Export Subsidies as Industrial Policy: the Case of the 19th Century Sugar Industry

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ABSTRACT This paper assesses export subsidies as a second-best policy to induce technological upgrading. Our analysis exploits a natural experiment in the nineteenth-century Austro-Hungarian beet-sugar industry, where a reform of the consumption tax unintentionally created an export subsidy. Crucially, the export subsidy emerged as the industry was transitioning to a new sugar extraction technology. Using newly assembled firm-level data on production and technology use, we show that the introduction of the export subsidy led to a reallocation of production towards higher export-access regions. Furthermore, factories in these regions upgraded to the frontier technology earlier, whereas those in low export-access regions upgraded last. Using complementary data on French sugar producers, we find that factories were more likely to upgrade to the new technology following an upgrade by a neighbor, consistent with spillovers that render private upgrading decisions inefficient. Did the export subsidy help? We construct a trade model with endogenous upgrading and spillovers. An export subsidy raises adoption due to positive selection into exporting and upgrading but distorts the allocation of production. We characterize this trade-off analytically. Calibrating the model to Austro-Hungarian data, we show that the historical subsidy increased adoption relative to no intervention but exceeded the optimal level, reducing welfare. In turn, interaction with the pre-existing protective tariff means that any positive export subsidy will have been counterproductive.

1. Introduction

Trade policy is the mainstay of industrial policy. Historically, import tariffs were used to engender domestic development of modern industry (Juhász and Steinwender, 2024). Today, import protection has largely given way to export promotion (Juhász et al., 2023). Indeed, both China and South Korea – two of the most dramatic growth experiences of the 20th century – saw government export support in technologically intensive industries. At the same time, little is known about the efficacy of export subsidies as industrial policy.

The argument for export subsidies as industrial policy can be summarized as follows. Technological upgrading, like any knowledge-intensive activity, can be subject to spillovers, whereby private upgrading decisions do not reflect the social benefits of upgrading, and thus fall short of the social optimum (Hall et al., 2010). In turn, evidence suggests exporting can drive technological upgrading (Shu and Steinwender, 2019). On the one hand, this relationship offers scope for potential use of export subsidies as a policy to induce upgrading. On the other hand, using export subsidies to correct a technological externality is a classical example of a poorly targeted policy that can cause misallocation (Bhagwati and Ramaswami, 1963). In this paper, we revisit this tradeoff between correcting for spillovers and misallocation when using export subsidies in a historical setting: the beet-sugar industry in nineteenth-century Austria-Hungary.[1]

We choose the Austro-Hungarian beet-sugar industry as our setting for two reasons. First, this is a setting where a reform of the consumption tax led to emergence of large, long-lasting and unintentional export subsidy. Second, this period coincided with the spread of a radical new sugar extraction technology – hot water extraction – still in use today.

The paper proceeds in three steps. First, we assemble firm-level data on production and technology use in the Austro-Hungarian beet-sugar industry. We document that the introduction of an export subsidy led to a dramatic reallocation of production toward higher export access regions. Furthermore, factories in these regions upgraded to the frontier technology earlier; whereas those in lower export access regions upgraded last. Second, using French firm-level data for the same industry, we show that factories were more likely to upgrade to the new technology following an upgrade by a neighbor, consistent with spillovers in firms' adoption decisions. Third, we build a quantitative trade model with endogenous technology choice and spillovers, and calibrate it to match initial levels and policy-induced changes in production and technology use in our historical setting. The calibrated model implies that export subsidies raised adoption relative to a no-intervention counterfactual but pushed it beyond the optimal level, leading to a welfare

1. Our period sees the political entity change from Austrian Empire, which included the Kingdom of Hungary, to the Dual Monarchy, Austria-Hungary. Our analysis tracks producers in both parts, we use Austria-Hungary throughout to avoid confusion.

loss. Moreover, due to the interaction with pre-existing patterns of misallocation, even a moderate export subsidy would have been counterproductive, with costs from misallocation outweighing the benefits from higher upgrading.

The context for our study is the meteoric rise of European beet sugar. Historically, nearly all sugar consumed in Europe was imported cane sugar. This changed in the 1800s, when the Napoleonic blockade of 1806-1814 cut continental Europe off from the colonial sugar supply, prompting experimentation with domestic sources of sugar. Sugar beet emerged as viable. By the end of the century, European beet sugar accounted for roughly half of world output. In turn, Austria-Hungary emerged as Europe's second largest producer.

The key force propelling Austro-Hungarian beet sugar was export subsidies. Remarkably, these arose unintentionally, due to a reform of the sugar consumption tax. From 1849, the tax was paid by producers, per weight of sugar beets used in production. Exports were tax-exempt; operationally, this entailed a rebate calculated per weight of sugar exported. In turn, the rebate rate was set at a level that, for an average producer, roughly offset the tax paid on production of exported sugar.

An export subsidy emerged in 1864, with a legal change that misaligned how the consumption tax and the export rebate were calculated. In particular, the law moved the basis for the consumption tax from the weight of beets used to beet processing capacity, calculated based on the installed machinery. The change required that the tax authorities take a stance on the processing capacity of contemporary machinery. This proved difficult, with the government systematically underestimating firms' true tax liability. Crucially, the export rebate was still calculated under the assumption that the tax *had been paid correctly.* As a result, from 1865 onward, export rebates exceeded the tax paid, yielding a net export subsidy.

The second driver behind the rise of Austria-Hungary's beet-sugar industry was innovation. While cane sugar required boiling, beet-sugar production called for complex, multi-stage processing. As successive stages were mechanized, extraction yields rose. Alongside this steady process of innovation, 1865 marked a breakthrough: the invention of hot water extraction. Compared to the earlier, press-based method, the new technology relied on chemical rather than mechanical extraction – and yielded a more complete sugar recovery. The new technology spread, and by 1885, adoption in Austria-Hungary was near-universal.

We study how the export subsidy affected production and adoption of this new technology in Austria-Hungary's sugar industry. Our empirical analysis is based on a novel, factory-level dataset for the universe of Austro-Hungarian sugar producers between years 1851 and 1883. Our production data comprise the annual, factory-level weight of beets used in production. Crucially, our dataset covers the period before and after the export subsidy emerged. Second, we use contemporary technical pamphlets and privately published firm directories to identify firms that had upgraded to the frontier technology in two years: 1870 and 1885. These two snapshots capture the early stage of the spread of the new technology, and a later period when most firms had upgraded.

Our strategy to identify the causal effect of the export subsidy relies on regional heterogeneity in export-market access. Before the introduction of the export subsidy, Austro-Hungarian sugar producers mainly supplied the domestic market. Thus, initial regional production largely reflected local market access. When export subsidies were introduced, some of the regions were much better placed to supply the largest market for sugar in nineteenth-century Europe: Britain. We leverage the pre-export-subsidy effective shortest distance via road, rail, and ship to London as our measure of policy exposure.

Using a region-level event study, we show that after the introduction of export subsidies, regions with high export market access saw (i) an increase in the weight of sugar beets processed, (ii) an increase in the number of operating firms, and (iii) an increase in the weight of sugar beets processed per firm. Finally, we show that the firms in high-export-access regions were more likely to upgrade to the frontier technology early in its spread. In turn, firms in low-export-access regions were the last to upgrade.

In the second part of the paper, we show that in addition to export market access, factories were more likely to upgrade to the frontier technology following an upgrade by a neighbor: a pattern consistent with spatial spillovers. The empirical challenge in establishing the presence of such spillovers is to distinguish a genuine causal link between neighbors' adoption decisions and spatially correlated unobservables. We address this challenge by collecting a companion dataset, covering firms' upgrading decisions for the universe of French sugar factories for the period from 1879 to 1889.

Using a staggered-adoption event study, we show that the first adoption by a factory within a 10-kilometer neighborhood increased local adoptions in the subsequent period. The main threat to our identification is time-varying unobservables that affect neighbors' adoption decisions but are unrelated to the proximity between producers. We argue that identification over a tight time window and short distances between neighbors rules out many of such confounders. However, we also control for region-time shocks to demand for technology (weather and export market access), and to the supply of technology (distance to the nearest machine shop). Our estimates remain robust across these specifications.

To assess the tradeoff between correcting for spillovers and misallocation when using export subsidies in our historical setting, we build a quantitative model. The heart of the model is Melitz (2003): firms select into exporting. Firms also face a binary technology adoption choice following Bustos (2011) – adopting frontier technology reduces the marginal costs of production, but entails a higher operating fixed cost. We allow for multiple regions to match our research design, and multiple sectors to allow for reallocation of resources between sugar and the rest of the economy. In line with our empirical evidence, we model spillovers in firms' adoption decisions by linking the cost of upgrading to the local share of adopters. The spillovers make firms' private upgrading decisions potentially inefficient.

We use our model to derive three results. First, we show that the introduction of an export subsidy increases (i) regional input use, (ii) the mass of operating firms, (iii) input use per firm, and (iv) the share of adopters, in line with our empirical findings. The reason the export subsidy induces upgrading in the model lies in the coincidence of selection into exporting and adopting. Specifically, due to fixed costs of upgrading, only firms with sufficient scale choose to upgrade. In turn, due to fixed costs of exporting, firms that export are more likely to attain sufficient scale to warrant upgrading. Thus, a policy that makes exporting cheaper also induces upgrading. Second, we show that despite this positive relationship between exporting and upgrading, and conditional on optimal tariff in place, the baseline with no spillovers calls for no export subsidies. In this case, the equilibrium share of adopters coincides with the social optimum. Third, we show that if the adoption of the frontier technology features spillovers, then the welfare effect depends on the balance of two terms: a positive effect of moving the adopter share closer to the social optimum, and an additional term that depends on how the export subsidy interacts with pre-existing misallocation. If there is no misallocation prior to the policy change – the second term is zero. If there is prior misallocation, the second term may be positive or negative, depending on whether the export subsidy worsens or ameliorates existing misallocation.

We calibrate the model to match the initial patterns of production and technology use, as well as the heterogeneous response in regional input use, the cross-regional adoption gap, and the aggregate adoption rate in the sugar industry five years into the policy change. Crucially, we calibrate the model to the pre-existing trade policy in our historical setting.

Using counterfactual analysis, we show that export subsidies in the sugar industry increased adoption of frontier technology. However, export subsidies decreased welfare relative to a no-intervention counterfactual. By constructing an efficient benchmark, we show that an export subsidy calibrated to the historical rate pushed adoption above the socially optimal level. Moreover, even a marginal export subsidy would have led to a welfare loss, a result arising from the interaction between the export subsidy and pre-existing trade policy. Since the sugar industry was subject to a high protective tariff before the subsidy was introduced, the economy already had excess resources allocated to sugar production. By directing further resources toward sugar production, any positive export subsidy would have led to a welfare loss.

Literature Review Our paper is closely related to the literature on trade liberalization and technological upgrading (Lileeva and Trefler, 2010; Atkeson and Burstein, 2010; Bustos, 2011; Impullitti and Licandro, 2018; Cai et al., 2022; Sampson, 2023; Aghion et al., 2024). Within this strand, Sampson (2016), Perla et al. (2021), and Buera and Oberfield (2020) show that trade liberalization can raise welfare in the presence of spillovers, but do not study the welfare effects of active trade policy. A smaller empirical literature – Atkin et al. (2017), Munch and Schaur (2018), Defever et al. (2020), and Buus et al. (2025) – examines the effect of export-promotion and subsidy programs on firms' technology decisions, typically without studying cross-firm spillovers or policy costs. We view our main contribution as bridging these two perspectives. We characterize the misallocation vs correction for spillovers trade-off for export subsidies theoretically and show how to assess it using a historical policy episode in a quantitative framework with parameters disciplined by causal evidence.

We are able to do this thanks to a unique feature of our historical setting that features a large, long-lasting, and unintended export subsidy shock in an industry transitioning from legacy to frontier technology. We study reallocation and adoption using firm-level panel data on production and technology choice. Our identification leverages the timing of the export subsidy shock interacted with exposure based on predetermined geography, in the spirit of Juhász (2018), who studies the infant-industry mechanism using the Napoleonic blockade as a protection shock and the pre-blockade location of cotton spinners as exposure. In turn, we discipline the strength of spillovers using newly digitized firm-level data for French sugar factories. Technological upgrading is rarely observed directly, so most studies measuring spillovers rely on proxies such as patents or R&D (Bloom et al., 2013; Matray, 2021). In contrast, we observe a direct measure of adoption for the universe of factories over a decade that spans much of the industry's transition.

Our paper is also related to a growing literature that studies the effects of industrial policy using modern causal inference techniques. Pascali (2017), Juhász (2018) and Hanlon (2020) leverage historical cases where exogenous changes in trade routes acted as protective barriers to assess the infant industry hypothesis. Gross and Sampat (2023), Kantor and Whalley (2023), and Mitrunen (2025) use war as an exogenous driver to study the effects of public R&D expenditure or state support to targeted industries, whereas Lane (2022) studies the government support for South Korea's heavy and chemical industry. We contribute to this literature by documenting a new historical case study that enables analysis of *export subsidies* – an intensely controversial type of industrial policy purported to have propelled Chinese and South Korean growth miracles – on firm-level production and technology choice. In related work, Matray et al. (2024) focus on government support for exporters. The authors leverage an effective shutdown of the Export-Import Bank of the United States to assess the effects of trade finance on firms. In comparison, our historical setting allows us to study not only the end but also the beginning of export support. In turn, the longer horizon of export subsidies in Austria-Hungary permits us to study firms' technological upgrading decisions after the arrival of a new frontier technology.

Finally, our paper relates to the recent wave of theoretical work on industrial policy. We contribute to the literature on coordination failures as a rationale for industrial policy (Buera et al., 2021; Choi and Shim, 2024; Choi and Levchenko, 2025) by flagging export subsidies as a potential second-best tool. Another related strand is the recent literature on industrial policy in open economies (Lashkaripour and Lugovskyy, 2023; Bartelme et al., 2025). In this prior work, sectoral production exhibits external economies of scale (EES), whereby sectoral productivity depends directly on sector size. Firms do not internalize that producing more raises everyone's productivity and therefore produce inefficiently little. This externality can be corrected with a sectoral production subsidy. In our case, the motive for intervention is principally different. Rather than external economies of scale, we model spillovers from firms' private upgrading decisions. This shifts the distortion to the share of upgraders – which is too low – and away from sectoral size. The production subsidy cannot correct this externality: by shifting demand for the marginal adopters' goods in lockstep with that for all other producers in the sector, it leaves relative demand unchanged and thus leaves the firm indifferent between upgrading and not. In turn, selection into exporting allows an export subsidy to induce upgrading. Since not all firms export, only the most productive exporters will enjoy higher demand due to the subsidy. As a result, the marginal exporter's scale increases, making upgrading worthwhile.

2. Historical Background

The emergence of beet sugar Until the nineteenth century, sugar cane was the sole source for the production of sugar on an industrial scale. Sugar was being produced in colonial plantations and then imported to Europe and the US. The main European consumer market was Britain, where sugar consumption flourished due to the comparatively high living standards, even among the working classes, and the complementarity of tea and sugar consumption, as sweetened tea became the favorite beverage of industrializing Britain (Mintz, 1986; Ward, 1994). In contrast, in Continental Europe, particularly in countries without colonies, sugar remained an expensive item of consumption and became even more unaffordable during the Napoleonic blockade (1806-14) that cut Europe from cane sugar imports (ORourke, 2006). Not having the right climatic conditions for sugar cane planting, the Blockade thus became an important driver for experimentation with domestic plants considered to be sources of sucrose. Beet turned out to be the most promising one. After initial setbacks, experiments were particularly successful in France and Prussia where new sugar beet varieties with double the sugar content were cultivated (Deerr, 1949). Over the nineteenth century beet sugar production expanded in Europe and by 1880 beet sugar represented half of the world sugar production.

Sugar industry in Austria-Hungary Initially, beet sugar production developed mainly in Germany and France (Diviš, 1891). Austria-Hungary was a late comer to beet sugar production but the industry quickly developed into one of the key industrial sectors in the Empire. This was underpinned by domestic innovation in the industry and from 1865 onward, export subsidies that arose due to a reform in the consumption tax.

Innovations in sugar production.—The key reason for the rapid expansion of European beet sugar was technological innovation in its production. The scope for innovation, in turn, derived from the technological complexity of extracting sugar from beet. Whereas sugar cane can simply be boiled to attain a liquid containing sucrose, extracting sucrose from beet required physical and chemical processing, where each step of production relied on steam-powered machinery.[2] As a result, in 1853, sugar industry in Austria-Hungary used as many steam engines as did the textile industry – the canonical 'leading sector' of nineteenth-century industrialization (K.k. Statistische Central-Commission, 1864).

In addition to gradual process improvement, in 1865 sugar production in Austria-Hungary saw a step change: the invention of hot water extraction method.[3] Whereas previously the beet slices will have been pressed with hydraulic presses, hot water extraction relied on a completely different mechanism: forcing the slices against hot water in purpose-built diffusion batteries, which released the sucrose into the medium. The new technology proved to be more efficient, with early experiments demonstrating a 1.5% increase in output compared to the earlier, press-based methods. Table A.1 documents the spread of this new technology. By 1870, 30% of firms in Austria-Hungary had converted their production. By 1885, only a handful of factories remained press-based.

