export prices in the later 19th century and Ireland's rural depopulation.

Other researchers have investigated and found evidence supporting positive changes in per-capita economic prosperity during this period, even as there was a contraction at the extensive margin. Boyer et al. (2005) document the dominant role played by emigration in helping lift wages, while Andersson and Lennard (2019) estimate that per-capita GDP trebled, in real terms, between 1842 and 1913. This is consistent with the greater commercialization of everyday life in Ireland in the late 19th century: the number of grocers and publicans per capita increased by almost one-third 1881–1911, while bank deposits rose from £8m to £43m between 1850 and 1900, at a time when consumer prices were largely stable (Ó Gráda, 1995).

Existing research on the impact of Ireland's rail network on the Irish economy is mixed. Lee's summary that "[s]ince 1850 Ireland has been an underdeveloped economy with a highly developed transport system" provides a reasonably accurate portrayal of thinking on this issue (Lee, 1976a, p.87). However, there is striking evidence of the transformative effect of rail across numerous areas of Irish society. Railways offered a greater variety of foodstuffs and helped diversify Irish diets away from the potato. Tobacco, manufactured textiles, and an assortment of other commercial goods, peddled by an army of travelling salesmen, also became a feature of everyday Irish life. Railways provided secure direct employment for 20,000 and fostered economic activity in multiple related sectors. For example, the development of Ireland's rail network helped create the Irish tourism industry as rail companies owned and operated hotels in several scenic coastal locations. Furthermore, railways helped fishermen in the West of Ireland rush freshly caught lobster to the lucrative London market and also gave poultry farmers a foothold in the British market for fresh eggs (Bardon, 2009, p.422). The tangible commercial importance of rail can be seen in both freight revenues—which rose from £175,000 to £2.1m between 1849 and 1912—and freight tonnage—which was twice as high in the early 1910s as in the early 1870s (Ó Gráda, 1995, p.266). Rail also provided less tangible benefits including the standardisation of time and improved access to important events. For example, Catholic funerals unsupported by offerings dropped by 70 per cent between the 1860s and 1890s in the Ulster town of Lurgan (Ó Gráda, 1995, p.239).[1]

Lee (1976a) suggests that rail was instrumental in the switch from tillage to pastoral farming. Whilst relative price shifts underpinned this agricultural transition,

[1] Even the lacklustre performance of the West Clare Railway conferred an unintended cultural benefit in the form of Percy French's: "Are Ye Right There Michael".

railways facilitated its execution. Furthermore, growth in British rail was also relevant to Irish farmers as quicker and cheaper carriage opened markets further away from ports in Britain's west. The relevance of British transport is also discussed by Kennedy (1981), who examined Irish agricultural specialization in the second half of the 19th century. Whilst Kennedy finds some evidence of specialization, this is not uniform across the sector. This suggests that rail's influence may be overstated in this regard. Furthermore, Kennedy also cautions against conflating specialization—and agricultural change more broadly—with the introduction and growth of railways. For example, technological change in the butter industry and the use of creameries meant that dairying would have become more specialized regardless of the transport infrastructure. All told, the unique development of the Irish economy during the nineteenth century, as its transport infrastructure evolved considerably, merits further study.

3 Data

In this section, we describe our data, in particular our outcomes of interest—population, land values and occupational structure—and our regressors of interest, access to markets and to ports. Table 1 provides the summary statistics for our variables of interest.

Table 1: Summary Statistics of Selected Variables

Statistic	N	Mean	St. Dev.	Min	Max
Log Growth in Population Density, 1851–1911	3,370	−0.608	0.406	−2.662	3.451
Log Growth in Non-Agri Population Density, 1851–1911	3,370	−0.730	0.709	−3.908	3.489
Log Growth in Agri Population Density, 1851–1911	3,370	−0.520	0.465	−3.622	1.873
Log Growth in Land Value per Acre, 1851–1911	3,370	0.185	0.285	−1.906	2.983
Log Growth in Market Access, 1851–1911	3,370	0.232	0.105	0.049	0.862
Log Growth in Port Access, 1851–1911	3,370	0.082	0.042	0.000	0.220
Log Growth in Market Access Under Drummond	3,370	0.220	0.351	−0.336	2.964
Log Growth in Port Access Under Drummond	3,370	0.083	0.125	−0.067	0.669
On Rail Line	3,370	0.356	0.479	0	1
Rail Line Within 5KM	3,370	0.241	0.428	0	1

3.1 Population, Land Values, and Occupational Structure

We use census data at the level of the District Electoral Division (DED), small administrative units that stayed, for the most part, consistent from the 1841 census on. DEDs provide a high-resolution image of Ireland's demographic and economic structure over time, with the area of the average DED just 25km^2. DED-level data are sourced from the Historical Mapping Atlas project completed by the All Ireland Research Observatory (AIRO) at Maynooth University, which contains the spatial boundaries and census population totals for 3,432 DEDs between 1841 and 2002 (Kelly & Fotheringham, 2011).[2] Table 1 reveals the scale of post-Famine Irish depopulation. Between 1851 and 1911, the island's population fell by a third, from 6.6m to 4.4m. In our data, this translates as a loss of population density for the average DED of 0.6 log points, although this variable exhibits substantial heterogeneity. The population of many existing or new urban districts grew, a group representing over 4 per cent of observations.

Our principal objective is to focus on changes that occurred between the Great Famine and the Great War (1851 to 1911). To this end, we supplement the AIRO data with additional data from both the 1851 and 1911 sets of Census reports. Both sets of reports contain information on DED land values and areas. We digitized both sources and successfully matched these to the AIRO spatial data.[3] These land values are known as the "Poor Law Values" (PLV) as they funded local poor relief efforts and they measured the net annual value of all hereditaments. In essence, this was a land tax assessed to measure fair rental values. In 1851, the census reported the values separately compiled by the 130 devolved administrative bodies (the Board of Guardians for each Poor Law Union) that arose from the introduction of the Poor Law in 1838. By 1911, the census enumerators were using the more rigorously measured values reported as part of Sir Richard Griffith's land valuations conducted 1847-1864 and continually updated afterwards via the *Primary Valuation of Ireland Revision Book*. Overall, the assessed value of land in the typical DED increased by around 19 per cent during this period, a figure comparable with Irish GDP growth between 1861 and 1911 (Geary & Stark, 2002).

[2] Our final dataset contains 3,370 observations. This sample size reduction occurred as we amalgamated a small number of DEDs to match our auxiliary 1911 census data source.

[3] There were a small number of DEDs with missing land value and area data, 11 in 1851 and 19 in 1911. In these instances, we interpolated the missing data points. Further details of our methodology to do this are available upon request.

It is plausible that the influence of railway-induced market and port access improvements affected the economic structure of each district. For example, if rail facilitated a (relative) transition to non-agricultural related occupations (mainly industrial and commercial), this change would be obscured by looking exclusively at total changes in population. Separating population density by sector—distinguishing *agricultural* from *non-agricultural* led population change—allows us to investigate this possibility in greater detail. Appendix A elaborates on this aspect of our data construction. From Table 1 we can see that, in the typical DED, the population involved in both broad sectors fell, although the fall in the non-agricultural population fell more sharply (0.73 log points) than the agricultural population (0.52 log points).