Export subsidies.—Initially, the sugar industry in Austria-Hungary was largely tax-exempt. However, in 1849, rising fiscal needs led the government to introduce an excise tax on sugar. The excise tax was implemented as a domestic production tax, which was rebated upon exportation. Note that per se, this rebate did *not* constitute an export subsidy: paired with the import duty, it implemented a tax on domestic consumption. Only later – after a change in how the tax base was calculated – did the system produce a true export subsidy.

Since the introduction of the excise tax on domestic producers, the industry had pushed back hard to reduce the tax burden. One demand was that the basis of taxation be moved to the 'German system' (Diviš, 1891). The 1849 Austrian law stipulated weight of beets used in production as the basis for taxation. Germany, instead, relied on the *estimated* weight, using the assumed capacity of machinery installed to calculate expected processing

2. In the 1850s, the process of making sugar from beet entailed the following steps. First, beets needed to be cleaned and cut into thin slices. Next, these were pressed with hydraulic presses. The sugary juice was then cleared using lime and carbon dioxide gas and filtered. This thicker juice was then boiled in vacuum pans and, finally, sugar crystals were separated from the by-products with the use of centrifuges.

3. Contemporary sources referred to this technology as diffusion method. In order to avoid confusion with the term diffusion with the meaning 'spread of' we use hot water extraction or frontier technology wherever possible, unless referring to installation of machinery used in hot water extraction method – diffusion batteries.

volume. In 1865, this demand was granted.[4] The new rule required the government to take a stance on the processing capacity of contemporary machinery. It did so incorrectly – underestimating the productivity of an average firm and reducing the effective tax paid. The export rebate, however, assumed the tax *had been paid correctly.* As a result, from 1865 onward, export rebates exceeded the tax paid, yielding a net export subsidy.[5]

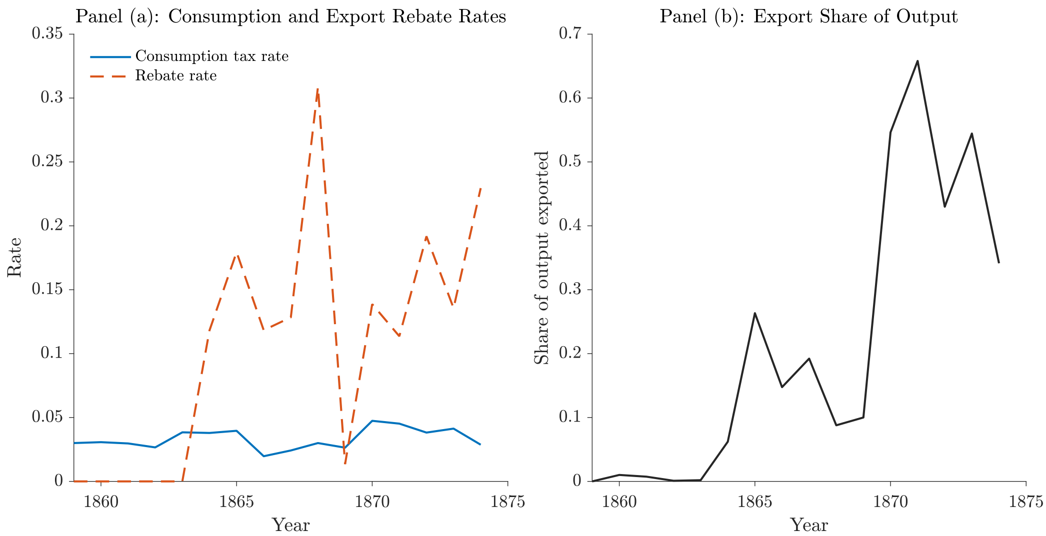
What was the size of export subsidies? Because the tax base differed between production and export rebates, it is difficult to measure the gap between the consumption tax and rebate directly. Table A.2 reports the annual value of export rebates and consumption tax collected, annual weight of beets used in production, as well as weight of sugar produced and exported. Figure 1 summarizes this information. In Panel A, we report the government receipt of consumption tax per centner of beets used in production and the government expenditure on export rebate, divided by value of sugar export. First, note that, despite the change in how the tax was administered, there was no break in consumption tax rate. Second, since the export subsidy regime began, exporters received approximately 15% ad valorem tax rebate. We calculate that between 1859 and 1874, the average government receipt of consumption tax as a share of aggregate value of sugar production was around 3%. Thus, from 1864, exporters started receiving a ad valorem export subsidy of around 12%. In Panel B, we report exports as a share of production. While before the reform exports were negligible, following the introduction of the subsidy Austro-Hungarian sugar exports went up on impact, and continued growing into 1870s.

The end of subsidies.—The use of export subsidies in sugar, referred to as ‘bounties’, was subject to significant debate and numerous international conferences. In addition to Austria-Hungary, these were practiced to a smaller or larger extent in most European sugar producing economies, most notably Germany since 1861 and France since 1884. Britain with its open market and colonial sugar production was particularly set against these practices and led international initiatives between 1863 and 1902 to try and abolish export promotion in sugar industry. This culminated in the 1902 Brussels Convention – the first multilateral trade agreement – which was signed by Austria-Hungary, Belgium, Britain, France, Germany, Netherlands, Romania, Spain and Sweden (Fakhri, 2014). The Convention limited import duties, prohibited export bounties and allowed participating states to put into place countervailing duties against countries selling sugar for dumping prices (Drachovský, 1902). This marked the end of export subsidies in European sugar.

4. The law came into effect in December of 1864, which meant that it applied fully to 1865 planting cycle. From here onward, we refer to the beginning of subsidies as 1865.

5. The mistake was realized, and in 1875 and later in 1878, the estimated quantities processed were increased. However, as technology continuously improved, the government remained one step behind. Thus, export subsidies persisted until their abolishment in 1902.

Figure 1. Consumption Tax, Export Rebate and Export Share



Sources: Statistisches Departement im k. k. Handelsministerium (1873); Central-Verein für Rübenzucker (1904).

3. Data and Empirical Strategy

3.1. Sources

Production We assemble a firm-level production panel for Austria-Hungary covering 1851-1853, 1857, 1861, 1868-1873, and 1883. The dataset comprises newly digitized and merged records. The panel draws on two types of sources: government statistical publications and privately published industrial reports. We describe these in turn.

Government statistical publications.—The first industrial census in Austria-Hungary dates from 1902. However, firm-level production statistics for selected industries predate these by at least half a century – notably for excise-monitored trades such as sugar, where administrative records were collected for taxation purposes. These statistics formed the basis for two officially published overviews of the sugar industry: *Mitteilungen aus dem Gebiete der Statistik: Rübenzucker-Fabrication in Oesterreich 1851-1853* (1854) and *Nachrichten über Industrie, Handel und Verkehr aus dem Statistischen Departement im K. K. Handelsministerium* (1876).[6] These publications provide firm-level production data for years 1851-1853 and 1868-1873, respectively. Since we are interested in long-run analysis, we aggregate consecutive years by taking means, such that the years in our analysis from these sources are 1851, 1853, 1868, 1870, 1872. The administrative nature of these reports means they cover the universe of sugar-producing factories in Austria-Hungary.

6. In 1868, the state had split into two autonomous halves: Austrian crownlands and the Kingdom of Hungary. As a result, Hungary obtained its own independent statistical bureau. We complement the data in *Nachrichten über Industrie* with firm-level production data from the corresponding issues of the Hungarian Statistical Yearbook series.

Privately published industrial reports.—Our second source of data are non-government reports on the sugar industry, written as practical guides and source of information for individuals directly involved in the sugar industry. *Rübenzucker-Industrie in Österreich beleuchtet vom Standpunkte der Volkswirtschaft und Finanzpolitik* published in 1858 focuses on the technical analysis and optimization of sugar production processes, and includes production at the factory-level. We combine this first source with production data reported in *Böhmens Rübenzuckerfabrikation in der Campagne 1857-1858* whenever the data is missing in the latter. We use this combined information as our main source of data for the year 1857. *Industrie-Atlas des Königreiches Böhmen* published in 1863 covers a wide range of industries and serves as a basis for our 1861 statistics. Finally, we use *Rukovt pro cukrovarníky a obchodníky cukrem* – a handbook for sugar manufacturers and sugar traders published in 1884 – as a source for production data in 1883.

Technology Our sample period coincides with a major technological transition in the industry: the switch from the older hydraulic-press-based mode of production to the newer hot water extraction method. We construct a binary variable indicating the use of hot water extraction for two years: 1870 and 1885.[7] The former represents the early stage of the spread of the new technology, when approximately 30% of firms had converted. The latter captures an almost full transition.

Our primary source for 1870 is *La diffusion de M. Jules Robert*, a contemporary technical pamphlet on the hot water extraction method, published by Joseph Adler, a long-time collaborator of Jules Robert, inventor of the method. The volume contains a complete list of firms that had installed diffusion batteries by 1868. A separate publication, *Das Saftgewinnungsverfahren der Diffusion*, lists the number of adopters by year. It further reports the number of new factories built with diffusion batteries installed and incumbent factories that converted. In 1869, 13 factories entered with diffusion batteries and one incumbent converted. Since our production data show 13 new entrants in total, we assign all of these as using frontier technology. In 1870, 27 entrants began operations with frontier technology, and no incumbents converted. We observe 31 entrants in 1870. To identify the 1869 converter and the four entrants with press-based production, we consult regional statistical reports. These allow us to identify the incumbent and three entrants directly. The remaining entrant is treated as measurement error.[8]

7. Hydraulic presses and diffusion batteries performed the same step in sugar production – juice extraction – and, as such, either one was used to the exclusion of the other. As a result, statistical sources classified firms as either diffusion- or press-based.

8. All Austro-Hungarian chambers of commerce were tasked with collecting data from their constituent counties for the Ministry of Commerce. However, the format of data collection was left to individual districts. Only a handful of chambers collected detailed statistics on sugar-extraction technology. For this reason, we do not use regional statistical reports as our primary source of technology data.

Our 1885 data comes from another privately published firm directory: Verzeichniss der Zuckerfabriken (1886). The directory lists all firms in Austria-Hungary and indicates the juice extraction technology in use. The number of firms reported matches the total number of firms active in 1885 in official statistics. Thus, we treat this data source as complete.

Linking factories across time We link observations across years by factory location. Since transporting sugar beets was costly, factories were located near the sugar-beet fields that supplied them. Thus, in virtually all cases, factory locations uniquely identify factories. When multiple factories existed within the same geographic unit, we use factory names and ownership to disambiguate. We use years of establishment to assign new firm identifiers to firms in locations where one factory shut down and a new one reopened.

3.2. Summary Statistics

Table 1 reports the number of sugar factories and average weight of beets used per factory by year. Two patterns stand out. First, there is extensive entry into the sugar industry: 90 factories operate in the first year of our sample; the number peaks at 247 in 1872, before settling at 198 by the end of our sample. Second, the scale of factory operations increases dramatically, with weight of beets used per factory quadrupling between 1851 and 1883.

Table 1. Summary Statistics

	1851	1853	1857	1861	1868	1870	1872	1883
Factories	90	113	109	115	168	231	247	198
Inputs/Factory	51.6	52.3	74.9	131.5	104.6	104.7	110.7	216.9

Notes: Inputs record weight of beets processed, in 1,000 Viennese Centners (1VC = 56kg).

In our empirical analysis, we study how export subsidies affect sugar production at the municipality level. This allows us to capture both the extensive and intensive margins of adjustment. Accordingly, we aggregate firm-level data to the municipality level. We measure three outcomes related to sugar production at the municipality level: total weight of beets used as inputs, the number of firms operating, and weight of beets used per firm. Because large parts of Austria-Hungary produce no sugar during the sample period, we restrict the main analysis to municipalities with at least one firm observed at any point (see Appendix Figure A.3). This yields a balanced panel covering years 1851, 1853, 1857, 1861, 1868, 1870, 1872 and 1883.

3.3. Empirical strategy

Empirical specification Our empirical strategy aims to estimate the impact of export subsidies on sugar production at a municipal level. To do this, we run the following event study regression:

$$\pi_{it} = \sum_{s=-m,\ldots,0,\ldots n} \gamma_s D_{1865+s} x_i + \alpha_i + \delta_t + \varepsilon_{it},$$

Here, π_{it} denotes total weight of beets used, number of firms, or weight of beets used per firm in municipality i, and year t. x_i is the measure of municipal export access, which we describe in the following segment. Our event study design lets the effect of x_i vary over time. $-m$ and n indicate the years before and after the export subsidy is introduced in 1865. D_{1865+s} are indicator variables for the years $1865 + s$. Our objects of interest are the coefficients γ_s: we expect $\gamma_s = 0$ for $s < 0$, and $\gamma_s > 0$ for $s > 0$. We use 1861 as the reference year – the closest pre-export-subsidy year with available data. Finally, α_i and δ_t are municipality and time fixed effects accounting for any unobserved municipality and year characteristics. We cluster standard errors at the municipality level.

Measuring export access We measure export access as the negative of the effective rail distance from each municipality to Britain: the key destination for Austro-Hungarian sugar exports.[9] To do so, we compute the lowest-cost route effective distance from each municipality i to London in 1864, which we denote τ_i. τ_i has three components: (i) the cost of road transport from each municipality i to the nearest railway line τ_{ir}, (ii) the cost of rail transport from this point to the relevant port p denoted by τ_{rp}, (iii) the cost of shipping between London l, and the port, denoted by τ_{pl}.[10] We allow for two ports – Hamburg or Trieste – the dominant routes for Austro-Hungarian exports (K.K. Statistische Zentralkommission, 1865).

To calculate τ_i from these different modes of transport, we convert them into effective railroad kilometers using the estimated cost of traveling in the nineteenth century from Donaldson (2018) for rail ($\alpha_{Rail} = 1$), road ($\alpha_{Road} = 4.5$), and sea ($\alpha_{Sea} = 2.25$). We then calculate i's lowest-cost route effective distance to any port as $\tau_i = \min_p \tau_{ir} + \tau_{rp} + \tau_{pl}$. The Appendix Figures A.1 and A.2 show existing export routes as well as the quartiles of effective export access across municipalities.

9. Nineteenth-century statistics do not report exports by destination. However, between 1868 and 1880, 84% of Austro-Hungarian raw-sugar exports left the country via Saxony – the shortest route from most of Austria-Hungary to the British market using the port of Hamburg (K.K. Statistische Zentralkommission, 1865). In 1910 – when data on export by final destination is available – the UK was still the main Austro-Hungarian export market responsible for 42% of sugar exports (Mikush, Gustav 1913, p.621). The next biggest single market – Ottoman Empire – accounted for only 13%.

10. We thank Tomas Cvrcek for sharing Austro-Hungarian railroad network data for 1864. For the distance between Austrian border crossings and the port of Hamburg, we use linear geographic distance.

Control variables In additional results, we explore robustness of our main specification to including a number of controls. First, as we discuss in Section 2, nineteenth century saw rapid mechanization of sugar manufacturing. As a result, access to coal became increasingly important as a determinant of the costs of production. We obtain our measure of distance to coal fields (hard coal and lignite) from Fernihough and O'Rourke (2021). The second important determinant of the costs of production is quality of sugar beet used as inputs. We proxy for sugar beet quality using a measure of soil suitability for sugar beets from Fischer et al. (2021). The Appendix Figures A.4 and A.5 map the soil suitability for sugar beet and access to coal across municipalities.

Identifying assumptions and threats to identification Our identifying assumption is that municipalities with greater access to export markets in the pre-period were not differentially exposed to subsequent shocks. Note that we do not require high- and low-exposure municipalities to be similar in levels. Instead, we rely on the standard parallel-trends assumption that outcomes for the two groups would have evolved similarly absent the introduction of export subsidies. We will visually assess the plausibility of the parallel trend assumption using our event study estimates.

The absence of differential trends prior to the introduction of export subsidies does not rule out confounders completely. Instead, it implies that any confounders would have had to drive differential dynamics after 1865, and not before. We are aware of one important shock to sugar industry that coincides with introduction of export subsidies: the invention of hot water extraction.[11] The arrival of new technology threatens identification if, *absent* export subsidies, high-export-access regions would have adopted at differential rates. While we cannot rule this possibility out directly, we provide two checks. First, in Appendix Figure A.6 we show that factories in high-export-access municipalities were not systematically larger – a correlate of technological upgrading in standard models. Second, as a robustness exercise, we control for proximity to the first factory to adopt hot water extraction, following a rich literature showing that geographic proximity to prior adopters shapes the spread of technology (Keller, 2004). Note that a causal interpretation of our estimates remains valid even if high-export-access municipalities adopt frontier technology differentially *given* the export subsidies are in place. In this case, γ_s recovers the total effect of the introduction of export subsidies: the direct effect from the shift in export demand and the indirect effect via increased upgrading by firms whose larger scale, thanks to export subsidies, made such upgrading worthwhile.

Finally, if there is interdependence between firms' technology choices, such as upgrades by early adopters reducing adoption costs for other firms, stable unit treatment value

11. We can rule out the invention being caused by export subsidies: the inventor, Jules Robert, continued work that was started by his father decades prior. 1865 saw the first commercial use of technology.

assumption may be violated. In that case, positive spillovers contaminate controls upward the estimated effects of the export subsidy are biased downward relative to the true impacts and should be interpreted as lower bounds.

Balance check We check that the treatment and control groups are comparable by verifying the balance of a number of characteristics that are relevant determinants of the development of sugar industry pre-export subsidy. To do this, we regress municipal weight of beets used in pre-subsidy years on export access by 1864, domestic market access, distance to coal reserves, river access, soil suitability, and the presence of a railroad line by 1864. Appendix Figure A.6 presents these results for the years 1851 to 1861.

We find that export market access was unrelated to sugar production in any year prior to the introduction of the export subsidy. This pattern is consistent with effectively no export activity in sugar before 1865. By contrast, domestic market access – measured as proximity to urban populations across Austria-Hungary – was the dominant determinant of sugar production throughout the period. The effect is sizable: a one-standard-deviation increase in domestic market access is associated with nearly a one-standard-deviation increase in local beet processing across all years. Access to coalfields became important from the 1860s onward, in line with the increased use of steam in sugar processing. Likewise, sugar beet suitability only became relevant by 1861, which suggests that farmers and factories required time to identify the most productive growing areas. We find little evidence that proximity to rivers or railroads mattered once export and domestic market access are accounted for. Local urban population similarly had no effect. Finally, Hungarian municipalities produced less, in line with the regions relatively lower level of economic development.

4. Effects of Export Subsidy

In Section 4.1, we examine the effect of the introduction of export subsidy on sugar production. Following the policy change, high-export-access municipalities experienced an increase in weight of beets processed. Both the intensive and extensive margins contribute to this aggregate effect. In Section 4.2, we study the effect of export access on technological upgrading. We show that early in the spread of hot water extraction method, firms with higher export access were more likely to upgrade. In turn, once the technology had largely spread, regions with low export access were the last to continue using old technology: hydraulic presses.

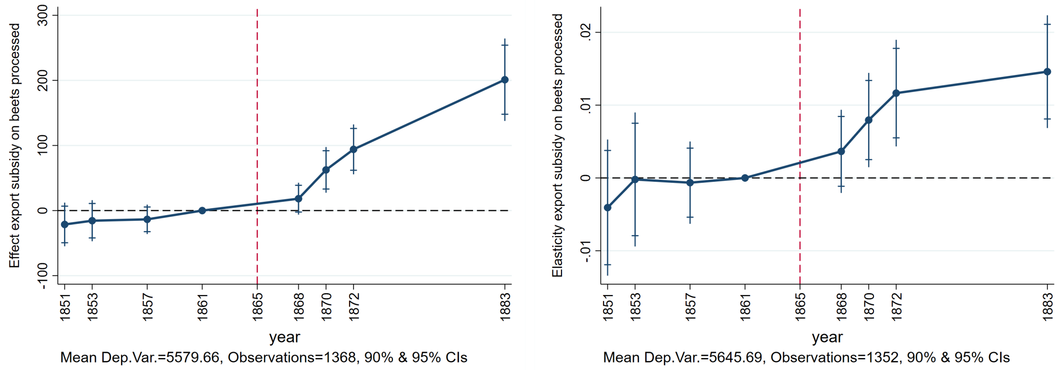
4.1. Export Subsidies and Sugar Production

Figure 2 presents the effect of the export subsidy on municipal sugar production. Panel (a) presents the effect on total amount of sugar beets processed using OLS, while Panel (b) presents elasticities estimated using Pseudo-Poisson Maximum Likelihood estimator (PPML). The results show that municipalities with higher export access start producing

Figure 2. Effect of export subsidy on sugar production

A) Total

B) Elasticity



Notes: The figure plots the event-study estimates for the effect of export market access on beets processed in tons (Panel A) and the elasticity (Panel B). In Panel A estimates are obtained using OLS. In Panel B elasticities are estimated using Poisson Pseudo Maximum Likelihood (PPML). Controls: Municipality and year fixed effects. Standard errors clustered at the municipality level.

more sugar after the export subsidy is introduced. In contrast, there is no difference in the growth rates before the policy change. We estimate that seven years after the policy change, a municipality at the 75th percentile of export access processes 4700 tons more beets than one at the 25th percentile. Two decades later, the production gap between the two regions widens further. Results in Panel (b), in turn, can be interpreted as the elasticity of weight of beets processed to export subsidy exposure. An increase in export access from 25th to 75th percentile of exposure results in a 58% increase in input use.

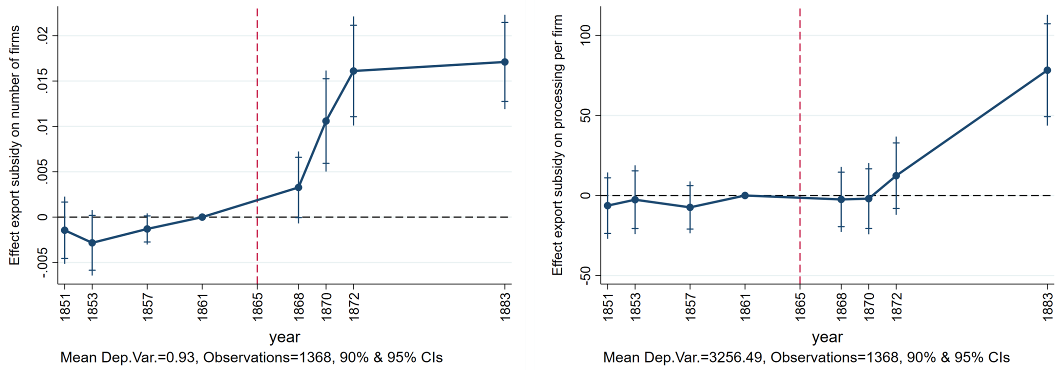
In Figure 3, we break down this increase in production into the extensive and intensive margins. Panels (a) and (b) report the results for the number of firms and weight of beets processed per firm, respectively. In the years following the introduction of the export subsidy, the municipalities with greater export market access saw a rapid increase in the number of operating firms. Seven years after the policy change, the number of firms in municipalities at the 75th percentile of exposure was almost double that in a municipalities at 25th percentile.[12] In other words, extensive entry into sugar production documented in Section 3.2 was largely directed at high-export-access areas.

Input use per firm in high-exposure municipalities increases with a lag, reaching a statistically significant difference vis-à-vis the control group by 1883. However, since the early years after the policy change witnessed extensive entry, input use per firm conflates composition effects from the entry of smaller producers with firm-level changes in input

12. We compute this as a product of the point estimate for γ_{1872} and the distance between the quartiles divided by the average number of firms in a municipality.

Figure 3. Effect of export subsidy on sugar production

A) Number of firms B) Processing per firm



Notes: The figure plots the event-study estimates for the effect of export market access on number of sugar factories (Panel A) and sugar beets processed per firm (Panel B). Estimates are obtained using OLS. Controls: Municipality and year fixed effects. Standard errors clustered at the municipality level.

use. In Appendix Figure A.8, we show that when we restrict the sample to firms that existed before the policy change – input use per firm responds on impact.

Robustness In Appendix Figure A.9, we report all our results together with our main robustness checks: controlling for (i) kingdom fixed effects, (ii) distance to coal reserves, (iii) distance to the first factory to use hot water extraction, all interacted with time. In all cases, our event studies show no statistically significant pre-trends and a comparable magnitude of effects after the policy change.

4.2. Export Subsidies and Technological Upgrading

We next study the effect of export subsidies on firms' technology adoption decisions. Since its invention in 1865, hot water extraction spread among sugar producers in Austria-Hungary. By 1870, 30% of firms had upgraded. By 1875, the share of converters reached 60%. By 1885, adoption was nearly universal, with 94% of firms having upgraded.

We conduct analysis as a cross-sectional regression for two years in which we observe firm-level technology: 1870 and 1885.[13] We regress the dummy variable which takes value one if the firm has upgraded on our measure of export access. We additionally report results with the full set of controls. Table 2 reports the results. An increase in export access from 25th to 75th percentile of exposure results in a 13% increase in probability of upgrading in 1870. In 1885, the effect of export access remains quantitatively similar.

13. The timing of invention of the hot water extraction method – 1865 – coincides with the beginning of the export subsidies. Thus, it is not possible to include pre-period adoption levels.

Table 2. Technological Upgrading and Export Access

Dependent Variable	D_{1870} (1)	D_{1870} (2)	D_{1885} (3)	D_{1885} (4)
Export Access	0.00266*	0.00305*	0.00232**	0.00176**
Controls	N	Y	N	Y
Observations	210	210	215	215

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Notes: This table reports the estimated effects of export access on technological upgrading. The dependent variable is an indicator variable that equals 1 if a factory has adopted hot water extraction by 1870 (D_{1870}) and by 1885 (D_{1885}). Export access is measured as negative of effective rail distance from each factory to Britain using railway network as of 1864. Estimates are obtained using OLS. Controls: (i) indicator variable for factories in Hungarian kingdom, (ii) distance to coal reserves, (iii) distance to the first factory to use hot water extraction method. Standard errors clustered at the factory level.

5. Spillovers

In this section, we show that, in addition to export market access, factories were more likely to upgrade to the frontier technology following a neighbor's upgrade – a pattern consistent with spatial spillovers. We do not interpret these correlations as causal effects, but as evidence that is compatible with spatial spillovers of knowledge.

Historical Context We conduct analysis using a companion dataset that covers firms' upgrading decisions for the universe of French sugar factories from 1879 to 1889. We turn to France to document patterns in the spread of the frontier technology for two principal reasons. First, for France we observe adoption status for the universe of sugar producers over a decade, which allows us to study firms' adoption decisions using a richer set of controls than is possible for Austria-Hungary. Second, France was an early leader in European beet sugar production but gradually lost its supremacy to Germany and Austria.[14] As a result, the new technology arrived relatively late in France. As such, we are able to trace out its spread from low initial level ($< 20\%$ national adoption rate) through to an almost universal uptake ($> 80\%$).

Historical sources point to a specific channel for local interdependence: farmers' reluctance to supply beets to factories that upgraded to hot water extraction (Paasche, 1891; Clout and Phillips, 1973). Under the older hydraulic-press extraction method, factories provided the supplying farmers with the pressed leftovers – pulp. In turn, this pulp was used as cattle feed. By contrast, the new method produced pulp with high water content, which was a major inconvenience for farmers. As a result, upgrading required not only expenditure

14. This loss was partially due to differences in national policy – unlike Germany and Austria, French taxation system did not produce indirect export subsidies. Furthermore, France had long-standing interests in Antilles colonies producing cane sugar, which created a conflict between colonial and metropolitan sugar industries.

on new equipment but also convincing local suppliers to accept the new, wet byproduct. Consequently, social learning among farmers could give rise to interdependence across firms upgrading decisions: as one factory in the region successfully convinced its suppliers to accept the new form of byproduct, others would have been more likely to follow suit.

These spillovers are consistent with aggregate trends in upgrading to the new technology in France. The lack of social acceptance of the method can explain why, by 1880, when even the least productive factories in Austria-Hungary and Germany had upgraded, few French factories had done so. In turn, once the technology began to spread, conversion was rapid (see Figure B.1 for the spread of the new technology across French départements). In this section, we present evidence consistent with spillovers in factories' upgrading decisions.

5.1. Data and Research Design

Sources Our primary source is a privately published annual directory – the *Liste générale des fabriques de sucre, raffineries et distilleries de France* – compiled by the sugar trade journal *Journal des Fabricants de Sucre*. For each campaign, the directory reports the universe of beet-sugar factories, with their address, proprietors, and – crucially – the juice-extraction technology. Hydraulic-press plants are flagged 'P.H.' (*presse hydraulique*); hot water extraction adopters are flagged 'D.' (*diffusion*). We digitize the 1879-1889 campaigns to construct a factory-year panel with location and an indicator for adoption status. Because plant names vary across issues, we aggregate the data at the municipal level and work with counts of adopters within a location.

Summary statistics There were 501 factories operating in 1879 and 380 in 1889. Production was highly spatially concentrated. In our sample, over 90% of factories were located in just eight départements, which constitute the northern region of France (see Figure B.2). Figure B.3 shows the distribution of factories per municipality in 1879. Most municipalities hosted one factory; however, having 2-5 factories was also relatively common. Figure B.4 plots the distribution of neighboring factories within a 10-kilometer band around each municipality. While most municipalities had no neighbors in this radius, there is a substantial mass with 1-24 nearby factories.

Empirical strategy We implement two complementary designs at the municipality-year level. First, we relate local adoption to lagged exposure to neighboring adopters. Second, we estimate an event-study around the first neighbor adoption. All specifications include municipality (δ_m)and region-year fixed effects (δ_{ct}), as well as baseline controls; standard errors are clustered at the municipality level.[15]

15. We construct regions as 1-by-1-degree-cells. 1 degree is approximately 111 kilometers.

We estimate whether local adoption followed adoption by neighboring factories using the following specification:

$$y_{m,t} = \alpha_r y^r_{m,t} + \gamma' \mathbf{X}_{m,t} + \delta_m + \delta_{ct} + \varepsilon_{m,t}. \tag{1}$$

Here, $y_{m,t}$ is the number of adopters in municipality m and year t. $y^r_{m,t}$ is the number of adopters in the $r-$radius neighboring municipalities in m and year t, defined using distance rings: 10, 15, 20, 30, 40, 50 km. We exclude local municipal adoption from the neighbor adoption construction to avoid introducing a mechanical relationship. We additionally estimate this specification using neighborhood donuts: one for 10-60 kilometers (this specification excludes the closest neighbors) and one for 50-100 kilometers (this specification excludes even distant neighbors and serves as a robustness check that our results are not confounded by regional trends). $\mathbf{X}_{m,t}$ includes export market access $\times$ year dummies, distance to press/diffusion battery producers $\times$ year dummies, and annual summer-rainfall variation; construction and sources appear in Appendix B.1. The coefficient of interest, α_r, captures the extent to which factories in a given municipality are more likely to upgrade their technology following upgrades by neighboring factories.

We next estimate an event-study with staggered first neighbor adoption as follows:

$$y_{m,t} = \sum_{k \neq -1} \beta_k D^k_{m,t} + \gamma' \mathbf{X}_{m,t} + \delta_m + \delta_{ct} + \varepsilon_{m,t}. \tag{2}$$

Here, $y_{m,t}$ is again the number of adopters in municipality m and year t. We define the event time dummies as $D^k_{m,t} : \mathbf{1}\{t - \tau^N_m = k\}$, where $\mathbf{1}$ is an indicator function and τ^N_m is the year in which the first factory in a neighboring municipality (within 10 km) upgrades to hot water extraction; k are leads and lags relative to that event. We omit $k = -1$ as the reference period, so β_k traces dynamic responses before ($k < 0$) and after ($k > 0$) the first neighboring adoption.

Threats to identification The main empirical challenge when estimating spillovers is to separate a genuine causal link between neighbors' adoption decisions from spatially correlated unobservables. Ideally, this is done via randomizing the treatment, and tracing out the effect on neighboring adoption. In our historical data, this is not possible. Our strategy is to identify likely confounders using historical sources that describe the inputs into firms' upgrading decisions, and control for these. Inasmuch as there remain spatially correlated unobservables, these preclude the causal interpretation of our results. We thus treat our findings as consistent with spillovers.

In both baseline specification and the event study, we control for annual regional summer-rainfall variation. Local weather shocks affect sugar-beet harvest and therefore the cashflow of local factories, which in turn affects firms' ability to make outlays for re-organization. Second, we control for local supply of technology using distance to nearest hydraulic-press and diffusion-battery producer, both interacted with time. We expect that factories nearest to diffusion battery suppliers would have been more likely to upgrade early, compared to those farther away, due to higher information frictions early on in the technology's spread. Third, we control for distance to London interacted with time. As in the case of Austria-Hungary, Britain was the key export market for French exporters. Changes in export demand will have affected the cashflow of exporters, with implications for their upgrading. Additionally, we include region-year fixed effects in all our specifications. These control for spatially correlated unobservables that vary at a medium-scale. This means that our baseline coefficient α_r is identified from *within-region-year* differential adoption between factories that share the same observed fundamentals, but differ in their exposure to last year's neighbor adoption. Finer-scale, time-varying spatially correlated shocks remain as a threat to identification.[16]

Identifying the event study coefficients β_k hinges on the assumption that municipalities whose neighbors are yet to upgrade and municipalities whose first neighbor has already upgraded form a credible counterfactual for municipalities whose first neighbor upgraded at τ^N, after accounting for our baseline controls, time-invariant differences between municipalities and common region-year shocks. A key advantage of the event study is that we can test for pre-trends: if spatially correlated local shocks (rather than spillovers) drive adoption, they would also move own adoption before the first neighbor's adoption, which would appear as non-zero lead coefficients ($k < 0$). Flat leads do not prove spillovers or rule out all common shocks, but their absence is suggestive of a spillover interpretation.