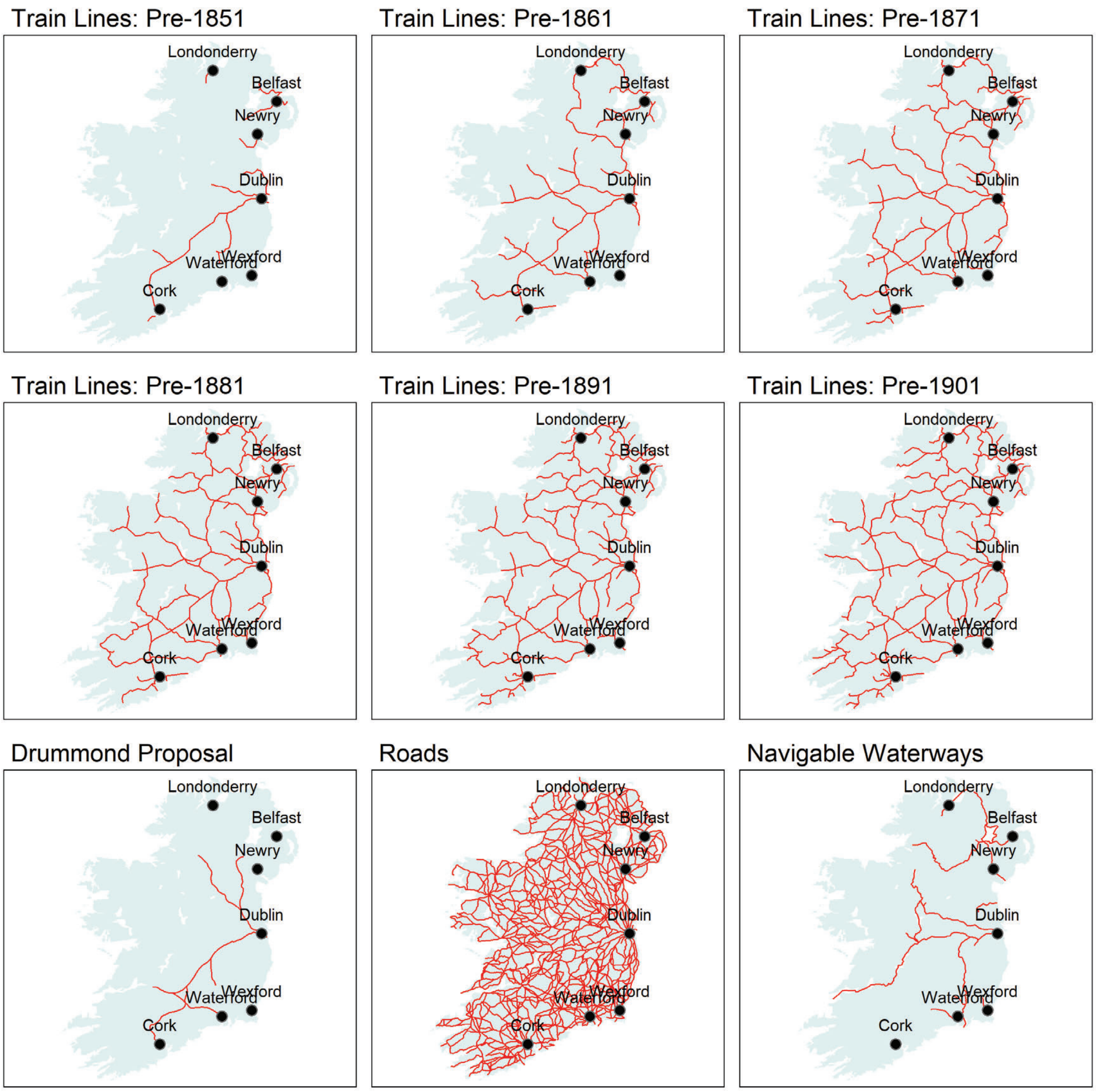
3.2 Transportation Networks and Market Access

This paper follows a "market access" approach which requires us to be able to calculate travel time and cost between all DED pairs in our data. We assume that before the introduction of rail, people and goods travelled via road or navigable waterway. Figure 1 summarizes these transport networks, showing the evolution of the rail system over time, as well as—in the bottom three panels—the pre-existing road and waterway networks and the network proposed by the Drummond Commission, described in more detail below.

Our road data are digitized from Lewis (1847), which provides a highly detailed image of Ireland's road network on the eve of the Great Famine. One limitation associated with this source is that it ignores differences in road quality. In particular, we cannot account for differences between turnpikes and less well-maintained roads common in more remote areas. Similarly, we do not account for new roads or improvements to existing roads in the post-famine half-century.

Navigable rivers and train lines are mapped in the appendix of the *Vice-Regal Commission on Irish Railways, including Light Railways* report (Great Britain, 1907). We capture the diffusion of Ireland's railway network by specifying the opening decade for each line. The line's opening dates are detailed in *Johnson's Atlas & Gazetteer of the Railways of Ireland* (Johnson, 1998). We separate broad (or Irish) and narrow gauge rail lines, which has implications for travel speed. For waterways, as with roads, we cannot distinguish between waterway quality

Figure 1: Ireland's Transport Network



or measure the improvements in water transport—largely as a response to the emergence of rail as a competitor for commercial freight—that occurred during our observation period.

We define market access as the collective sum of every other district's land value weighted by a trade friction term τ—in other words, districts with easier access to more valued locations have greater market access. Here, τ_{ijt} measures the cost of travelling from i to j at time t. As with Donaldson and Hornbeck (2016), the total cost τ_{ijt} is computed as an iceberg trade cost:

$$\tau_{ijt} = 1 + \frac{t_{ijt}}{\bar{P}} \tag{1}$$

where t_{ijt} measures the total transport cost of moving one ton of freight between i and j at time t and $\bar{P}$ is the average value of a ton of freight. We measure τ for each district by superimposing transport network raster images on all Irish land and then applying a least-cost marching algorithm (Dijkstra, 1959). Initially, we calculate market access using the network as it stood in 1841. We then gradually introduce rail lines to the cost surface thus capturing improvements in market access. Transport costs (t) fall via two channels: freight costs and time improvements. As in Jaworski and Kitchens (2019), the variable t is computed based on:

$$\begin{aligned} t_{ijt} =& (\text{distance in miles}_{ijt} \times \text{cost per mile}_t) + \\ & (\text{travel time in hours}_{ijt} \times \text{hourly labour costs}_t). \end{aligned} \tag{2}$$

Constructing the cost surfaces necessitates specifying the speed and pecuniary values associated with various transport modes. Appendix C provides a thorough account of our values and the relevant sources from which these values are drawn. In summary, we designate that travel on a standard (or Irish) gauge rail occurred at a speed of 25mph. Narrow gauge rail achieved speeds of 19mph. Road and waterway transport occurred at 7 and 2.5mph respectively. Finally, movement across "land"—parts of the cost surface lying outside any transport network—proceeded at a pace of just 1mph. The pence per ton-mile freight costs for rail, road, waterway, and "land" were 2, 6, 2½, and 30 respectively. Thus, rail was over 3.5 times quicker and 3 times cheaper than road. Rail's cost advantage, a 25 per cent improvement, over waterway was less impressive but rail was vastly superior, by a factor of 10, in terms of speed. Finally, we assume an hourly labour cost of 3*d* given the pre-Famine daily rate of 8*d* (Doran, 2021a). This rate is based on the assumption that men worked an eight-hour day and that each transport mode required three workers.

With the trade friction term τ, and where θ is the elasticity of trade parameter, we compute district i's market access using the following formula:

$$MA_{it} = \sum_{j\neq i}^{N-1} \tau_{ijt}^{-\theta} Value_j. \tag{3}$$

We hold land values $Value_j$ constant, at the pre-Famine levels reported in the 1851 census. This means that the τ term represents the only channel through which market access can improve. Our analysis focuses on changes to market access, not levels, and we measure these gains via the following:

$$\begin{aligned} \Delta MA_{it} = & 6/21[\ln(MA_{i,t=1851}) - \ln(MA_{i,t=1841})] \quad + \\ & 5/21[\ln(MA_{i,t=1861}) - \ln(MA_{i,t=1851})] \quad + \\ & \vdots \qquad\qquad\qquad\qquad\qquad\qquad + \\ & 1/21[\ln(MA_{i,t=1901}) - \ln(MA_{i,t=1891})]. \end{aligned} \tag{4}$$

The market access gains made by district i are a time-weighted function of the cumulative log gains between 1841 and 1901.[4] Time-weighting in this manner ensures that districts that gain rail access earlier benefit more.