Instrument for neighbor adoption We additionally estimate our baseline and event study specifications using a shift-share instrument for the number of adopters in the $r-$radius neighboring municipalities. We construct the instrument for municipality m at time t by interacting the pre-determined, 1879 number of neighbor firms within r-radius with the national adoption rate at $t-1$, which we calculate by excluding the municipality's own adoption to avoid introducing a mechanical correlation.

The relevance of this instrument draws on the aggregate shocks to the costs and benefits of upgrading contained in the national aggregate adoption rate which are likely to affect municipality's neighbors' adoption decisions. The validity of this instrument relies on the exclusion restriction: $\mathbb{E}[y^{r}{}_{t-1}^{IV}\varepsilon_{m,t}|\mathbf{X}_{m,t},\delta_m,\delta_{ct}] = 0$. Note that our exclusion restriction is conditional on our baseline controls, municipality, and region-time fixed effects. The region-year fixed effect controls for the direct effect that the aggregate shocks contained

16. Two further variables that vary at such finer-scale – changes in local transportation network and common ownership across neighboring factories – are currently under construction.

in the national shifter could have on municipal adoption. The municipality fixed effect controls for possible time-invariant unobservables that differ between municipalities within the same region that might be correlated both with count of neighbors and time-invariant propensity to adopt. The threat to identification that remains is time-varying shocks to municipal adoption that correlate with municipality's number of neighbors. In the event-study setting, in order to violate our exclusion restriction, such shocks need to lead to differential *changes* in adoption by municipalities within the same region, that share the same observed fundamentals, but differ in the number of neighbors in 1879. An example of such shock would be a time-varying receptiveness to new technology that is higher i) early in technology's spread, ii) in municipalities that are a part of a denser network of producers, that is not mediated via neighbors' adoption. This is a type of the confounder we can not rule out. However, we can assess the validity of the Conditional Parallel Trends assumption by visually assessing the estimated coefficients on the pre-treatment leads. While flat leads are not sufficient to rule out a later divergence between the treated municipalities and the control group in a no-exposure counterfactual, this does require the potential time-varying receptiveness to new technology to have been inactive pre-exposure.

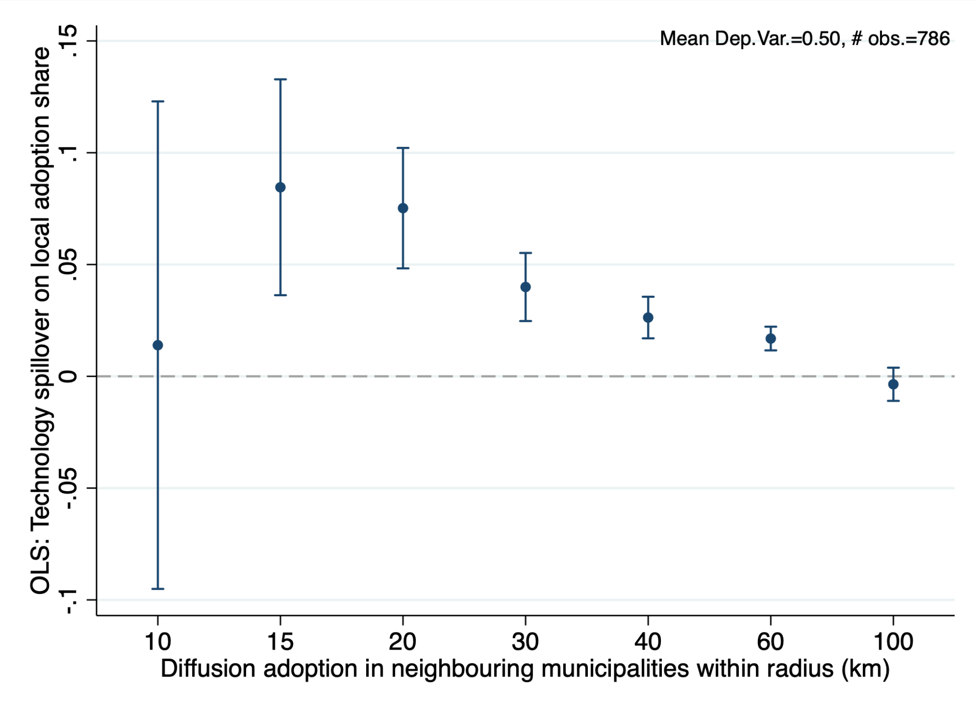
5.2. Results

Baseline result Figure 4 visualizes the baseline OLS coefficients that relate local adoption to neighboring adoption in $t-1$ across distance bands. Exposure within 10-20 km is associated with 0.01-0.08 additional local adopters. At further distances, the coefficient estimate for spillovers starts to decline. Adoption in the 10-60 km ring remains positively associated, while effects for 50-100 km are near zero. We interpret these estimates as association consistent with local spillovers.

Robustness.— Results are stable across alternative controls, clustering, estimators, and samples. Appendix Figure B.8 reports results for (i) specification without baseline controls (weather, machine-shop proximity and export-market access interacted with year), (ii) correction for potential spatial correlation in the error term using Conley standard errors, (iii) conditioning on lagged local counts of firms and adopters, (iv) Poisson-Pseudo Maximum Likelihood specification, (v) using the full sample of municipalities including locations that had zero firms, (vi) using an instrument. Our results are robust to these different specifications.

Event study Figure 5 presents our event-study estimates. First, we do not see differential trends in adoption before the first neighboring firm adopts hot water extraction. After the first neighbor adoption, we observe a growing effect on local adoption, which becomes significant one year later. Notably, the effect of the first neighbor adoption is considerably larger in magnitude, with the estimated effect suggesting 0.3 additional local firms having

Figure 4. Technology spillovers (OLS)



Notes: The figure plots the OLS estimates for lagged number of adopters in neighboring municipalities on number of adopters in the municipality. x-axis denotes inclusive neighborhood bands. Controls: Municipality & region-year fixed effects, distance to manufacturer of presses×Year, distance to manufacturer of diffusion batteries×Year, export market access×Year, and summer-rainfall variation (Pauling et al., 2006). 90% confidence intervals clustered at the municipality level.

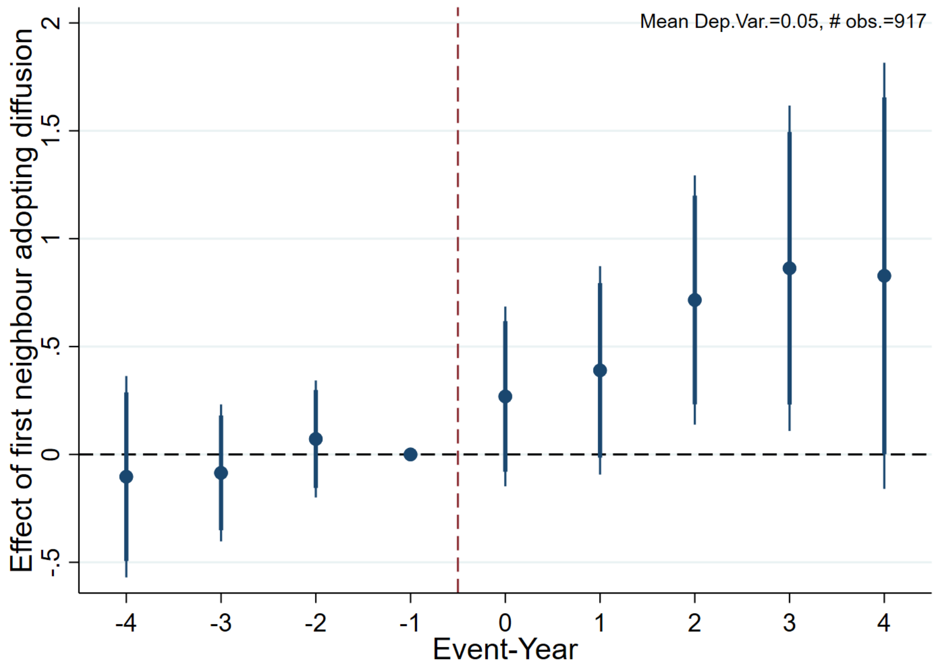
upgraded; three years later, the magnitude increases to 0.8 additional local firms having upgraded to frontier technology.

Robustness.— Appendix Figure B.7 re-estimates the event-time coefficients using the de Chaisemartin-D'Haultfoeuille and Callaway-Sant'Anna estimators for staggered adoption. The profiles are similar: no discernible pre-trends and a statistically significant increase after the first neighboring adoption. Second, adding controls for lagged local adoption and for the number of local firms leads to quantitatively similar results. Finally, using an instrument for first neighbor adoption leaves the results essentially unchanged.

6. Model

In this section, we put forward a model that rationalizes the empirical results obtained in Section 4. We use Bustos (2011) binary technology adoption framework to model firm's upgrading decisions. We model multiple regions to match our research design, and multiple sectors to allow for reallocation of resources between sugar and the rest of economy. We model spillovers in firms' adoption decisions by linking the cost of upgrading to the local share of adopters. These spillovers make firms' private upgrading decisions potentially inefficient. Finally, the government sets import tariffs, input taxes and export subsidies, in

Figure 5. Technology spillovers (Event-study)



Notes: The figure plots the event-study estimates for the first adopter in a municipality within 10km radius. Controls: Municipality & region-year fixed effects, distance to manufacturer of presses×Year, distance to manufacturer of diffusion batteries×Year, export market access×Year, and summer-rainfall variation (Pauling et al., 2006). 90 & 95% confidence intervals clustered at the municipality level.

line with government policy toolkit in our historical setting. The model setup is presented in Section 6.1. Section 6.2 presents comparative statics that form the basis of our empirical specification in Section 4. Finally, in Section 6.3 we discuss optimal policy and welfare effects of an introduction of a marginal export subsidy.

6.1. Setup

Environment.—We consider a small open economy with K sectors and N regions. The preferences and production structure are as follows. All details of model derivation are provided in Online Appendix A.1.

Demand.— The economy is populated by L identical agents. Each agent supplies one unit of labor and spends their income on a continuum of domestic and imported varieties of sectoral goods. Preferences across sectors are Cobb-Douglas with expenditure shares α_k, while preferences across varieties within each sector follow a CES form with elasticity of substitution $\sigma > 1$. These preferences generate a demand function $q(\omega) = \alpha_k R P_k^{\sigma-1} p_{rk}(\omega)^{-\sigma}$ for every variety ω, where P_k is the sectoral price index satisfying $P_k^{1-\sigma} = \int_{\omega\in\Omega_k} p_{rk}(\omega)^{1-\sigma} d\omega$, Ω_k is the set of sectoral varieties available for domestic consumption regardless of their origin, and R is household's total expenditure. Foreign household is specified analogously, with demand for domestic variety ω given by

$\alpha_k^F R^F (P_k^F)^{\sigma-1} p_{rk}(\omega)^{-\sigma}$, where $p_{rk}(\omega)$ is the price charged by an exporter from region r's sector k. From the domestic producers' perspective, $D_k \equiv \alpha_k^F R^F (P_k^F)^{\sigma-1}$ is exogenous. Labor is perfectly mobile across regions and sectors.

Government policy toolkit.— We allow the government to employ two types of trade policies: export subsidies and import tariffs, and an input tax. If the government employs an export subsidy in sector k, exporters charging p receive $s_k p$, where subsidy $s_k \geq 1$ applies ad valorem. If the government imposes an import tariff in sector k, domestic households pay $t_k^m p$ for a unit of imported variety with price p. If the government imposes an input tax in sector k η_k, the firms in k pay $\eta_k w$ per unit of input. $s_k = 1$, $t_k^m = 1$ and $\eta_k = 1$ correspond to no export subsidy, no import tariff and no inpu tax respectively.

Firms.—Regions are populated by monopolistically competitive firms producing differentiated varieties of sectoral goods using labor as the only factor of production. In order to produce, firms need to enter a region of production. Regions differ in their iceberg cost of exporting τ_r and are otherwise symmetric. Entry entails paying a fixed cost f_e denominated in units of labor. Moreover, regional entry is subject to frictions. Effective cost of entry into region r's sector k which employs L_{rk} workers is $w f_e L_{rk}^{\kappa}$, where parameter $\kappa \in [0, 1]$ governs the strength of entry frictions and w denotes the wage in the economy. Firms can enter only one region, and can ship domestically at no cost.

Upon entry, firms draw their idiosyncratic productivity φ from the cumulative distribution function $G(\varphi) = 1 - (\varphi/b_k)^{-\beta}$. As is standard, we assume $\beta > \sigma - 1$. In order to operate, firms must pay a fixed cost f. If a firm chooses to export, it pays an additional fixed cost f^x. Firms can also choose to upgrade to frontier technology. Upgrading increases firms' productivity by a factor γ, but entails an additional fixed cost λf paid in units of labor.[17] We allow for interdependence in firms' adoption decisions by linking the fixed cost of upgrading, λf, to the region-sector share of upgraders among the operating firms m^u.[18] Specifically, we assume that

$$\lambda_{rk} = \lambda_0 {m_{rk}^u}^{-\lambda^s}, \tag{3}$$

where $\lambda^s < \frac{\sigma-1}{\beta}$ ensures that the equilibrium is unique. We assume firms operate for one period and then exit.[19]

The firms' problem is as follows:

$$\max_{l, q^d, q^x, \mathbb{I}^x, \mathbb{I}^u} s_k p^x(q^x) q^x + p^d(q^d) q^d - \eta_k w l - w(f + \mathbb{I}^x f^x + \mathbb{I}^u \lambda_{rk} f),$$

17. We assume common fixed costs across sectors for ease of legibility and without loss of generality. Our calibration procedure in Section 7 allows for arbitrary sector-level fixed cost.

18. We model spillovers as local in line with local spillovers we estimate in Section 5.

19. This allows us to treat firm decisions as static and obtain closed-form solutions for optimal policy.

where $\mathbb{I}^x$ and $\mathbb{I}^u$ are indicator variables for decisions to export and upgrade respectively.

The CES specification of demand means that firms optimally charge a constant markup over their marginal cost. Conditional on not upgrading, this gives rise to domestic revenues of $r^d_{rk}(\varphi) = \alpha_k RP_k^{\sigma-1}(\rho\varphi/\eta_k w)^{\sigma-1}$ and export revenues of $r^x_{rk}(\varphi) = D_{rk}s^\sigma_k(\rho\varphi/\eta_k w)^{\sigma-1}$, where $D_{rk} = D_k\tau_r^{1-\sigma}$ is the region-sector export demand shifter which combines foreign demand conditions with the region-specific cost of exporting τ_r. For upgraders, these are $r^d_{rk}(\gamma\varphi) = \alpha_k RP_k^{\sigma-1}(\gamma\rho\varphi/\eta_k w)^{\sigma-1}$ and $r^x_{rk}(\gamma\varphi) = D_{rk}s^\sigma_k(\gamma\rho\varphi/\eta_k w)^{\sigma-1}$ respectively. In turn, serving domestic and foreign markets yields $\sigma^{-1}r^d_{rk}(\varphi)$ and $\sigma^{-1}r^x_{rk}(\varphi)$ in gross profits.

As is standard in Melitz-style models, equilibrium in each region and sector is characterized by threshold productivity levels. Firms with productivity above φ^p_{rk} produce, those with productivity above φ^x_{rk} export, and those with productivity above φ^u_{rk} upgrade. From here onward, we assume that the parameter values are such that $\varphi^p < \varphi^x < \varphi^u$ for all r, k.[20]

The cutoff productivities are pinned down by three indifference conditions for each region-sector pair. First, the marginal producer φ^p_{rk} earns zero profit after paying the fixed cost of operation:

$$\pi(\varphi^p_{rk}) = \frac{1}{\sigma}\alpha_k RP_k^{\sigma-1}\left(\frac{\rho\varphi^p_{rk}}{\eta_k w}\right)^{\sigma-1} - wf = 0. \tag{4}$$

Second, the marginal exporter φ^x_{rk} earns zero profits from exporting:

$$\pi^x(\varphi^x_{rk}) = \frac{1}{\sigma}D_{rk}s^\sigma_k\left(\frac{\rho\varphi^x_{rk}}{\eta_k w}\right)^{\sigma-1} - wf^x = 0. \tag{5}$$

Third, the marginal upgrader φ^u_{rk} is indifferent between upgrading and not upgrading:

$$\frac{D_{rk}s^\sigma_k + \alpha_k RP^{\sigma-1}}{\sigma}\left(\frac{\rho\varphi^u_{rk}}{\eta_k w}\right)^{\sigma-1}(\gamma^{\sigma-1} - 1) = w\lambda_{rk}f.$$

Substituting for domestic and foreign demand shifters using (4) and (5) we obtain

$$m^u_{rk} = \left(\frac{\gamma^{\sigma-1}-1}{\lambda_{rk}}\left(1 + {m^x_{rk}}^{\frac{\sigma-1}{\beta}}\frac{f^x}{f}\right)\right)^{\frac{\beta}{\sigma-1}} = \left(\frac{\gamma^{\sigma-1}-1}{\lambda_0}\left(1 + {m^x_{rk}}^{\frac{\sigma-1}{\beta}}\frac{f^x}{f}\right)\right)^{\frac{1}{\frac{\sigma-1}{\beta}-\lambda^s}} \tag{6}$$

where the second equality employs the functional form of the cost of adoption from equation (3), and $m^x_{rk} \equiv \frac{1-G(\varphi^x_{rk})}{1-G(\varphi^p_{rk})} = \left(\frac{\varphi^x_{rk}}{\varphi^p_{rk}}\right)^{-\beta}$ and $m^u_{rk} \equiv \frac{1-G(\varphi^u_{rk})}{1-G(\varphi^p_{rk})} = \left(\frac{\varphi^u_{rk}}{\varphi^p_{rk}}\right)^{-\beta}$ denote the shares of exporters and upgraders in region r's sector k respectively.

20. We assume upgrading is more costly than exporting to match the early phase of the spread of the technology, when only a small share of firms upgraded. The explicit parametric condition is provided in Online Appendix A.1.

First, note that the share of upgraders increases in the marginal cost improvement brought by the frontier technology γ and decreases in the fixed cost increase associated with it. Intuitively, both affect the relative attractiveness of frontier technology compared to the earlier vintage. Second, observe that all else constant, a higher share of exporters m^x_{rk} is associated with a higher upgrader share. This result arises because upgrading entails a higher fixed cost and therefore requires sufficient scale of production. Exporters have a relatively larger scale as they can access both domestic and foreign customers. As a result, the more firms in the region export, the more of them find it worthwhile to upgrade. Third, note that spillovers that link the cost of upgrading to share of upgraders operate by magnifying the effect of the relative benefit of upgrading and the share of exporters: a given change in either $\frac{\gamma^{\sigma-1}-1}{\lambda_0}$ or m^x leads to a larger increase in the share of adopters when spillovers are present ($\lambda^s > 0$) compared to a no spillover scenario ($\lambda^s = 0$).

Conditions (4)-(6) allow us to characterize regional production. But first, it is helpful to take note of how the production cutoff φ^p_{rk} varies across regions.

Lemma 1. *Marginal producer productivity is equal across regions: $\varphi^p_{qk} = \varphi^p_{rk}\ \forall q, r \in N$.*

Proof. The proofs of propositions in this section can be found in Online Appendix C.2. □

This follows immediately from the zero cutoff profit condition (4). Since internal trade is costless, all domestic firms compete in one market. Since labor is perfectly mobile across regions, all regions face the same cost of labor. As a result, the marginal producer to break even has the same productivity across regions.

Next, consider two regions r and q, such that the outward iceberg trade cost τ is lower in region r: $\tau_r < \tau_q$. The following two propositions establish the relative shares of exporters and upgraders in the two regions.

Proposition 1. *The share of exporters is higher in the lower τ region: $m^x_{rk} > m^x_{qk}$.*

This proposition follows from condition (5) – zero export profit for marginal exporter. Exporters across regions face the same export demand, but lower export cost regions set lower prices and enjoy higher demand. As a result, the marginal exporter in the lower export cost regions can afford to be less productive to break even. Combining this with Lemma 1, we obtain the result in Proposition 1. We next turn to upgrader shares.

Proposition 2. *The share of upgraders is higher in the lower τ region: $m^u_{rk} > m^u_{qk}$.*

Condition (6) states that the upgrader share increases with the exporter share. Since more producers in the lower outward iceberg trade cost regions choose to export, more producers also find it worthwhile to upgrade.

Imports.—Domestic households can import sectoral varieties produced abroad. Foreign producers compete monopolistically and set their price as a markup over the marginal cost $w^F \tau^F / \varphi$, where φ is producer productivity drawn from the cumulative distribution function $G(\varphi) = 1 - (\varphi / b_k^F)^\beta$, w^F is foreign wage and τ^F denotes the iceberg trade cost of exporting to home.[21] To access domestic market, the foreign exporters have to pay a fixed cost F. The marginal foreign exporter φ_k^m earns zero profit from export:

$$\pi(\varphi_k^m) = \frac{1}{\sigma} \alpha_k R P_k^{\sigma-1} t_k^{m-\sigma} \left(\frac{\rho \varphi_k^m}{w^F \tau^F} \right)^{\sigma-1} - w^F F. \tag{7}$$

The mass of foreign exporters is $M_k^m = (1 - G(\varphi_m)) M_k^F$, where M_k^F is the total mass of foreign varieties in sector k. Under the small open economy assumption, M_F is exogenous from home's perspective. We thus normalize $M_F = 1$.

Free entry.—Free entry requires that in each region and sector, the aggregate spending on entry equals expected profit:

$$w f^e L_{rk}^\kappa (1 - G(\varphi_{rk}^p)) = \mathbb{E}\pi_{rk} = M_{rk}^{-1} \left[\int_{\omega \in \Omega_{rk}^d} \pi_{rk}^d(\omega) d\omega + \int_{\omega \in \Omega_{rk}^x} \pi_{rk}^x(\omega) d\omega \right].$$

In Online Appendix A.1. we show that expected profits can be expressed as a function of fixed costs

$$\mathbb{E}\pi_{rk} = (\theta - 1) \left(f + m_{rk}^x f^x + m_{rk}^u \lambda f \right), \tag{8}$$

where M_{rk} is the mass of firms operating in region r's sector k and $\theta = \frac{\beta}{\beta - (\sigma - 1)}$.

Firms that choose to enter region r's sector k hire labor to enter, produce, and pay fixed costs of operation, exporting and upgrading. Aggregating these labor expenditures across firms yields an expression for the mass of firms

$$M_{rk} = w L_{rk} (\sigma \theta w \left(f + m_{rk}^x f^x + m_{rk}^u \lambda f \right))^{-1} = \frac{\theta - 1}{\sigma \theta} \left(\frac{\varphi_{rk}^p}{b_k} \right)^{-\beta} \frac{L_{rk}^{1-\kappa}}{f_e}, \tag{9}$$

where the second equality substitutes fixed costs using condition (8).

21. We model foreign firms as not having an option to upgrade. From a small open economy's standpoint, this is equivalent to assuming that foreign firms can upgrade, but the upgrading decisions are not affected by foreign exports to home. Thus, we rule out upgrading for ease of exposition and without loss of generality.

Closing the model.—We close the model by imposing region-sector goods market clearing, labor market clearing, as well as by determining the government net revenue and household income. We begin by linking region-sector employment costs to region-sector revenue:

$$wL_{rk} = X_{rk}^d + s_k X_{rk}^x \equiv Y_{rk}. \tag{10}$$

where X_{rk}^d and $s_k X_{rk}^d$ stand for revenue from domestic and export sales respectively. Note that the latter also accounts for the receipt of the export subsidies. This condition holds due to free entry, which ensures that all of the revenue generated in r, k ultimately accrues to labor as either compensation for production or via fixed costs.

Domestic expenditure on varieties from r, k is $X_{rk}^d = \mu_{rk}\alpha_k R$, where $\mu_{rk} = \left(P_{rk}^d/P_k\right)^{1-\sigma}$ is the expenditure share on varieties from r, k, P_{rk}^d is the price index for varieties produced in r, k and sold domestically. X_{rk}^d can be obtained by combining conditions (4), (6)–(9) with expression for domestic demand to yield

$$X_{rk}^d = \frac{A_k w^{-\zeta} L_{rk}^{1-\kappa} \gamma_{rk}^d}{\sum_q A_k w^{-\zeta} L_{qk}^{1-\kappa} \gamma_{qk}^d + A_k^F \left(t_k^m w^F\right)^{-\zeta}} \alpha_k R, \tag{11}$$

where $\zeta \equiv 1 - \frac{\sigma\beta}{\sigma-1}$. $A_k = b_k^\beta f^{\frac{1}{1-\theta}}/f_e$ and $A_k^F = (b_k^F/\tau^F)^\beta F^{\frac{1}{1-\theta}}$ are exogenous domestic and foreign productivity shifters, whereas $\gamma_{rk}^d = 1 + (\gamma^{\sigma-1} - 1) {m_{rk}^u}^{1/\theta}$ is an endogenous productivity shifter that increases as more firms in r, k choose to upgrade. Note that this representation takes a familiar gravity form: domestic sales depend on costs of production in r, k, compared to that in other domestic regions and abroad.

Import expenditure can be expressed analogously:

$$X_{rk}^m = t_k^m \frac{A_k^F \left(t_k^m w^F\right)^{-\zeta}}{\sum_q A_k w^{-\zeta} L_{qk}^{1-\kappa} \gamma_{qk}^d + A_k^F \left(t_k^m w^F\right)^{-\zeta}} \alpha_k R. \tag{12}$$

Finally, foreign expenditure on region r sector k varieties can be expressed as

$$X_{rk}^x = A_k \tau_r^{-\beta} (w/s_k)^{-\zeta} L_{rk}^{1-\kappa} \gamma_{rk}^x \overline{D}_k, \tag{13}$$

where $\gamma_{rk}^x = 1 + (\gamma^{\sigma-1} - 1) \left(\frac{m_{rk}^u}{m_{rk}^x}\right)^{1/\theta}$ is an endogenous export productivity shifter that accounts for exporter upgrading decisions and $\overline{D}_k$ is a constant defined in Online Appendix

A.1. It is helpful to express the region-sector exporter share as a function of domestic and foreign sales and endogenous productivity shifters:

$$m^x_{rk} = \frac{s_k X^x_{rk}}{X^d_{rk}} \left(\frac{f^x \gamma^x_{rk}}{f \gamma^d_{rk}} \right)^{-1}. \tag{14}$$

The government net revenue is the sum of receipts from import tariffs and input tax less expenditure on export subsidies

$$T = \sum_k (t^m_k - 1) X^m_k + \sum_{rk} (\eta_k - 1) w L_{rk} - \sum_{rk} (s_k - 1) X^x_{rk}. \tag{15}$$

The household income combines labor income with the government's net revenue:

$$R = wL + T. \tag{16}$$

Finally, the aggregate labor market clears

$$L = \sum_{rk} L_{rk}. \tag{17}$$

Equilibrium.—Equilibrium is a set of region-sector employment levels L_{rk}, domestic, export and import revenues X^d_{rk}, X^x_{rk} and X^m_k, exporter and upgrader shares m^x_{rk}, m^u_{rk}, as well as government net revenue T, household income R and wage w that satisfy conditions (6) and (11)-(17).

6.2. Comparative statics

We next turn to comparative statics of the model. To do so, we log-linearize the model. The details of the derivations are presented in Online Appendix C.3.

Exporter and upgrader shares.—We begin by considering the impact of export subsidies on regional composition of firms. Propositions 3 and 4 link export subsidies to the shares of exporters and upgraders respectively.

PROPOSITION 3. *Suppose the government increases export subsidy in sector k: $ds_k > 0$. The change in region-sector share of exporters is then*

$$d \ln m^x_{rk} \equiv d \ln m^x_k = \frac{\beta}{\sigma - 1} \left(\sigma ds_k - (d \ln R + (\sigma - 1) d \ln P_k) \right) > 0.$$

Note that the change in the share of exporters is the same across regions. Moreover, the endogenous technology choice has no impact on the change in exporter shares, other than via the general equilibrium changes in domestic demand shifter $\alpha_k R P_k^{\sigma-1}$. A constant change in exporter shares, in turn, results in a larger increase in exporter share in absolute terms in regions with lower costs of exports. In the rest of this section, we will use this common change in the share of exporters, $d\ln m_k^x$, as a shorthand for the sum of the direct effect of the export subsidy σds_k and its indirect effect due to general equilibrium response in domestic demand shifter $-\left(d\ln R + (\sigma-1)d\ln P_k\right)$. Consider two regions r and q such that $\tau_r < \tau_q$. Beginning with upgrader shares,

Proposition 4. *Suppose the government increases export subsidy in sector k: $ds_k > 0$. The relative change in upgrader shares in the two regions is then*

$$d\ln m_{rk}^u - d\ln m_{qk}^u = \frac{1}{1-\lambda^s\beta/(\sigma-1)}\left[\frac{{m_{rk}^x}^{\frac{\sigma-1}{\beta}} f^x}{f + {m_{rk}^x}^{\frac{\sigma-1}{\beta}} f^x} - \frac{{m_{qk}^x}^{\frac{\sigma-1}{\beta}} f^x}{f + {m_{qk}^x}^{\frac{\sigma-1}{\beta}} f^x}\right] d\ln m_k^x > 0.$$

The terms in square brackets are the semi-elasticities of the sector-region upgrader shares with respect to the change in exporter share m^x. These are positive and increasing in the share of exporters. Proposition 2 establishes that regions with higher exporter shares have more upgraders. Proposition 4, in turn, shows that as export subsidies induce more firms to export, regions with higher export shares to begin with will see a larger response in upgrading. Note further that the higher is the elasticity of user cost of frontier technology with respect to the share of upgraders – in other words, the higher is λ^s, the more responsive is upgrading to export subsidies.

Region-sector inputs.—We next discuss the effect of export subsidies on region-sector total inputs. Let $x_{rk} = s_k X_{rk}^x / wL_{rk}$ denote the region-sector export share of revenue before the subsidy change. This variable will capture the exposure of firms in r, k to the change in export subsidy. Propositions 5 and 6 establish the link between regional sectoral input use following an increase in the sectoral export subsidy conditional on no spillovers ($\lambda^s = 0$) and on positive spillovers ($\lambda^s > 0$) respectively.

Proposition 5. *Suppose the government increases export subsidy in sector k: $ds_k > 0$. Suppose there are no spillovers from upgrading: $\lambda^s = 0$. The relative change in sectoral input use in the two regions is then*

$$d\ln L_{rk} - d\ln L_{qk} = \frac{x_{rk} - x_{qk}}{\kappa} d\ln m_k^x > 0.$$

Once again, conditional on the change in exporter share, the endogenous technology choice has no impact on the relative change in sectoral input use.

Proposition 6. *Suppose the government increases export subsidy in sector k: $ds_k > 0$. Suppose there are positive spillovers from upgrading: $\lambda^s > 0$. The relative change in sectoral input use in the two regions is then*

$$d \ln L_{rk} - d \ln L_{qk} = (x_{rk}\nu_{rk} - x_{qk}\nu_{qk})\, d \ln m_k^x > 0,$$

where $\nu_{rk} = \dfrac{1}{\kappa} + \dfrac{1}{\theta}\dfrac{\gamma_{rk}^x}{\gamma_{rk}^x - 1}\dfrac{\lambda^s}{(\sigma-1)/\beta - \lambda^s}$ *and* $\nu_{rk} < \nu_{qk}$.

Note that $\nu_{rk} < \nu_{qk}$ implies that conditional on the change in exporter shares, positive spillovers in use of frontier technology can amplify or attenuate the relative response of input use in the two regions. Crucially, this is not due to cross-regional spillovers: our spillover specification applies within regions only. Instead, as export subsidies induce more firms to export and more firms to upgrade, the costs of adopting frontier technology decrease in both regions, inducing further upgrades. How this additional change in the share of upgraders affects the relative input use across the two regions, in turn, depends on the strength of spillovers, as well as levels of exporter and upgrader shares before the policy change in both regions.

From inputs to outputs.—Free entry ensures that all of the region-sector revenue is spent on inputs: $wL_{rk} = Y_{rk}$. As a result, the relative change in input use maps exactly into regional change in output. Formally,

Proposition 7. *Suppose the government increases export subsidy in sector k: $ds_k > 0$. The relative change in region-sector output is then*

$$d \ln Y_{rk} - d \ln Y_{qk} = d \ln L_{rk} - d \ln L_{qk} > 0.$$

Intensive and extensive margins.—We now break down the differential response in regional input use into intensive and extensive margins. From condition (9),

$$d \ln M_{rk} = -\beta d \ln \varphi_{rk}^p + (1-\kappa) d \ln L_{rk}$$

In turn, Lemma 1 shows that the marginal producer is the same across regions. Let $l_{rk} = L_{rk}/M_{rk}$ denote input use per firm. The following proposition pins down the intensive and extensive margins in the relative change in the regional input use.

Proposition 8. *Suppose the government increases export subsidy in sector k: $ds_k > 0$. The relative change in mass of firms and input use per firm is then*

$$d \ln M_{rk} - d \ln M_{qk} = (1 - \kappa) (d \ln L_{rk} - d \ln L_{qk}) > 0,$$

$$d \ln l_{rk} - d \ln l_{qk} = \kappa (d \ln L_{rk} - d \ln L_{qk}) > 0.$$

In other words, whether the differential response in the input use across regions following an export subsidy comprises of differential entry and exit or input use per firm depends solely on how stringent are the frictions in entry into regional production.

Taking stock.—We now briefly summarize the results of the comparative statics exercises. An increase in an export subsidy induces a larger proportion of firms to turn to exporting (Proposition 3). As more firms export, more firms attain sufficient scale to upgrade. Moreover, this effect is stronger in low export cost regions (Proposition 4). An increase in an export subsidy leads to a higher increase input use and output in lower export costs regions relative to those with higher export costs (Propositions 5, 6 and 7). Finally, the relative magnitudes of the response of extensive and intensive margins depends on the relative severity of the frictions in regional entry (8).