Both Equations (2) and (3) require us to impose values reflecting the trade elasticity (θ) and the average value per ton of freight ($\bar{P}$). Whilst the literature offers us an approximate range of plausible values, it is reasonable to expect that they differ by context. In this application, we estimate both values by performing an iterative grid search over values ranging from 0.01 and 10.51 and running a bivariate regression of mid-19th century per-acre land values as a function of mid-19th century market access. We then select values for θ and $\bar{P}$ that maximize the goodness-of-fit R^2 statistic. Our results suggest a trade elasticity of 5.46, a value centred between the Donaldson and Hornbeck (2016) estimate of 8.22 and the 2.75 value used in Hornbeck and Rotemberg (2019); Appendix B explores the robustness of our re-

[4]The specific equation, with a divisor of 21, reflects the sum of decades between 1851 and 1911. With this set-up, an improvement in market access that applied 1901-1911 receives one sixth of the weight of an improvement that applied 1851–1911.

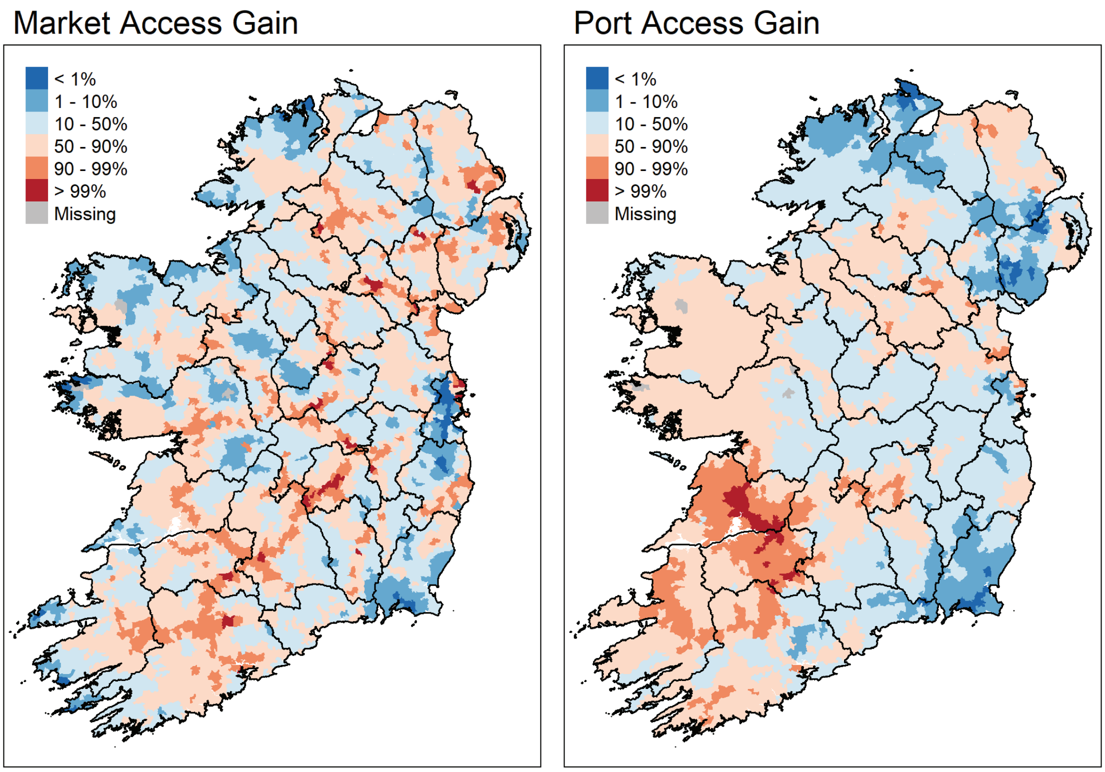
sults to alternative trade elasticity values. The Great Britain (1838a) Commission report offers an insight into the plausibility of our $\bar{P}$ estimate of 0.98 as the values and weights of trade (imports and exports) of 40 ports is listed for the year 1835. This average value differed substantially by port. For example, the average per-ton value of freight was nearly £30 in Belfast but only £1 for the small port of Balbriggan, Co. Dublin. Our estimate matches the smaller port value reflecting the lower value of goods moving internally.

Market access, as we define it, quantifies the development of Ireland's internal transport network. However, the Irish railway system also boosted access to non-domestic markets, both for goods, mainly Great Britain, and for people (in particular Britain and the United States) as it provided easier access to ports. As discussed in Section 2, the second half of the 19th century saw both extraordinarily high emigration rates from Ireland, compared to other countries, and a transition in the dominant form of agriculture from labor-intensive tillage for export, supported by the potato as a subsistence crop, to more land-intensive pastoral agriculture.

We account for this by constructing a "port access" variable that proxies for foreign market access. Here, port access is defined as the minimum cost (as measured in Equation 2) to reach the following ports: Belfast, Cork, Dublin, Londonderry, Newry, Waterford, and Wexford. By 1911, these seven ports accounted for 96 per cent of steamship tonnage cleared, nearly all of Ireland's export activity and its carriage of persons overseas (Solar, 2006).[5] Port access gain between 1851 and 1911 is then computed by adapting Equation (4), replacing market access with port access: decennial port access gains are measured by subtracting new port access from lagged port access, e.g. for 1851 this would be the minimum cost to

[5]The vast majority of Irish emigrants left for the Americas, in particular the USA, and Britain, as well as Australia. Many of those leaving for the US typically did so through Liverpool port. A British Parliamentary report of 1900 estimates that just over 240,000 left the UK (including Ireland) in 1899, of which 43,000 where Irish. Roughly 29,000 left through Queenstown (Cork), while almost 6,000 left through Londonderry. The bulk of the remainder went through Liverpool, which was the port of departure for almost half (119,000 of 241,000) of all UK emigrants (Great Britain, 1900). Those in the north-east and east of Ireland who emigrated to the US are likely to have done so through Belfast and Dublin ports, which were well-served with regular steam-ship connections to Liverpool. For example, an advertisement in 1900 for the City of Dublin Steam Packet Company lists five sailings per week between Dublin and Liverpool, while one of its rivals, the Dublin & London Steam Packet Company, had three sailings per week. The same newspaper page contains an ad for Anchor Line, whose Furnessia steamer sailed from Londonderry to New York directly, at a cost (in steerage) of £5 5*s*.

Figure 2: Rail Induced Market and Port Access Growth, 1851–1911, Percentiles



any port in 1841 minus the minimum cost in 1851. In our econometric analysis, we include market and port access variables as rail enhanced both in parallel.

Figure 2 maps the spatial distribution (in centiles) of market access and port access gains experienced across the island in the second half of the 19th century. As both variables measure changes, not levels, the emergence of rail has the potential to benefit districts further away from economic activity. The left-hand panel in Figure 2 demonstrates that a disproportionate share of market access gains accrued in counties between the big urban centres of Belfast, Dublin, and Cork. These include counties Laois and Tipperary in the southern part of the island and counties Monaghan and Armagh in the north. Market and port access are related, although this correlation is far from perfect (correlation coefficient is 0.50) and this variation is central in our analysis. For example, Limerick and Clare, on Ireland's west coast, appear as the chief beneficiaries of port access but experienced only moderate market access gains.

Reverse causality is a valid concern in this application. If the spatial distribution of population and economic activity influenced the shape of the rail network, then our outcomes may explain the emergence of Ireland's rail network rather than the other way around. We address this issue with five complementary approaches in Section 4.