6.3. Welfare

The previous section analyzed the positive effects of an export subsidy. We now address the normative aspect of the use of export subsidies. We begin by characterizing the optimal trade policy in the presence of endogenous technology choice, and then outline the welfare effects of an introduction of a marginal export subsidy. The solution follows that in Costinot et al. (2020). The details of the derivation are provided in Online Appendix C.4.

Optimal policy.—The solution for optimal policy leverages the idea that at the optimum, small feasible changes in resource allocation have no first order effect on welfare.[22] Welfare is given by $W = (R/L)/P$, where $R/L = w + T/L$ is income per capita and $P = \prod_k P_k^{\alpha_k}$ is the consumer price index. Log-differentiation of welfare yields

$$d \ln W = (dwL + dT)/R - \sum_k \alpha_k \, d \ln P_k.$$

22. Feasibility here requires that trade is balanced and changes in region-sector input use satisfy aggregate input constraint $\sum_{rk} L_{rk} = L$.

Consider first the case with no spillovers from upgrading. In Online Appendix C.4. we show that in this case, the change in welfare can be expressed as

$$d \ln W \propto \sum_{rk} (1 - s_k) X_{rk}^x d \ln Q_{rk}^x + \sum_k \left(t_k^m - \frac{1 + \varepsilon_k^m}{1 - \varepsilon_k^d} \right) X_k^m d \ln Q_k^m, \tag{W1}$$

where $Q_k^m \equiv X_k^m / P_k^m$ and $Q_{rk}^x \equiv X_{rk}^x / P_{rk}^x$ are import and export quantities obtained using import and export price indices, $\varepsilon_k^d = \sigma^{-1}$ is the export demand elasticity and $\varepsilon_k^m = -\frac{\beta - (\sigma - 1)}{\sigma\beta - (\sigma - 1)}$ is the import supply elasticity. The next proposition specifies optimal policy when upgrading is not subject to spillovers.

Proposition 9. *If upgrading is not subject to spillovers, $\lambda^s = 0$, then the optimal export subsidies and import tariffs satisfy $s_k^* = \bar{t}$ and $t_k^{m*} = \frac{1 + \varepsilon_k^m}{1 - \varepsilon_k^d} \bar{t}$ for some common shifter $\bar{t}$.*

Setting export subsidies and import tariffs to s_k^* and t_k^{m*} makes the two brackets multiplying changes in export and import quantity changes zero. As as a result, there does not exist any small feasible change allocation of resources that can increase welfare. Therefore, s_k^* and t_k^{m*} are optimal. Note further that normalizing $\bar{t} = 1$ results in no export subsidy ($s_k = 1$) and an optimal tariff $t_k^m = \frac{\sigma\beta}{\sigma\beta - (\sigma - 1)}$ which coincides with the optimal tariff in a wide range of models with no endogenous upgrading.[23] Thus, absent spillovers, the presence of endogenous upgrading by itself does not warrant the use of export subsidies, as long as the import tariff is set at the optimal level.

Consider now the scenario where sector k features positive spillovers from technological upgrading: $\lambda_k^s > 0$, whereas there are no spillovers in other sectors $\lambda_n^s = 0 \; \forall \, n \neq k$. In this case, the change in welfare can be expressed as

$$d \ln W \propto \sum_{rk} (1 - s_k) X_{rk}^x d \ln Q_{rk}^x + \sum_k \left(t_k^m - \frac{1 + \varepsilon_k^m}{1 - \varepsilon_k^d} \right) X_k^m d \ln Q_k^m \tag{W2}$$

$$+ \sum_r \frac{\gamma_{rk}^x - 1}{\gamma_{rk}^x} \frac{1}{\theta} \frac{\lambda_k^s}{\frac{\sigma - 1}{\beta} - \lambda_k^s} s_k X_{rk}^x d \ln m_{rk}^x. \tag{18}$$

Note that if the policy is set at the optimal level for no spillovers scenario, $s_k = 1$ and $t_k^m = \frac{1 + \varepsilon_k^m}{1 - \varepsilon_k^d}$, the first two terms are zero. The third term captures the welfare effect of allocating extra resources towards exporters in presence of spillovers. Proposition 4 shows that incentivizing more exports can increase the scale of operating firms and thus induce more firms to upgrade. Since in presence of positive spillovers adoption in section k is

23. In particular, Demidova et al. (2024) show that this optimal tariff applies in Armington, Eaton-Kortum, and Krugman models (with or without EES, and with or without nested preferences) as well as in Melitz-Pareto model with fixed costs paid in source or destination country labor.

inefficiently low, inducing more firms to upgrade can be welfare improving. Proposition 10 formalizes this insight:

Proposition 10. *Suppose upgrading in section k is subject to spillovers, $\lambda_k^s > 0$, and $\lambda_n^s = 0\ \forall\, n \neq k$. In this case, the optimal export subsidies and import tariffs satisfy $s_k^* > \bar{t}$, $s_n^* = \bar{t} \quad \forall\, n \neq k$ and $t_k^{m*} = \bar{t}\frac{1+\varepsilon_k^m}{1-\varepsilon_k^d}$ for some common shifter $\bar{t}$.*

Again, normalizing $\bar{t} = 1$ yields import tariffs across sectors set at $t_k^m = \frac{1+\varepsilon_k^m}{1-\varepsilon_k^d}$, the optimal tariff level in models with no endogenous upgrading. No-spillover sectors call for no export subsidies: $s_n = 1\ \forall\, n \neq k$, and sector with positive spillovers features a positive optimal subsidy $s_k > 1$.

We conclude by discussing welfare effects of introducing a marginal export subsidy in sector k given initial trade policy is set at some arbitrary level $\bar{t}_k^m$, $\bar{s}_k$.

Proposition 11. *Suppose upgrading in section k is subject to spillovers, $\lambda_k^s > 0$, and $\lambda_n^s = 0\ \forall\, n \neq k$. Suppose initial trade policy is set at some arbitrary level $\bar{t}_k^m$, $\bar{s}_k$. In this case, the welfare change due to the introduction of a marginal export subsidy in sector k, $ds_k > 0$, can be represented as a sum of two terms:*

$$d\ln W = d\ln W^r + d\ln W^u,$$

where

$$d\ln W^r \propto \sum_{rk} \left(1 - \bar{s}_k\right) X_{rk}^x d\ln Q_{rk}^x + \sum_k \left(\bar{t}_k^m - \frac{1+\varepsilon_k^m}{1-\varepsilon_k^d}\right) X_k^m d\ln Q_k^m \lesseqgtr 0$$

and

$$d\ln W^u \propto \sum_r \frac{\gamma_{rk}^x - 1}{\gamma_{rk}^x} \frac{1}{\theta} \frac{\lambda_k^s}{\frac{\sigma-1}{\beta} - \lambda_k^s} \bar{s}_k X_{rk}^x d\ln m_{rk}^x > 0.$$

The second term, $d\ln W^u$, captures the welfare increase when export subsidy induces more firms to upgrade, given these new upgrades reduce costs of upgrading for other firms in sector k. This term is positive as $\gamma_{rk}^x - 1$ is always weakly positive and $d\ln m_{rk}^x/ds_k > 0$ from Proposition 3. In turn, $d\ln W^r$ captures the welfare effect arising due to reallocation of resources in the economy, given the prior policy wedges $\bar{t}_k^m$, $\bar{s}_k$. The sign of the second bracket will depend on two things. First, whether import tariffs and export subsidies were set above or below the optimal level. Second, it will depend on the patterns resource reallocation caused by the introduction of the marginal export subsidy. Intuitively, trade policy set at suboptimal levels causes misallocation in the economy. As a result, the welfare effect of a change in policy will depend on whether the policy change worsens or ameliorates pre-existing misallocation. If the policy change directs resources to sectors or activities that were already excessive compared to socially optimal level, welfare declines. If instead policy change directs resources out of such sectors and activities, welfare increases.

Consider the following example. Suppose $\bar{s}_k = 1 \ \forall\, k$: no export subsidies in any sector to begin with. Suppose further import tariffs were set optimally in sectors other than k: $\bar{t}_n^m = \frac{1+\varepsilon_k^m}{1-\varepsilon_k^d} \ \forall\, n \neq k$. In this case, the reallocation term collapses to $d\ln W^r \propto \left(\bar{t}_k^m - \frac{1+\varepsilon_k^m}{1-\varepsilon_k^d}\right) X_k^m d\ln Q_k^m$. If import tariff in sector k exceeded the optimal level t_k^{m*} defined in Proposition 10, the reallocation term of the welfare effect of an export subsidy will be negative *if* the export subsidy reduces imports in sector k: $d\ln W^r \propto \left(\bar{t}_k^m - \frac{1+\varepsilon_k^m}{1-\varepsilon_k^d}\right) X_k^m d\ln Q_k^m < 0$. Intuitively, an excessively high protective tariff will mean excessive domestic production of k to begin with. By directing further resources to sector k, an export subsidy will further aggravate misallocation.

7. Calibration

We calibrate the model to the Austro-Hungarian economy in years 1865 and 1870, featuring two production sectors – sugar (s) and a composite non-sugar sector (n), and two regions that differ in their iceberg costs of export. The calibration proceeds in four steps. First, we reformulate the equilibrium system in 'exact-hat algebra' form, expressing all endogenous variables as changes from initial level. Second, we document the historical sources and construction of initial-level data that constitutes the baseline equilibrium. Third, we summarize externally imposed parameters drawn from the literature or calibrated outside the model. Finally, we implement the internal calibration that identifies the combination of parameters and shocks that rationalize the patterns in sugar production and technology upgrading documented in Section 4.

7.1. Model in Changes

We recast the model of Section 6 in 'exact-hat algebra' form. For any variable x_t, define $\hat{x}_t \equiv x_{t+1}/x_t$ as the change from period t to $t{+}1$. We rewrite the equilibrium conditions (6) and (11)-(17) for period $t+1$, so next-period values are $\hat{x}_t x_t$ for each x. We suppress time subscripts for readability; all hats denote changes from t to $t+1$, and all level variables refer to period t. The result is a system of equations in three types of unknowns: (i) endogenous variables in levels at t, (ii) exogenous changes in technology and policy $\hat{\gamma}$, $\hat{s}_k$, and $\hat{t}_k^m$, and (iii) changes in endogenous variables between t and $t+1$:

$$\hat{\gamma}_{rk}^d \gamma_{rk}^d = 1 + \left((\hat{\gamma}_k \gamma_k)^{\sigma-1} - 1\right)^{\frac{\theta}{\theta-1}} \left(1 + (\hat{m}_{rk}^x m_{rk}^x)^{\frac{\theta-1}{\theta}} f^x (f)^{-1}\right)^{\frac{1}{\theta-1}} \tag{C1}$$

$$\hat{\gamma}^x_{rk}\gamma^x_{rk} = 1 + ((\hat{\gamma}_k\gamma_k)^{\sigma-1} - 1)^{\frac{\theta}{\theta-1}} \left(1 + (\hat{m}^x_{rk}m^x_{rk})^{\frac{\theta-1}{\theta}} f^x(f)^{-1}\right)^{\frac{1}{\theta-1}} (\hat{m}^x_{rk}m^x_{rk})^{-\frac{1}{\theta}} \tag{C2}$$

$$\hat{\mu}_{rk} = \frac{\hat{w}^{\,-\zeta}\hat{L}_{rk}^{\,1-\eta}\hat{\gamma}^d_{rk}}{\sum_r \mu_{rk}\hat{w}^{\,-\zeta}\hat{L}_{rk}^{\,1-\eta}\hat{\gamma}^d_{rk} + \left(1 - \sum_{r,k}\mu_{rk}\right)\hat{t}_k^{m\,-\zeta}} \tag{C3}$$

$$\hat{X}^x_{rk} = \left(\frac{\hat{w}}{\hat{s}_{rk}}\right)^{-\zeta} \hat{L}_{rk}^{\,1-\eta}\hat{\gamma}^x_{rk} \tag{C4}$$

$$\hat{X}^d_{rk} = \hat{\mu}_{rk}\hat{R} \tag{C5}$$

$$\hat{X}^m_k = \frac{1}{t^m_k\hat{t}^m_k}\frac{1 - \sum_r \hat{\mu}_{rk}\mu_{rk}}{1 - \sum_r \mu_{rk}}\hat{R}R \tag{C6}$$

$$\hat{m}^x_{rk} = \hat{s}_{rk}\frac{\hat{X}^x_{rk}}{\hat{X}^d_{rk}}\frac{\hat{\gamma}^d_{rk}}{\hat{\gamma}^x_{rk}} \tag{C7}$$

$$\hat{w}\hat{L}_{rk}wL_{rk} = \hat{X}^d_{rk}X^d_{rk} + \hat{s}_{rk}\hat{X}^x_{rk}s_{rk}X^x_{rk} \tag{C8}$$

$$\hat{w}wL = \sum_{r,k}\left(\hat{X}^d_{rk}X^d_{rk} + \hat{s}_{rk}\hat{X}^x_{rk}s_{rk}X^x_{rk}\right) \tag{C9}$$

$$\hat{R}R = \hat{w}(wL_{rk}) + \sum_{r,k}(1 - \hat{s}_{rk}s_{rk})\,\hat{X}^x_{rk}X^x_{rk} + (t^m_k\hat{t}^m_k - 1)\hat{X}^m_k X^m_k. \tag{C10}$$

Our calibration strategy consists of fitting the model in changes (C1)-(C10) to match historical data conditional on two exogenous changes: arrival of hot water extraction technology and the introduction of export subsidy in sugar. In what follows, we will normalize both the export subsidy and the initial period productivity gain from upgrading to one. Thus, we define $ds_s \equiv \hat{s}_s - 1$ and $d\gamma_s \equiv \hat{\gamma}_s - 1$ and use this convention throughout.

7.2. Initial Values

Timing.— We initialize the economy in 1864, the year before the export subsidies begin, and estimate the model in changes targeting levels of endogenous variables in 1870, five years after the policy is introduced.

Sectors and regions.— We consider two sectors – sugar (s) and non-sugar (n), and two regions – low-export cost and high export cost. Non-sugar aggregates are defined residually, as economy aggregates less sugar, unless specified otherwise. Employment is the only variable observed at the region-sector level. We map the low- and high-export-cost regions to Bohemia (b) and the rest of Austria-Hungary (r), respectively.[24]

24. Bohemia bordered Saxony and as a result was farthest along the trade route to London via Hamburg compared to the interior.

Imports, exports, and trade policy.— We use the 1864 volume of *Austro-Hungarian Foreign Trade Returns* (hereafter Trade Returns, K.K. Statistische Zentralkommission (1864)) to collect values of exports, imports, and import tariff revenues. We set sectoral imports and exports, X_k^m and X_k^x, to those in the data. We compute import tariffs for the two sectors, t_k^m, as the ratio of import-tariff revenue to the value of imports in each sector. In line with no known use of export subsidies before those in sugar, we set $s_k = 0$ for all sectors. We set net government revenue as a sum of import tariff revenue across all sectors: $T = \sum_k (t_k^m - 1) X_k^m$. The resultant values are an import tariff of 57% in sugar industry and 5% for the non-sugar aggregate. As a result of the high protective barrier, sugar imports into the country were negligible, at $< 1\%$ of sugar consumption. In turn, export of sugar was modest, constituting about 5% of domestic production in 1864.

Employment.— We obtain regional employment in the sugar industry from *Nachrichten über Industrie, Handel und Verkehr, 1873* – the trade and industry report that serves as one of our sources for firm-level inputs (hereafter 'Nachrichten').[25] We assign non-sugar regional employment using the 'industry and commerce' category in the 1880 census, scaling both regions back to 1864 by population change between 1880 and 1864.

Revenue and consumption.— In 1864, sugar represented 1% of the total industrial production (Komlos, 2014). We set sectoral sugar revenue Y_s to the value in Nachrichten and infer non-sugar revenue Y_n from the 1% share: $Y_n = Y_s(1 - 0.01)/0.01$, with aggregate revenue $Y \equiv wL = Y^s/0.01$. Sectoral consumption is $X_k \equiv Y_k - X_k^x + X_k^m$, and domestic sales are $X_k^d \equiv Y_k - X_k^x$. Aggregate income combines aggregate revenue and net tariff revenue: $R = wL + T$.

Regional domestic sales.— We allocate X_k^d across regions using equilibrium condition (11) which links domestic sales to regional employment: $X_{bk}^d / X_{rk}^d = (L_{bk}/L_{rk})^{1-\kappa}$.

Upgrader shares.— The first commercial use of hot water extraction was in 1865. We therefore set the initial share of upgraders in sugar to zero, $m_{rs}^u = 0$ for both regions. In line with the sugar industry being by far the most mechanized industry in 1864 (sugar industry was responsible for 26% of all steam engines used in manufacturing, while representing mere 1% of output), we set $m_{rn}^u = 0$ for the non-sugar sector. We normalize the initial level of the productivity gain from upgrading to one for both sectors: $\gamma_s = \gamma_n = 1$. This parametric assumption is in line with zero initial upgrader shares in both sectors and yields initial domestic and exporter endogenous productivity shifters equal to one: $\gamma_{rk}^x = \gamma_{rk}^d = 1$.