Firstly, we control for hypothetical changes in market access in a scenario where Drummond's Irish Railway Commission's proposed network was built (Great Britain, 1838a). The purpose of the Commission was to propose a rail network that best suited Ireland's future transportation needs, thereby avoiding inefficiencies associated with a wholly privatised system, such as the duplication of lines and services. Following an extensive surveying period that considered cost-inducing geological constraints as well as likely traffic based on internal population structure and commercial trade, the Commission proposed a fairly parsimonious system that consisted of several lines radiating from Dublin city. For example, the Commission determined that the existing road and canal network were sufficient to service Dublin-Galway intercity traffic. In practice, the Commission's proposals were largely ignored and a much larger railway network was developed, although it is worth noting that, by the second half of the 20th century, Ireland's railroads receded to such an extent that the network resembled their proposed system (Horner, 1977). The transport network image in the bottom-left panel of Figure 1 maps the Drummond proposal rail lines, which we use to create a variable that measures the counterfactual market gains that would have occurred had the Commission's report been adopted in full.

Secondly, as is standard in the literature, our analysis is undertaken on the first differences of population density and land values, rather than levels, which is conceptually equivalent to DED-specific fixed effect in levels. Thirdly, we control for other spatial factors by including non-linear controls for latitude and longitude. We also include county-specific fixed effects, to account for any factors that relate to the capacity of local government, which had fixed borders, rather than place *per se*. Further, our conclusions are based on using spatially robust standard errors.

In addition to these three methodological approaches, we run two additional forms of analysis. We revise our measure of market access to exclude all market access improvements with a 25km buffer zone in each district. An equivalent method was employed in Donaldson and Hornbeck (2016). The motivation of this approach is to focus on improved access to more distant markets within Ireland, reflecting the transformational effect of rail over longer distances. This also guards against concerns that our results reflect coincidental localised political conditions—particularly given the highly politicised nature of railway line authorization (Esteves & Mesevage, 2021). Finally, we replicate the instrumental variable (IV) approach used in Jaworski and Kitchens (2019). In the first stage, market and port access variables are instrumented using market and port access improvements that discount the within-county (i.e. local) rail network. This method differs from the "buffer zone" approach because it preserves and includes local (in this case intra-county) markets in the overall market access computation, whereas local markets are cropped entirely under the "buffer zone" schema. Collectively, we believe that these overlapping approaches, undertaken in Section 4, help us to understand the causal effects of improved access to markets and ports on local Irish outcomes.

4 Analysis

In this section, we outline our empirical strategy and document the results of our analysis. Overall, our analysis employs several variations of the following regression model:

$$\ln(Y_{it}) = \beta_1 \ln(MA_{it}) + \beta_2 \ln(PA_{it}) + \gamma_i + \lambda_{ct} + f(Lat_i, Lon_i)\delta_t + \mathbf{X}\boldsymbol{\alpha} + \epsilon_{it} \quad (5)$$

where the outcome Y_{it}, population density or land value per acre, is a function of market access (MA_{it}) and port access (PA_{it}) alongside several other explanatory factors. Our outcome and both market and port access variables are expressed as natural logarithms meaning the estimated coefficients can be interpreted as elasticities. The γ_i term is a DED fixed effect that controls for time-invariant differences between districts. County-time differences—factors that changed between the 32 counties over time—are incorporated via λ_{ct} term. We model spatial variation in the data by allowing the geographic coordinates to enter as an isotropic smooth of latitude and longitude coordinate pairs (i.e. $f(Lat_i, Lon_i)$) interacted with time (δ_t). In practice, this means estimating Equation 5 with a Generalized

Additive Model (GAM) approach (Wood, 2017). We address spatial autocorrelation by applying the Conley (1999) correction and allowing spatial autocorrelation at a range of 25km. The matrix $\mathbf{X}$ contains additional control variables. Finally, the ϵ_{it} term represents a stochastic noise component.

Since our data only refer to two time periods, 1851 to 1911, we can estimate Equation 5 using a cross-section of first-differenced variables. Table 2 displays our main results, where log population density serves as the outcome of interest. In Column (1), we regress log population density on log market and port access omitting all other control variables — although since these data are expressed as first differences, this model still incorporates DED and time fixed effects. We find that market access reduces population density whilst port access has the opposite effect. The estimated elasticities are relatively small, -0.2 and 0.4, and not statistically significant at any conventional level. Column (2) addresses spatial confounding by adding an isotropic smooth term that accounts for geospatial patterns. The estimated elasticities of population to market and port access, 0.6 and -2.1, are the reverse sign, larger in magnitude and statistically significant. Better access to markets increased population density, while port access had a negative effect.

To contextualise these results, we calculate effect sizes by multiplying the estimated elasticities by the average change in market/port access and dividing by the mean change in logged population density between 1851 and 1911. In essence, this effect size measures counterfactuals: what share of population change is attributable to rail's introduction? Increased port access accounts for one-fifth of the population density decline during this period. However, this contribution is offset, almost entirely, by simultaneous increases in market access. The fall in Ireland's post-Famine population would have been worse without rail-influenced market access gains. Overall, the countervailing forces of market and port access suggest that the net effect of rail on the Irish population was small. But this aggregate effect masks a substantial locational reorientation. Improved (relative) domestic market access offered a degree of protection against depopulation, albeit at the expense of districts that gained access to foreign markets.

Column (3) of Table 2 adds county fixed effects to the model specification. This addition slightly reduces the coefficient estimates, although the qualitative interpretation remains unchanged. This result suggests that the spatial smooth-

Table 2: Estimated Impact of Market and Port Access on Population Density

	Log Population Density					
	(1)	(2)	(3)	(4)	(5)	(6)
Log Market Access	-0.177	0.569^{***}	0.560^{***}	0.518^{***}	0.249^{**}	1.613^{**}
	(0.160)	(0.137)	(0.124)	(0.177)	(0.116)	(0.663)
Log Port Access	0.435	-2.119^{***}	-1.792^{***}	-2.103^{***}	-1.553^{***}	-1.950
	(0.601)	(0.507)	(0.457)	(0.477)	(0.565)	(1.711)
On Rail Line				0.047	0.063^{***}	-0.056
				(0.029)	(0.021)	(0.077)
Rail Line Within 5KM				0.026	0.026	0.074^{*}
				(0.019)	(0.018)	(0.042)
Log Market Access Under Drummond				-0.049	-0.004	-0.092
				(0.036)	(0.038)	(0.071)
Log Port Access Under Drummond				0.286	0.139	0.110
				(0.204)	(0.211)	(0.424)
Estimation	OLS	OLS	OLS	OLS	OLS	IV
Lat-Lon Controls	No	Yes	Yes	Yes	Yes	Yes
County Fixed Effects	No	No	Yes	Yes	Yes	Yes
Market Access with 25KM Buffer	No	No	No	No	Yes	No
First Stage F-Statistic: Market Access						44.352
First Stage F-Statistic: Port Access						43.134
Market Access Effect Size (%)	6.762	-21.695	-21.342	-19.753	-15.195	-61.445
Port Access Effect Size (%)	-5.833	28.440	24.053	28.227	20.843	26.168
Observations	3,370	3,370	3,370	3,370	3,370	3,370

Note: Columns (1)–(6) regress the log growth in population density in a variety of regression specifications. Column (1) regresses logged population growth on market and port access. Column (2) repeats this exercise but controls for geographic position. Column (3) adds County fixed effects. Column (4) adds controls accounting for distance to rail lines and the expected market and port access improvements that would have occurred had the Drummond Commission's proposals been adopted. Column (5) repeats column (4) but uses a revised market access measure that excludes all market access improvements with a 25km buffer zone of each district. Column (6) reports the second-stage regression wherein the market and port access variables are instrumented using market and port access improvements that discount the within-county (i.e. local) rail network. Effect size calculated as $(100 \times \hat{\beta} \times \bar{A})/\bar{P}$ where A and P represent log market/port access growth and logged growth in population density. Conley standard errors that allow spatial correlation within a 25km radius in parentheses. $^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$.

ing procedure reported in column (2) sufficiently controls for spatial confounding. Column (4) displays the results when the model is augmented to control for differences in the distance to the rail line network and also the hypothetical improvement in market access that would have occurred had the Drummond Commission's proposals been adopted. Around 36 per cent of all districts had a rail line pass through their boundaries and, as column (4) shows, the population density of these districts grew, in relative terms, by 5 per cent compared to districts located more than 5km from a rail line. Districts located within 5km of a rail line (but not on one) experienced a smaller benefit, at least in terms of population density. Controlling for the hypothetical Drummond-approved market access gain further alleviates the endogeneity concern that rail line construction is a function of the existing and expected economic and population structures. This control thus acts like a placebo treatment and, reassuringly, does not affect either outcome.

In Column (5), we alter the definition of "market access" to exclude all districts within a 25km buffer radius for each observation. The rail network can only benefit a district when it is outside this radius, eliminating the potential for local shocks to influence both our access and outcome measures. This change causes some attenuation in the market access elasticity, reducing it from around 0.5 to 0.25. However, the relative sizes of the effects are consistent, with the -15 per cent market access contribution (i.e., population would have fallen by more without rail-induced market access improvements) offsetting a large portion of the 21 per cent port access effect.

The final column displays the second-stage 2SLS regression results wherein we address the endogeneity issue using an IV methodology. Following Jaworski and Kitchens (2019), we instrument both access measures using their equivalents after removing the rail network from within the district's county boundaries. This differs from the market and port access variables in Column (5) because it incorporates intra-county non-rail transport. Removing the within-county rail network tackles the concern that rail routes were driven by local concerns, such as political lobbying on behalf of railway companies seeking parliamentary approval, that correlate with outcomes such as population density or land values.

The results of Column (6) suggest that the previous coefficient values may have underestimated the market access effect. The market access elasticity of 1.6 is larger than the previous estimates and is still statistically significant at the 5 per cent level, although the associated standard errors are markedly increased. This loss of precision also affects the port access estimates, and the coefficient is no longer statistically significant, although the estimated value is similar in magnitude to the other estimates. The first-stage F-statistics—a diagnostic for weak instruments—indicate that both instruments have sufficient explanatory power to validate this methodology. The overall effect sizes appear to suggest that market access effects may have overpowered the negative port access effect, leading to a conclusion that Ireland's population would have fallen even further in the absence of rail. However, given the larger reported standard errors, this interpretation is only tentative

Table 3: Estimated Impact of Market and Port Access on Land Values

	Log Land Value					
	(1)	(2)	(3)	(4)	(5)	(6)
Log Market Access	0.103	0.577***	0.575***	0.351***	0.291***	0.379
	(0.127)	(0.095)	(0.084)	(0.100)	(0.111)	(0.266)
Log Port Access	0.641	−1.106***	−0.993***	−0.896**	−0.845*	−0.643
	(0.471)	(0.420)	(0.341)	(0.353)	(0.461)	(1.001)
On Rail Line				0.090***	0.094***	0.083**
				(0.014)	(0.012)	(0.034)
Rail Line Within 5KM				0.034**	0.038***	0.038
				(0.014)	(0.014)	(0.025)
Log Market Access Under Drummond				0.051*	0.073***	0.058
				(0.027)	(0.028)	(0.044)
Log Port Access Under Drummond				−0.105	−0.180	−0.164
				(0.112)	(0.119)	(0.232)
Estimation	OLS	OLS	OLS	OLS	OLS	IV
Lat-Lon Controls	No	Yes	Yes	Yes	Yes	Yes
County Fixed Effects	No	No	Yes	Yes	Yes	Yes
Market Access with 25KM Buffer	No	No	No	No	Yes	No
First Stage F-Statistic: Market Access						44.352
First Stage F-Statistic: Port Access						43.134
Market Access Effect Size (%)	12.933	72.170	71.919	43.833	58.315	47.368
Port Access Effect Size (%)	28.220	−48.740	−43.742	−39.472	−37.228	−28.326
Observations	3,370	3,370	3,370	3,370	3,370	3,370

Note: Columns (1)–(6) regress the log growth in land value in a variety of regression specifications. Column (1) regresses logged population growth on market and port access. Column (2) repeats this exercise but controls for geographic position. Column (3) adds County fixed effects. Column (4) adds controls accounting for distance to rail lines and the expected market and port access improvements that would have occurred had the Drummond Commission's proposals been adopted. Column (5) repeats column (4) but uses a revised market access measure that excludes all market access improvements with a 25km buffer zone of each district. Column (6) reports the second-stage regression wherein the market and port access variables are instrumented using market and port access improvements that discount the within-county (i.e. local) rail network. Effect size calculated as $(100\times\hat{\beta}\times\bar{A})/\bar{V}$ where A and V represent log market/port access growth and logged growth in land value. Conley standard errors that allow spatial correlation within a 25km radius in parentheses. ***$p<0.01$, **$p<0.05$, *$p<0.1$.

Table 3 replicates the analyses from Table 2, but with value per acre as the outcome. Overall, similar to population density, we find that improved market access increases land values, while improved port access has the opposite effect. Generally, the market access effect accounts for between 40 to 70 per cent of the land value appreciation between the Great Famine and the Great War. This large effect is mostly offset by the effect of better port access, which, when accounted for, implies that land values would have increased by more had it not been for cheaper and quicker access to foreign markets.

It is important to note that the effects of port access on land values are relative, meaning that a negative effect does not necessarily mean that port access caused a decrease in land values. These results also show significant geographic variation, with areas that gained access to external ports experiencing a decline in relative land values compared to those that benefited from improved internal access. The similarity between the results for land values and population density suggests that there are positive externalities associated with population. This interpretation is consistent with the urban economics literature on agglomeration forces, which suggests that population loss can reduce a location's attractiveness due to amenities (Glaeser & Gyourko, 2005).

In our context, changing market access suggests a link between population loss, land values and agglomeration. With similar results across Tables 2 and 3, population loss may have constrained land value growth. The redistribution of Ireland's (declining) population, brought about in part by its changing transport network, may have promoted agglomeration forces, as people disproportionately left more remote areas.

Table 1 showed that, across all districts, post-Famine population loss was more acute in the non-agricultural sector. This is consistent with households where the head is employed outside the agricultural sector being more likely to leave their home district in the post-Famine period. Table 4 explores this sector-specific change, replacing the population density outcome in Table 2 with the sector-specific version and replicating the model specification reported in Column (4). Both the market and port access coefficients in Columns (1) and (2) of Table 4 have similar signs. However, the magnitude of the coefficients associated with the agriculture-led population density channel is almost double and also more precisely estimated. Around a quarter of the population loss in the agricultural

Table 4: Estimated Impact of Market and Port Access on Sector-Specific Population Density

	Non-Agricultural	Agricultural
	(1)	(2)
Log Market Access	0.269	0.791***
	(0.226)	(0.155)
Log Port Access	−2.240**	−2.076***
	(0.943)	(0.616)
On Rail Line	0.304***	−0.215***
	(0.035)	(0.021)
Rail Line Within 5KM	0.018	0.037*
	(0.030)	(0.020)
Log Market Access Under Drummond	−0.262***	0.022
	(0.069)	(0.052)
Log Port Access Under Drummond	0.892***	−0.042
	(0.337)	(0.207)
Estimation	OLS	OLS
Lat-Lon Controls	Yes	Yes
County Fixed Effects	Yes	Yes
Market Access Effect Size (%)	−8.537	−35.247
Port Access Effect Size (%)	25.045	32.603
Observations	3,370	3,370

Note: Columns (1) and (2) show the model results when we model the log growth in non-agricultural and agricultural-specific population density. Both columns regress the respective logged population growth measure on market and port access with controls for geographic position, distance to rail lines, the hypothetical Drummond Commission market access improvement, and county fixed effects. Effect size calculated as $(100 \times \hat{\beta} \times \bar{A})/\bar{P}$ where A and P represent log market/port access growth and logged growth in non-agricultural or agricultural-specific population density. Conley standard errors that allow spatial correlation within a 25km radius in parentheses. ***p <0.01, **p <0.05, *p <0.1.