Missing levels.— Two initial levels are unobserved: region-sector exports X_{rk}^x and exporter shares m_{rk}^x. From (11), $X_{rk}^x / X_{qk}^x = (L_{rk}/L_{qk})^{1-\kappa} (\tau_r/\tau_q)^{-\beta}$, so given region-sector employment, allocating observed sectoral exports across regions amounts to estimating

25. Regional production, by contrast, was not covered in this report. More generally, since beet inputs formed the tax base, virtually all of the contemporary statistics relied on beet use as a measure of production.

the ratio between the outward trade-costs in the two regions $\tau \equiv \tau_r/\tau_q$. From (14), $m^x_{rk} = \frac{X^x_{rk} f^p}{X^d_{rk} f^x}$, where $s_k = \gamma^d_{rk} = \gamma^x_{rk} = 1$ are set following the baseline. Conditional on the export allocation, solving for exporter shares requires observing the fixed-cost ratio $f \equiv f^x (f^p)^{-1}$. Henceforth we treat these as observed, conditional on estimated τ and f.

We report the sources and assigned values of initial levels in Appendix Table C.1.

7.3. Externally Calibrated Parameters

We fix four parameters and one exogenous change outside the calibration routine: (i) the elasticity of substitution across varieties σ, (ii) the Pareto shape parameter of firm productivity β, (iii) the entry friction parameter, (iv) the elasticity of upgrading cost with respect to the share of upgraders, and (v) the size of the export subsidy increase, ds_s.

Elasticity of substitution.— In the model, the elasticity across varieties σ governs how strongly sectoral input use responds to an export subsidy shock (see Propositions 3-6 in Section 6.2). Holding the subsidy size fixed, a higher σ implies a larger reallocation of production toward the targeted sector. We set $\sigma = 3.5$, following the median estimate for 4-digit commodities in Broda and Weinstein (2006).

Pareto tail of productivity.— We calibrate β using the upper tail of the factory input use distribution. In the model, the tail exponent of input use is $\beta/(\sigma - 1)$. A log-rank-log-size regression in the data yields a tail estimate of 4.6, implying $\beta = 11.6$ given $\sigma = 3.5$.

Entry friction parameter.— Parameter κ governs the relative strength of extensive- versus intensive-margin adjustment in regional input use. A higher κ raises the effective cost of entry, shifting adjustment toward an increase in the scale of incumbent firms. Proposition 8 in Section 6.2 shows that $1 - \kappa$ is identified by the ratio of event-study responses of the mass of firms and the input use following an export subsidy shock. Evaluating this ratio for 1870 yields 0.42 (see Table A.3). We thus set $\kappa = 0.58$.

Spillover elasticity.— Spillover elasticity λ^s governs how the fixed cost of upgrading varies with the local share of upgraders. $\lambda^s < 0$ implies that individual adoption lowers the local cost of upgrading, resulting in a positive externality. We estimate $\lambda^s = -0.14$ using a log-linear approximation of the equilibrium condition (6). The details of the estimation appear in Appendix C.1.

Export subsidy.— We observe the size of the export subsidy in the sugar industry directly from the data. In particular, Nachrichten reports the total export subsidy payout by year. We divide the 1870 payout by the value of exports from the Trade Returns and subtract the input tax rate, estimated as the ratio of the excise tax collected reported in Nachrichten and the value of production in 1870. This yields an export subsidy of 11.2%. Since there is no export subsidy in the initial period, $s_s = 1$, we set $ds_s = 0.11$.

Table 3 summarizes the externally calibrated parameters.

Table 3. Parameterization

Parameter	Value	Target	Source
σ	3.5	Elasticity of substitution across varieties	Broda and Weinstein (2006)
β	12	Tail exponent of input use (log-rank-log-size)	Data, see text
κ	0.58	Event-study ratio: firms vs. input response	Table A.3
λ^s	-0.14	Spillover elasticity in upgrading cost	Appendix C.1
ds_s	0.11	Export subsidy increase	Nachrichten; Trade Returns

7.4. Calibration Procedure

Overview.— We calibrate two parameters and one exogenous shock $\Theta = \{f, \tau, d\gamma_s\}$ to match three moments. We search over the fixed costs ratios f, the relative iceberg cost of exporting τ, and the change in the productivity gain from upgrading to frontier technology in sugar $d\gamma_s$ to match: (i) the heterogeneous response in regional input use, $\hat{L}_{bs} - \hat{L}_{rs}$; (ii) the cross-regional adoption gap, $m^u_{bs} - m^u_{rs}$; and (iii) the aggregate adoption rate in sugar, m^u_s. Throughout, we interpret the empirical moments as *conditional* on two exogenous changes between 1865 and 1870: the export subsidy in sugar, ds_s, and the unobserved increase in the productivity gain from upgrading to hot water extraction method, $d\gamma_s$. We impose no change in import tariffs and non-sugar policies and technology: $dt^m_k = ds_n = d\gamma_n = 0$.

Targets and construction.— We obtain the target for the heterogeneous response in regional input use from the event study around the introduction of export subsidies. Specifically, we combine the 1870 coefficient on the export access interaction from the input use regression (see Table A.3) with the cross-region difference in export access. We construct the latter as the average export market access for firms in Bohemia less that in the rest of Austria-Hungary. The resulting product gives the model-consistent differential response conditional on the $(d\gamma_s, ds_s)$ shocks. We build the cross-regional adoption gap target analogously: by combining the point estimate from the regression of upgrader status on export access in 1870 with the export access difference between the two regions. Finally, the aggregate sugar upgrader share m^u_s for 1870 comes directly from the data.

Identification intuition.— While the parameters are determined jointly, each target is most informative about a distinct object. From Proposition 5, the heterogeneous response in input use is determined primarily by the difference in the iceberg costs of exporting between the two regions. In the model, export market access determines the export share of revenue, which acts as a measure of exposure to export subsidy shock. The cross-regional adoption gap disciplines the ratio of fixed costs f. Finally, the aggregate adoption level determines the technology shift $d\gamma_s$ consistent with the observed take-up.

Table 4. Estimated Parameters

Parameter	Value	Targeted Moment
τ	0.974	Regional input use differential, $\hat{L}_{bs} - \hat{L}_{rs}$
f	1.293	Cross-regional adoption gap, $m^u_{bs} - m^u_{rs}$
$d\gamma_s$	0.146	Aggregate sugar adoption level, m^u_s

Estimation routine.— For any candidate $\Theta = (f, \tau, d\gamma_s)$, we solve the system in changes (C1)-(C10) taking ds_s as given to obtain model-implied moments:

$$\mathcal{M}^{\text{model}}(\Theta; ds_s) = \left\{\hat{L}_{bs} - \hat{L}_{rs},\ m^u_{bs} - m^u_{rs},\ m^u_s\right\}.$$

We choose Θ to match the data by minimizing the quadratic loss with identity weighting

$$\mathcal{M}^{\text{model}}(\Theta; ds_s) = \mathcal{M}^{\text{data}}.$$

As the system is just-identified, the model matches the targets exactly. Table 4 summarizes the estimated parameter values.

8. Results

We solve the model under alternative combinations of two exogenous changes in the sugar industry: the introduction of an export subsidy, ds_s, and the increase in the productivity gain from upgrading to the frontier technology, $d\gamma_s$. We consider three scenarios: (i) *baseline*, where both export subsidy and improvement in frontier technology are set to values estimated in Section 7 ($ds_s = 0.11$, $d\gamma_s = 0.21$), (ii) *technology only*, ($ds_s = 0$, $d\gamma_s = 0.21$); and (iii) *subsidy only*, ($ds_s = 0.11$, $d\gamma_s = 0$). We hold import tariffs and non-sugar policies and technology fixed across all counterfactuals: : $dt^m_k = ds_n = d\gamma_n = 0$.

Table 5 summarizes the model outcomes across the three scenarios. In the baseline (column (i)), sugar production rises by 35%. The *subsidy only* scenario results in a 22% increase, suggesting that the aggregate expansion was largely due to policy rather than technology. In turn, virtually all of the increase in production is driven by exports. To see why, note that in 1864, sugar imports comprised 1% of domestic sugar consumption: demand was essentially met by domestic supply. Together with Cobb-Douglas preferences, this means that home demand moved mainly with aggregate expenditure rather than relative prices. By contrast, Austro-Hungarian exports comprised a small share of world sugar supply, making export volumes highly responsive to technology- and policy-induced price changes.

Next, note that the relative importance of export subsidy is not due to the greater size of the marginal cost reduction associated with upgrading compared to the subsidy: at our baseline calibration, upgrading entailed a higher cost reduction (21%) than did the export

Table 5. Counterfactuals

	(i) Baseline $(ds_s, d\gamma_s)$	**(ii) Technology-only** $(0, d\gamma_s)$	**(iii) Subsidy-only** $(ds_s, 0)$
Sales (change vs. 1864, %)			
Total	35	6	22
Domestic sales	1	0	0
Export sales	452	73	287
Shares (1870, % of firms)			
Share of exporters	60	13	46
Share of adopters	35	19	0

Notes: Sales are percentage changes relative to 1864. Shares are percent levels in each counterfactual. Scenarios as labeled; tuples indicate the policy/technology changes applied. Export subsidy change is $ds_s = 0.1$, improvement in frontier technology is $d\gamma_s = 0.21$, as estimated in Section 7. In all counterfactuals, non-sugar policies/technology and import tariffs are fixed: $dt_k^m = ds_n = d\gamma_n = 0$.

subsidy (11%). Instead, the difference was driven by different rates of selection into the two types of cost reduction: in the baseline, more firms took up exporting than did upgrading.

Finally, note that the baseline production rose by more than the sum of that in the subsidy-only and technology-only counterfactuals. This super-additivity reflects an interaction between exporting and technological upgrading: by inducing additional firms to export, the subsidy raised average scale, making upgrading worthwhile for more firms. As a result, Table 5 shows that upgrader share in the baseline was 16 percentage points higher than that in the technology-only scenario.

Regional heterogeneity.— In Section 4 we document a wide gap in sugar production that opened between high- and low export access regions in the wake of the export subsidy. To understand its causes, we report results for Bohemia and rest of Austria-Hungary separately in Table 6. First, we find that the increase in sugar production in the baseline was driven almost entirely by higher production in Bohemia (69%), with virtually no contribution by the rest of Austria-Hungary (1%). Notably, both subsidy and technology contributed to this skew in regional production. In the technology-only case, the difference is explained by the higher take-up of frontier technology in Bohemia, where 21 percent of firms choose to upgrade compared to 18 in the rest of Austria-Hungary. Initially higher export market access meant larger scale for the average Bohemian firm, so that when the new technology arrived, more firms found it worthwhile to upgrade, leading to higher domestic and export sales. In turn, export subsidy boosted exports in both regions but more so Bohemia. In subsidy-only counterfactual, Bohemia also saw its domestic sales expand – at the expense of the rest of Austria-Hungary. To see why, note that in our model export subsidies interact with increasing returns to scale, whereby subsidy-driven growth in exports can raise the average scale and lower average costs. As the export expansion was larger in Bohemia – the operation of this mechanism was stronger, lowering its costs and crowding out production elsewhere.

Table 6. Counterfactuals, Regional Breakdown

	(i) Baseline		(ii) Technology-only		(iii) Subsidy-only	
	Bohemia	*Rest*	*Bohemia*	*Rest*	*Bohemia*	*Rest*
Sales (change vs. 1864, %)						
Total	69	1	12	0	43	1
Domestic sales	22	-20	5	-5	14	-13
Export sales	518	343	72	76	324	224
Shares (1870, % of firms)						
Share of exporters	75	44	17	10	58	34
Share of adopters	39	31	21	18	0	0

Notes: Sales are percentage changes relative to 1864. Shares are percent levels in each counterfactual. Scenarios as labeled; tuples indicate the policy/technology changes applied. Export subsidy change is $ds_s = 0.1$, improvement in frontier technology is $d\gamma_s = 0.21$, as estimated in Section 7. In all counterfactuals, non-sugar policies/technology and import tariffs are fixed: $dt_k^m = ds_n = d\gamma_n = 0$.

8.1. Welfare

We conclude by assessing the welfare effects of the export subsidy in the sugar industry.

Measurement.— We compute welfare as $\hat{W} = \hat{I}/\hat{P}$, where $I = w + T/L$ is income per capita and $P = \prod_k P_k^{\alpha_k}$ is the consumer price index. Since sugar comprises a small share of the consumption basket, even large changes in the sugar industry yield only marginal changes in utility. For this reason, we report all welfare changes as compensating changes in sugar consumption that yield an equivalent increase in welfare: $\hat{W}(Q_s^{1870}, Q_n^{1870}) = \hat{W}(Q_s^{1864}\hat{Q}_s^*, Q_n^{1864})$, where $\hat{W}(Q_s^{1870}, Q_n^{1870})$ is the change in welfare under some counterfactual, Q_s^{1864} and Q_n^{1864} are quantities of sugar and non-sugar consumption in the initial equilibrium, and $\hat{Q}_s^*$ is the compensating variation we report as our welfare metric. Under our assumption of Cobb-Douglas outer utility, $\hat{Q}_s^* = \hat{W}^{1/\alpha_s}$.

Efficient benchmark.— To aid welfare analysis, we construct a constrained-efficient benchmark. To do so, we add a fourth policy instrument – technology adoption subsidy t_s^λ (see Online Appendix A.5.) – and search over the parameter space of t_s^λ to find the value that maximizes welfare conditional on (i) the initial state of economy, (ii) arrival of frontier technology $d\gamma_s = 0.21$, and (iii) no export subsidy in place $ds_s = 0$. This process yields $t_s^{\lambda *} = -0.013$, or a subsidy of 1.3% of the fixed cost of adoption.

Table 7 reports changes in welfare under four counterfactual scenarios: *baseline*, *technology-only*, *subsidy-only*, and *efficient benchmark*. First, note that the arrival of the new technology by itself raised welfare (column (iii)). However, this increase fell short of the welfare gains attainable under the efficient benchmark (column (iv)). To see why, note that, absent policy intervention, upgrading was inefficiently low. In the competitive equilibrium, private incentives to upgrade did not account for the additional social returns from lowering the cost of upgrading, leading to suboptimally low uptake. Despite the potential scope for policy intervention, we find that in the baseline with the export subsidy, welfare declined:

Table 7

	(i) Baseline $(ds_s, d\gamma_s)$	(ii) Technology $(0, d\gamma_s)$	(iii) Subsidy $(ds_s, 0)$	(iv) Efficient $(0, d\gamma_s, t^\lambda)$
CV (%)	-0.82	1.49	-1.92	1.52
Welfare (CV%)	35	19	0	25

Notes: The table reports welfare changes under four counterfactual scenarios. Welfare is expressed as compensating variation (CV) in sugar consumption that yields an equivalent welfare change, relative to the initial equilibrium in 1864. Column (i) shows the baseline with both technology arrival and the export subsidy in place; Column (ii) reports the outcome when only the new technology is introduced; Column (iii) reports the outcome when only the export subsidy is applied; Column (iv) presents the constrained-efficient benchmark obtained under the adoption subsidy t_s^λ that maximizes welfare.

the welfare loss due to the use of the export subsidy more than offset the welfare increase from the arrival of frontier technology. Note further that this occurred *despite* the export subsidy inducing a large increase in technology adoption. Indeed, subsidy-driven adoption substantially exceeded that in the efficient benchmark.

We conclude by asking: how close could a correctly sized export subsidy get to the efficient benchmark? We do so by constructing a series of counterfactuals that vary the export subsidy from -5 to 15 percentage points while keeping the technology improvement at its baseline level. The constrained-optimal export subsidy that obtains from this exercise is -0.008: an export *tax* of 0.8 percentage points. The negative value reflects two competing forces. First, trade policy in our 1864 benchmark is set suboptimally. In particular, as documented in Section 7, sugar imports face an import tariff much higher than the economy average. By moving resources towards a sector that is already suboptimally large, export subsidy exacerbates the misallocation caused by the import tariff. An export tax partially corrects this. Second, an export subsidy can move adoption closer to the social optimum. However, under our baseline calibration, the welfare losses from misallocation outweigh the benefits from higher upgrading almost immediately. In particular, simulating a range of export subsidies starting from an initial equilibrium recalibrated to set import tariffs at the optimal level yields an optimal export subsidy of 0.2 percentage points. This policy increases upgrading by 2 percentage points relative to the technology-only scenario, but it remains well below the optimal level of upgrading.

9. Conclusion

Can export subsidies function as industrial policy? In this paper, we re-visit this question using a historical case of export subsidies in nineteenth-century beet-sugar industry.

Our historical setting combines a large, unintended export subsidy which coincides with arrival and spread of a frontier extraction technology. The export subsidy emerged in 1864, with a legal change that misaligned how the consumption tax and the export rebate were calculated. We assemble factory-level data for 1851-1883, including annual beet inputs and technology status in 1870 and 1885, and we construct a companion French panel on technology adoption for 1879-1889. The empirical strategy exploits exposure to the subsidy through pre-subsidy export access – effective distance to London – and uses region-level event studies as well as a staggered-adoption design based on the first neighbor's upgrade.