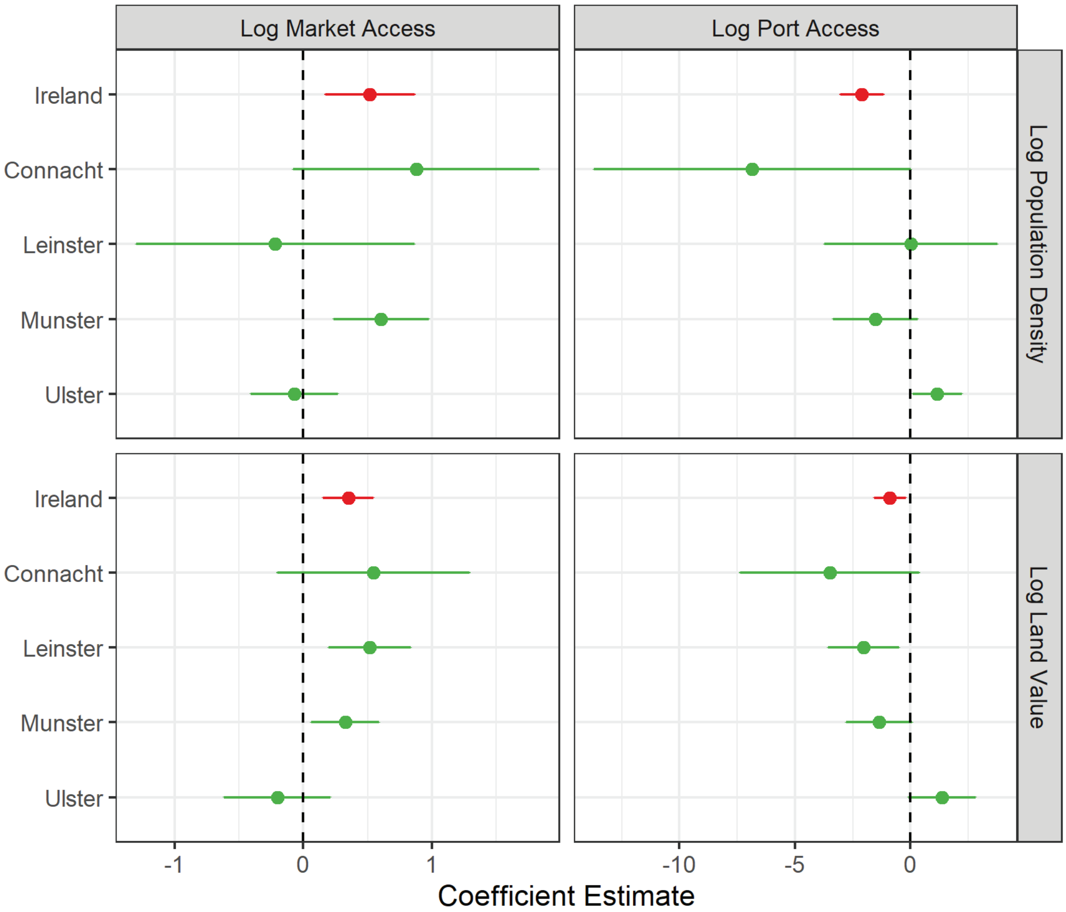
sector can be explained by port access improvements, although the negative effect of port access was largely offset by increased domestic market access. The comparison for the non-agricultural sector in Column (1) estimates that 25 per cent of the sector-specific population loss was caused by port access but market access gains partially offset this, by 9 percentage points.

With the district-level average share in agriculture rising from 64 per cent to 67 percent between 1851 and 1911, Ireland's failure to industrialize meant that agriculture was always the largest economic sector, even if there were important regional differences, as discussed below. Despite the famine's devastating impact on Ireland's rural population, it was those employed outside of agriculture who left in greater numbers, particularly in more remote parts of the island. This created a paradox whereby the Famine made the majority of districts even more reliant on primary-sector economic activity. This change—linked to the consolidation of farms and the move from tillage to pasture—meant that rail was introduced at a time of pronounced economic turmoil in the agricultural sector unmatched in the areas of commerce and industry. Given the context, rail's influence on the agricultural sector appears plausible.

The results thus far consistently demonstrate opposing market and port access effects. This suggests that the introduction of railways created economic winners and losers determined by geography. Districts who benefited in terms of domestic access benefited at the expense of their port-access gaining counterparts. Figure 3 explores the spatial dimension in greater detail, estimating the model from Column (4) in Tables 2 and 3 on each of the four provinces separately. The top panels refer to population density, while the bottom panels refer to land values; the left-hand side refers to (log) market access, while the right-hand side refers to port access. Shown are the point estimates for (log) market and port access, accompanied by 95 per cent confidence interval error bars; the within-province effects are shown in green, while red refers to the full dataset, as shown in Tables 2 and 3.

For population growth, the impact of market access appears to be similar across all four provinces, even if the standard errors are noisy: only in Ulster is it likely that the effect is different to the national coefficient in a statistically significant way, although also in Connacht and Leinster a null of zero effect would not be rejected. For port access, again the standard errors — in particular for Connacht — are very large, but what is perhaps more noteworthy is the fact that the coeffi-

Figure 3: Heterogeneous Effects



cient for Ulster is positive, rather than negative. Ulster was by far the most industrialized province within Ireland by 1911, home to large linen and ship-building sectors in particular.

Turning to land values, again Ulster appears to be the outlier, particular when considering the impact of port access. While greater access to ports is associated with a fall in land values in three provinces, in Ulster the same treatment brought about an increase in land values. This is consistent with the hypothesis that rail facilitated specialization in areas of comparative advantage, with different effects in Ulster, which specialized in labour-intensive industry, compared to the rest of the country, which increasingly specialized in land-intensive agriculture. For the impact of domestic market access on land values (bottom left panel), again, Connacht, Leinster and Munster are closely aligned with the national average, while the effect in Ulster is negative (albeit not statistically significant) rather than positive.

Our results indicate that the effects of market and port access largely cancel each other out, suggesting that railways had a limited effect on the Irish population. However, this conclusion is a national average and these opposing effects were not uniformly distributed, as shown earlier in Figure 2 . In some areas, positive domestic market access outweighed negative port access, whilst in others the opposite was true. The two panels of Figure 4 map the predicted "net effect" from a regression on the set of covariates listed in column (4) of Tables 2 and 3 of log differences in population density (left panel) and land values (right panel). The uneven spatial distribution of net effects is apparent. Across both outcomes, the pattern is strikingly similar and reflected in the high correlation (correlation coefficient of 0.95) between the two.

Figure 5 elaborates on this theme. The two scatterplots—across both outcome dimensions—illustrate these opposing forces with a dashed minus 45-degree line separating net beneficiaries from losers. There is an overall negative correlation, highlighting that districts that gained by way of domestic market access also tended on average to lose out via increased port exposure. However, this correlation was far from perfect and some districts experienced net gains and others net losses.

How much explanatory power do these "net effects" have? To examine this issue we aggregate the data to the level of the county, of which there were 32 in Ire-

Figure 4: Net Effect Maps

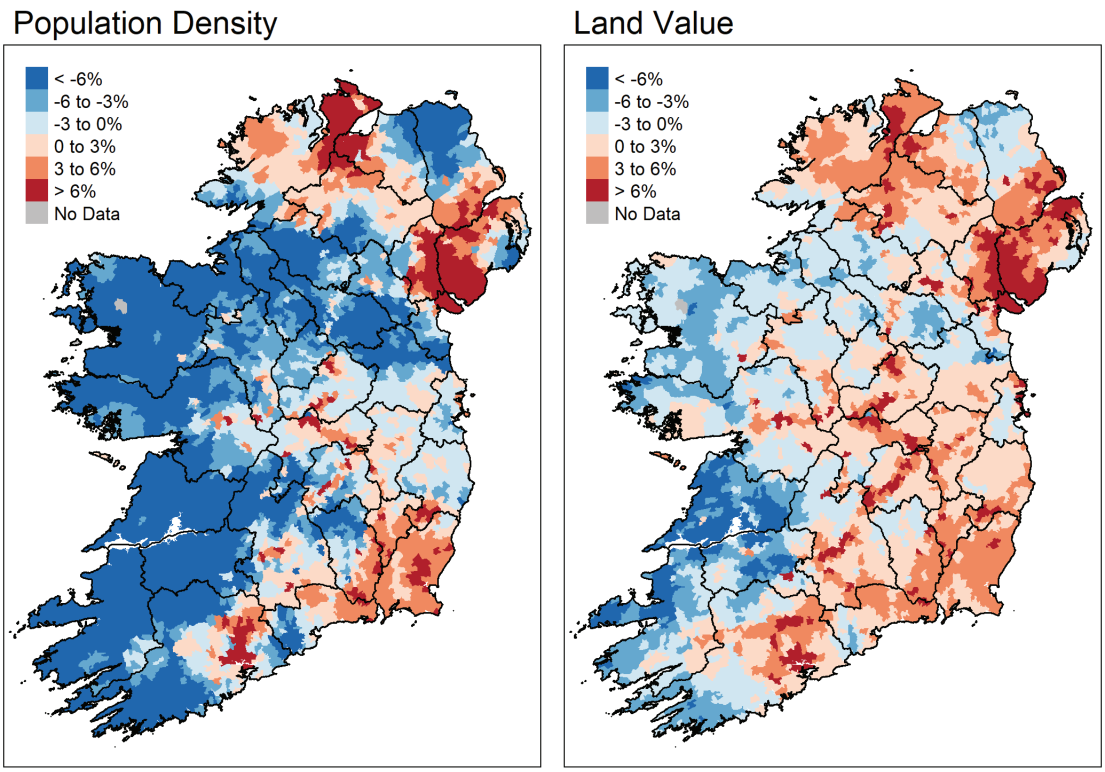
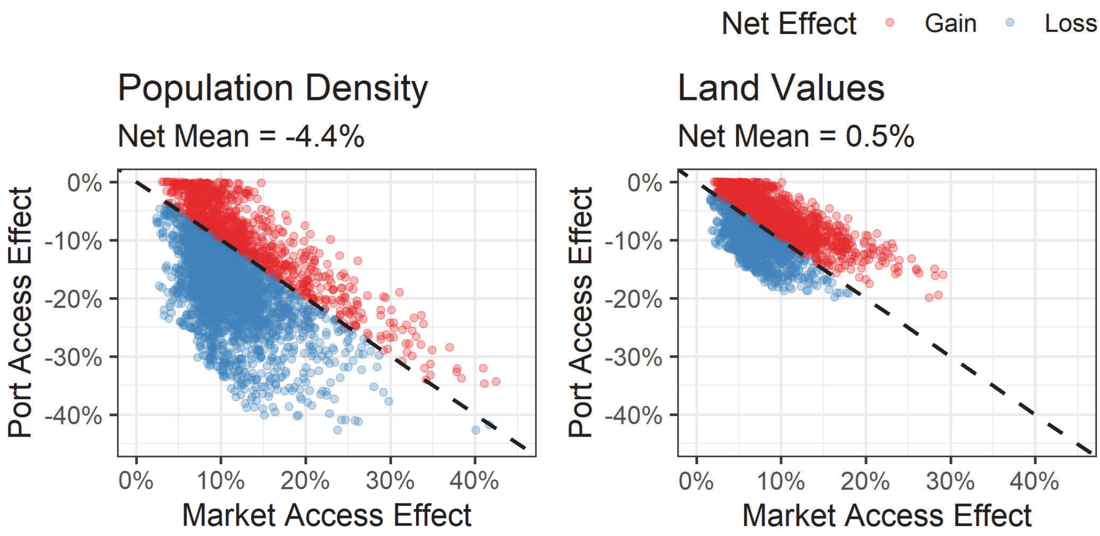


Figure 5: Winners and Losers

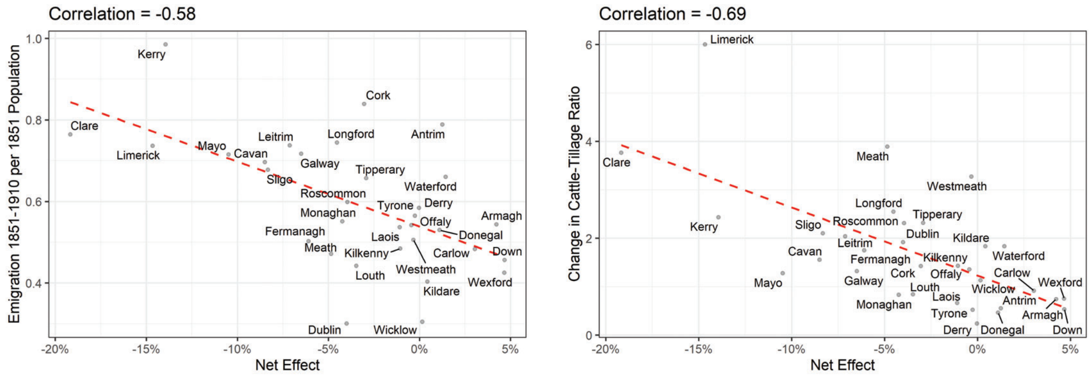


land, and look at two important features of the post-Famine economy: emigration and the switch from tillage to pasture. We focus on the total net effect based on our population density analysis, as the equivalent results for land values are so similar. Figure 6a uses the Dowling et al. (1997a) emigration series to create a variable measuring the number of emigrants between 1851 and 1910 as a share of the 1851 population. The correlation between this and the county's predicted net effect—a county-level weighted mean net effect, weighted according to the 1851 population size—is reasonably strong: -0.58. Counties where the negative port effect outweighed domestic market access improvements suffered from greater levels of emigration, and vice versa. Figure 6b repeats this exercise using data from the Dowling et al. (1997b) digitisation of various annual agricultural statistics. To capture the shift from labor-intensive tillage to land-intensive pasture, we use changes in a cattle-tillage ratio between 1852 and 1911.[6] In other words, this measure looks at the proportion of cows relative to the land area used to grow crops: growth in this ratio indicates a switch from tillage to pasture. Figure 6b is consistent with the belief that rail effects helped this transition. The correlation coefficient between these two variables is -0.69 and a simple bivariate regression

[6]We use 1852 instead of 1851 because tillage acreages were not available at a level of aggregation compatible with this analysis in the earlier year.

Figure 6: County-Level Outcomes

(a) Emigration (b) Cattle-Tillage



model yields an R^2 of 0.43; potentially over two-fifths of differences in the rate of tillage to pasture switch can be explained by the net effects of Ireland's railway network.

5 Conclusions

Rail transformed the economic geography of the world economy in the late nineteenth century and the potential effects on regional economic outcomes are still of topic of considerable interest to policymakers, politicians and voters in the 21st century. We document the impact of rail on the economy of Ireland, at the time a part of the United Kingdom, the world's largest economy. We distinguish between the impact of rail on domestic (i.e. Irish) market access and its impact on access to foreign labor and goods markets through shipping ports. This distinction, unique to the growing literature on the impact of rail, is particularly pertinent given Ireland's extraordinary economic openness in the later 19th century: in addition to being in a single market for goods, labor and capital with Great Britain, the economy experienced very high emigration rates to North America.

Using methods that we believe provide strong support for a causal interpretation of the coefficients obtained, we found evidence that the effects of access to domestic markets and international ports largely offset each other. Specifically, we found that greater access to domestic markets increased a district's population density between the Great Famine and the Great War, while greater access to international ports had the opposite effect. In our most detailed OLS estimates, with and without the exclusion of access to markets within 25km, these opposing effects ranged from around 20 to 30 per cent, with the negative effects of access to international ports generally dominating. This suggests that rail contributed to Ireland's depopulation, although this contribution was likely less than 10 per cent of the island's post-Famine decline. These results are largely the same when the outcome of interest is the change in land values between 1851 and 1911, with the main difference being the overall scale of change explained, which was roughly 40 per cent in either direction.

An analysis of province-level outcomes provides suggestive evidence of some important regional differences, even though statistical power becomes an issue. In particular, differences between Ulster, home to the region of Ireland that did industrialize in the later 19th century, and the rest of Ireland suggest the importance of further research on sector-specific impacts of improved access to markets. Further, the distinction made here—on access to local versus international markets—is new to the literature. There are likely rich avenues for future research that combines data on overland transport technology, such as rail, with more detailed data on improvements in shipping technology during the pivotal period for the world economy before World War I.

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A Constructing Agricultural and Non-Agricultural Population Density

Our analysis distinguishes between changes in agricultural and non-agricultural population density. Each district in our data records the number of household heads engaged in agriculture. The 1851 census reported this data at the civil parish, and not DED, resolution. Like DEDs, the civil parish data are highly disaggregated spatial units (2,437 observations with data from: Great Britain, 1856 matched to GIS data: OpenStreetMap Ireland, 2020), and we can translate the civil parish observations to DED equivalents via areal weighting methods (Pebesma, 2018).[7] For 1911, we have data on a DED level but the agricultural share is based on individual data, which we aggregate to match our data (National Achieves of Ireland, 2019). This process relies on the character transcriptions although we note a high degree of concordance (correlation coefficient of 0.97) between the reported county agricultural shares—the proportion of men aged 20 and over working with a profession defined as "agricultural class" and our transcribed and aggregated equivalent.

With data on both the numbers per household (NHH), the agricultural share AG, and the DED area ($ACRE$) we can construct our measure of agricultural density:

$$AgDensity = \ln\left(\frac{NHH \times AG}{ACRE}\right). \tag{6}$$

The non-agricultural equivalent is calculated by subtracting AG from 1 and replicating the above.

[7]We test the accuracy of the areal weighting method for the two variables that we have data for both at a DED and civil parish levels: population density and value per acre. In both cases, the parish-derived and true reported values (in natural logs) are closely related. The correlation coefficient for population density is 0.77 and the value per acre equivalent is 0.89.

B Different Thetas

Table B.1: Different θ Elasticity and $\bar{P}$ Value

	Log Population Density				
	(1)	(2)	(3)	(4)	(5)
Log Market Access	0.518***	0.927***	1.398**	0.307***	1.216***
	(0.177)	(0.208)	(0.589)	(0.072)	(0.359)
Log Port Access	−2.103***	−3.431***	−1.984***	−1.711***	−4.863***
	(0.477)	(0.786)	(0.624)	(0.504)	(1.341)
θ Elasticity	5.46	5.46	1.815	8.22	5.46
$\bar{P}$ Value	0.98	1.96	0.98	0.98	5.36
Baseline Controls	Yes	Yes	Yes	Yes	Yes
Lat-Lon Controls	Yes	Yes	Yes	Yes	Yes
County Fixed Effects	Yes	Yes	Yes	Yes	Yes
Market Access Effect Size (%)	−19.753	−35.693	−34.262	−10.829	−40.303
Port Access Effect Size (%)	28.227	35.676	26.626	22.968	29.190
Observations	3,370	3,370	3,370	3,370	3,370
	Log Land Value				
	(1)	(2)	(3)	(4)	(5)
Log Market Access	0.351**	0.651***	1.376**	0.238***	0.956***
	(0.177)	(0.208)	(0.589)	(0.072)	(0.359)
Log Port Access	−0.896*	−1.364*	−0.917	−0.679	−2.126
	(0.477)	(0.786)	(0.624)	(0.504)	(1.341)
θ Elasticity	5.46	5.46	1.815	8.22	5.46
$\bar{P}$ Value	0.98	1.96	0.98	0.98	5.36
Baseline Controls	Yes	Yes	Yes	Yes	Yes
Lat-Lon Controls	Yes	Yes	Yes	Yes	Yes
County Fixed Effects	Yes	Yes	Yes	Yes	Yes
Market Access Effect Size (%)	43.833	82.203	110.677	27.505	132.295
Port Access Effect Size (%)	−39.472	−46.548	−40.391	−29.904	−41.898
Observations	3,370	3,370	3,370	3,370	3,370

Note: Columns (1)–(5) in the top panel shows the regression results obtained from regressing the log growth in population density on rail-induced market access growth for varying elasticities of trade θ and average value of trade $\bar{P}$. The bottom panel repeats this exercise with log land value as the outcome variable. All columns employ regression specifications that measure market and port access with controls for geographic position, distance to rail lines, the hypothetical Drummond Commission market access improvement, and county fixed effects. Effect size calculated as $(100 \times \bar{\beta} \times \bar{A})/\bar{Y}$ where A and Y represent log market/port access growth and logged growth in population density/land value respectively. Conley standard errors that allow spatial correlation within a 25km radius in parentheses. ***p <0.01, **p <0.05, *p <0.1.

C Travel Costs and Speeds

Speed		
Mode	**Speed (MPH)**	**Sources**
Rail: Standard Gauge	25	Great Britain (1838b, Appendix A., No. 13, p. 86): According to William Cubitt, who compiled a report on using railways to improve the postal service, a speed of 25 miles per hour was realistic: "…and should a velocity of 25 miles per hour be obtained on the Railways". Other estimates exist in this report. Some are as high as 30 and others as low as 20. See also Lee (1976b, p.79): "The railway shortened the journey for passengers by over half, the steam engines chugging along at over 20 m.p.h. compared with less than 10 by coach or car."
Rail: Narrow Gauge	19	"Bradshaw's April 1910 Railway Guide" (n.d.) provides time and distance information. Here, we take the average speed between the following stations (start and end points of each line branch). The average of which was 19mph. • Listowel to Ballybunion • Killybegs to Donegal • Ballyshannon to Donegal • Donegal to Stranolar • Glenties to Stranolar • Stranolar to Strabane • Strabane to Londonderry • Ballycastle to Ballymoney • Ballymena to Parkmore

Waterway	2.5	Great Britain (1838b, Appendix III, p.46): "And again, on a canal with the usual barges, 1 lb will draw, at 2.5 miles per hour, 400 lbs. of useful load."
Waterway	7	Great Britain (1838b, p.105): "...; and assuming the speed by the ordinary conveyances to be seven miles per hour,..."
Land	1	Schimpl et al. (2011) find an average walking speed of 2.8 miles per hour. However, this figure was calculated based on people walking short distances. Once rests, which would be necessary on long-distant journeys, are factored in we think that a figure of 1 mile per hour, which would mean that one could walk 24 miles per day, is a reasonable baseline.
	Cost	
Mode	**Cost (d per ton mile)**	**Sources**
Rail: Standard Gauge	2	Great Britain (1838b, p.17): "It must, however, be observed, that the Canal charges average nearly 2½ d per ton per mile, whereas the Railway charge will, on an average, be about 2d. per ton per mile...". See also Lee (1976b, p.78): "Railway rates varied widely for different classes of goods, but in general worked out at 2d per ton per mile, much the same as by canal, the railway of course being much faster".
Rail: Narrow Gauge	2	See above. We assume the same freight rate on narrow gauge.
Waterway	2.5	Great Britain (1838b, p.17).
Road	6	Great Britain (1838b, Appendix B, No. 8, p.67): "The average price of carriage per ton per mile by water, may be estimated at 2d., and by land at 6d." The numbers here are for the Rockfarm Limestone Quarries in Co. Cork. Note that the water freight rate in this location was cheaper than the national average.

Land	27	The pre-railway average daily wage was 9d. (Doran, 2021b). Assuming that you would need to hire 30 men to carry approximately 34kg per man at a rate of 1d. per hour (and also a speed of 1 mile per hour).

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