Three findings emerge. First, after the subsidy, production reallocated toward regions with high export access: beet processing rose, more factories operated, and scale per factory increased. Second, factories in these regions adopted the frontier technology earlier, while low-access regions upgraded last. Third, in the French data, a nearby first adoption raised local adoptions in the subsequent period, consistent with spatial spillovers.

We build a quantitative model to interpret these patterns. The framework combines Melitz selection into exporting with a binary technology choice à la Bustos (2011) and local spillovers that lower adoption costs as the local adopter share rises. Both exporting and upgrading are subject to selection, so an export subsidy boosts adoption. Calibrated to pre-policy levels and policy-induced changes in production and adoption, the model implies that the historical subsidy increased adoption but reduced welfare relative to no intervention. This happens for two reasons: the subsidy pushes adoption beyond the social optimum and interacts with pre-existing protection in sugar, further misallocating resources toward the sector. In this environment, even a modest export subsidy would have been counterproductive.

Our results highlight a central tradeoff for export-promotion as industrial policy: correcting technological spillovers versus worsening resource misallocation. In the case we study, the latter dominates. External validity depends on the strength of local spillovers, the geography of export access, and the configuration of existing trade policies. The historical lens and the technology snapshots we observe anchor identification and quantification but also bound our conclusions to settings with similar features.

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Appendix A: Data

Table A.1. Spread of hot water extraction method

Year	(1) Austria–Hungary	(2) Bohemia	(3) Rest of Austria–Hungary
1865	0%	0%	0%
1866	1%	3%	0%
1867	8%	9%	7%
1868	15%	19%	12%
1869	22%	26%	18%
1870	31%	39%	19%
1871	41%	52%	22%
1872	50%	59%	35%
1873	55%	64%	38%
1874	61%	71%	43%
1875	76%	83%	63%

The table reports the upgraders to hot water extraction method as a share of operating firm for (1) all of Austria-Hungary, (2) Bohemia, and (3) Austria-Hungary excluding of Bohemia. Sources: Hořínek (1891); Verein zur Hebung der Zuckerfabrikation im Königreiche Böhmen (1874).

Table A.2. Sugar: Policy and Production

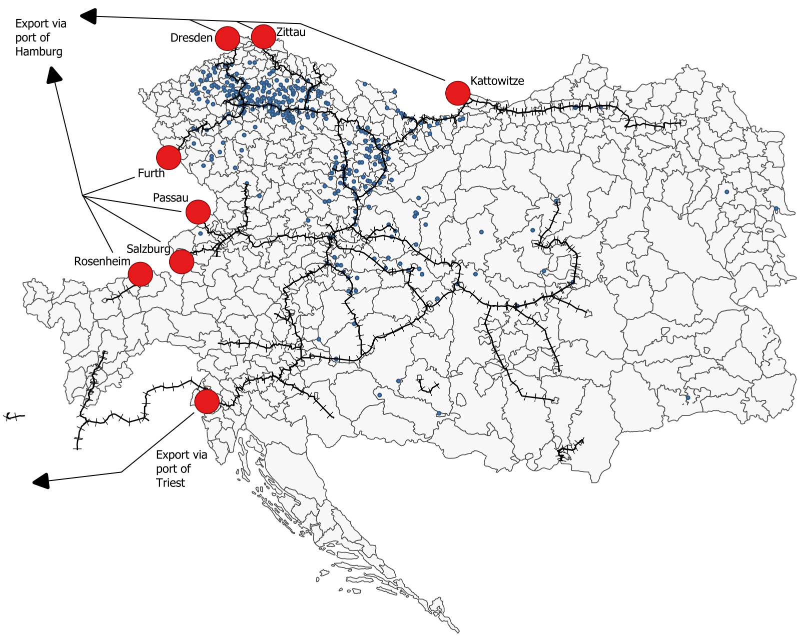
Beets used (t)	Production (t)	Export (t)	Export Rebate (fl.)	Consumption tax (fl.)
839,406	72,800	112	0	5,112,225
802,802	72,800	655	0	5,759,202
775,932	84,000	481	815	5,586,811
956,459	78,400	75	0	6,989,829
829,695	78,400	134	849	6,030,099
1,097,200	100,800	4,347	401,522	7,926,202
863,847	117,600	23,700	2,081,056	6,116,587
1,145,265	123,200	15,490	1,207,133	7,886,940
1,005,437	134,400	21,143	2,606,772	7,352,261
793,438	128,800	10,532	2,408,108	5,805,850
1,229,117	134,400	11,499	159,180	8,983,127
1,593,119	156,800	65,557	4,867,152	11,650,865
1,361,425	162,400	92,137	6,976,966	9,962,720
1,733,318	179,200	62,332	6,615,686	12,674,894
1,377,388	207,200	87,125	6,551,746	10,072,149

Notes: Weights converted to metric tons (t). Wiener Centner = 56 kg; Zoll-Centner = 50 kg. fl. are Austro-Hungarian Guldens. Export rebate and consumption tax are annual receipts and expenditures by the government, respectively.

A.1. Export cost data

We construct our measure of transport costs based on the distance between the centroid of a district/factory and the nearest railway (i.e. road transport), the distance from this railroad point to harbours used to export the sugar (Hamburg or Triest) to the UK and the sea-route distance between the export harbour and London. In the case of export via Hamburg we add the distance between border crossing and the port of Hamburg to the distance covered by railroad.[26] Following Donaldson (2018), we convert the different transport modes into effective railroad distance in kilometers utilizing the parameters from Donaldson (2018) whereby $\alpha_{Rail} = 1$, $\alpha_{Sea} = 2.25$ and $\alpha_{Road} = 4.5$. We than find the optimal path for export from each location. Note that as the railroad network is not yet fully integrated, creating 4 distinct areas of exporting via the rail network that are not connected.[27] Consistent with the high cost of off-loading, transport and on-loading at terminal station, we do not allow road transport in between rail transport.

Figure A.1. Map of Austro-Hungarian rail lines and border crossings in 1864.



Notes: Sugar factories that existed between 1851-1883 shown with blue dots. Shapefile of 1910 Austro-Hungarian bezirks and 1864 railroad lines from Tomas Cvrcek.

26. Considering that the German rail network is already very dense by 1864 and that we only have data for railroad lines of Austria-Hungary we utilize the geographic distance between border crossing and Hamburg.

27. Due to terminal stations in Vienna, Prague, and Budapest as well the Tirolean railroad line being connected to the German network but not the remainder of the Austro-Hungarian one.

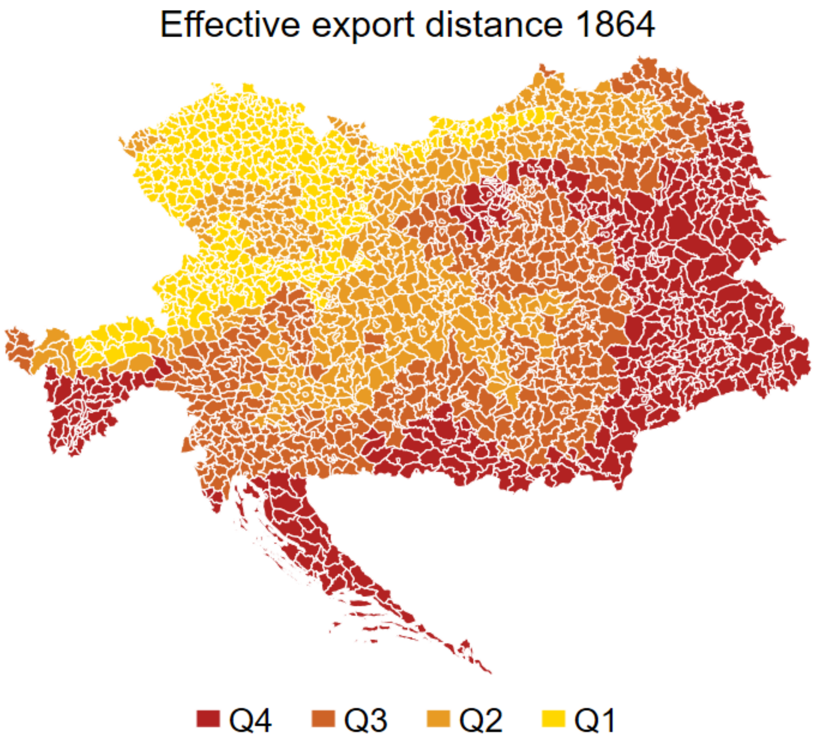
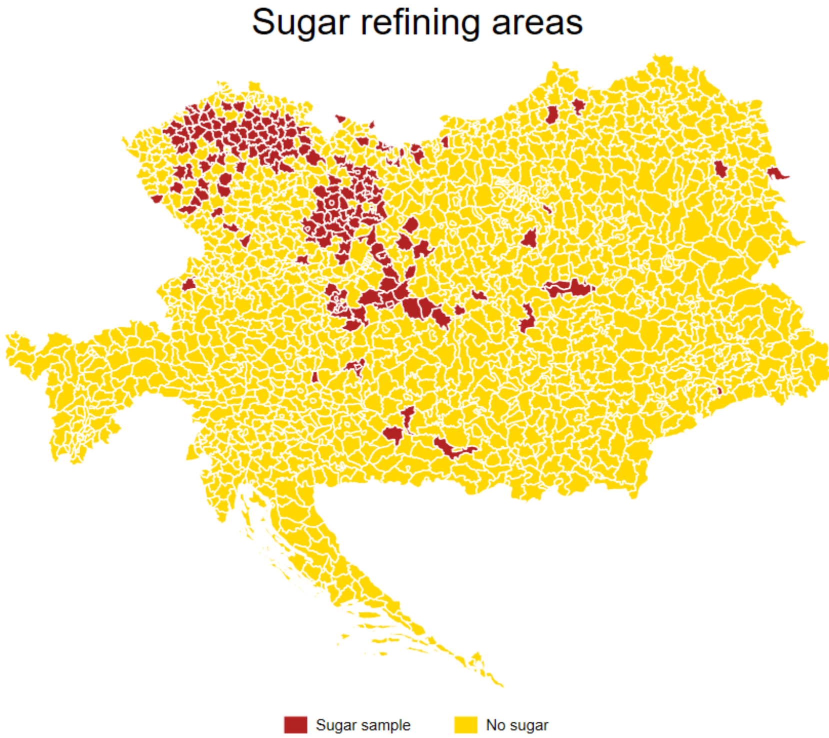


Figure A.2. Map of effective distance to London from Austro-Hungarian district in 1864.
Notes: Effective distance calculated using rail, sea and road transport (with parametres for different transport modes from Donaldson (2018): $\alpha_{Rail} = 1$, $\alpha_{Sea} = 2.25$ and $\alpha_{Road} = 4.5$). Shapefile of 1910 Austro-Hungarian district boundaries from Tomas Cvrcek.

A. Municipality level



B. District level

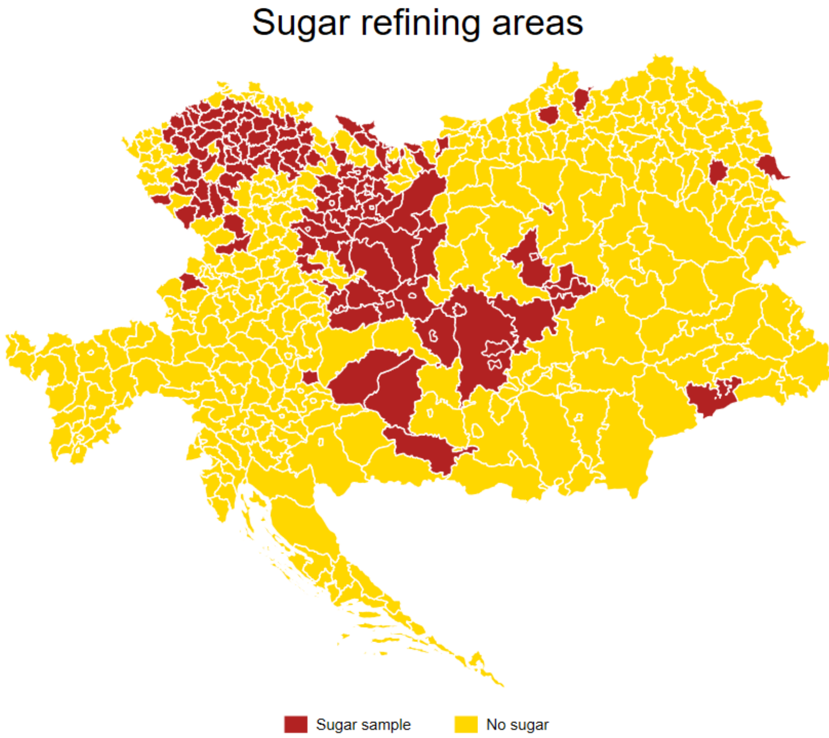


Figure A.3. Map of places with sugar refining across Austria-Hungary. Notes: Map shows locations in the sample that have at lest one firm that does sugar refining at some point in the sample period. Shapefile of 1910 Austro-Hungarian district boundaries from Tomas Cvrcek.

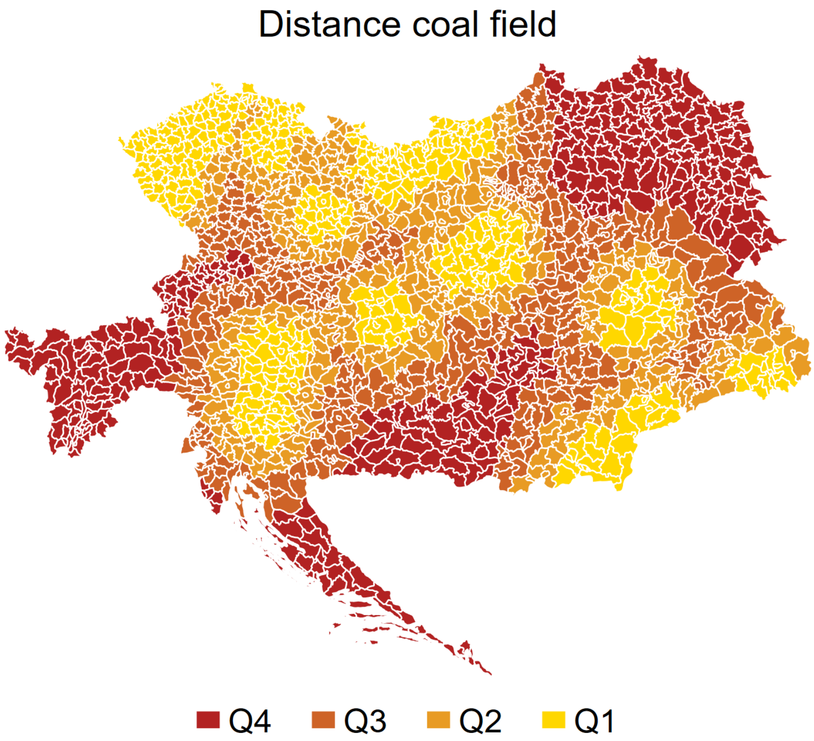


Figure A.4. Map of distance to coal fields across Austria-Hungary. Notes: Distance to coal fields (hard and lignite coal mining) based on data from Fernihough and O'Rourke (2021). Shapefile of 1910 Austro-Hungarian district boundaries from Tomas Cvrcek.

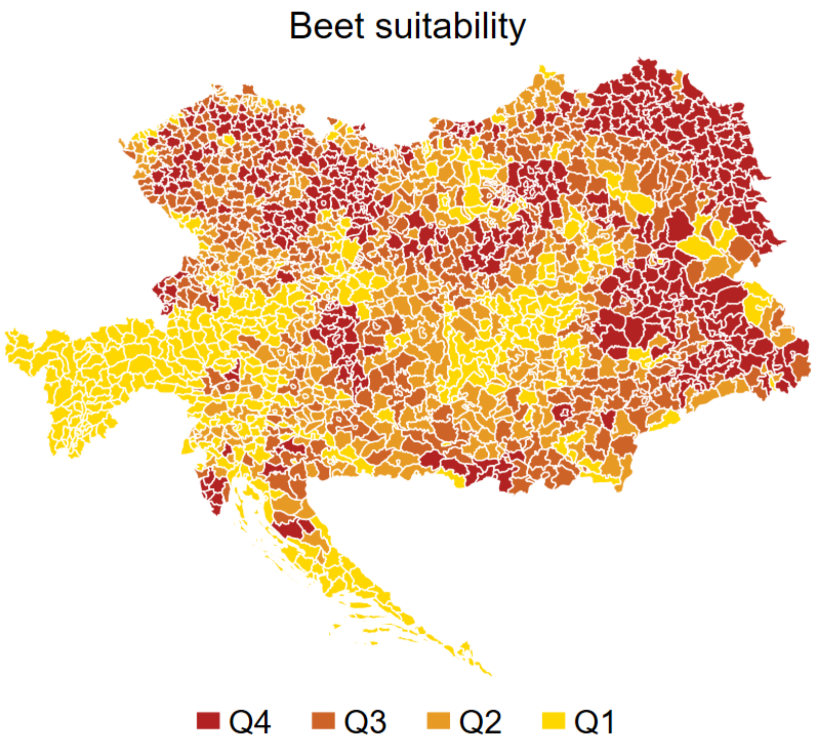
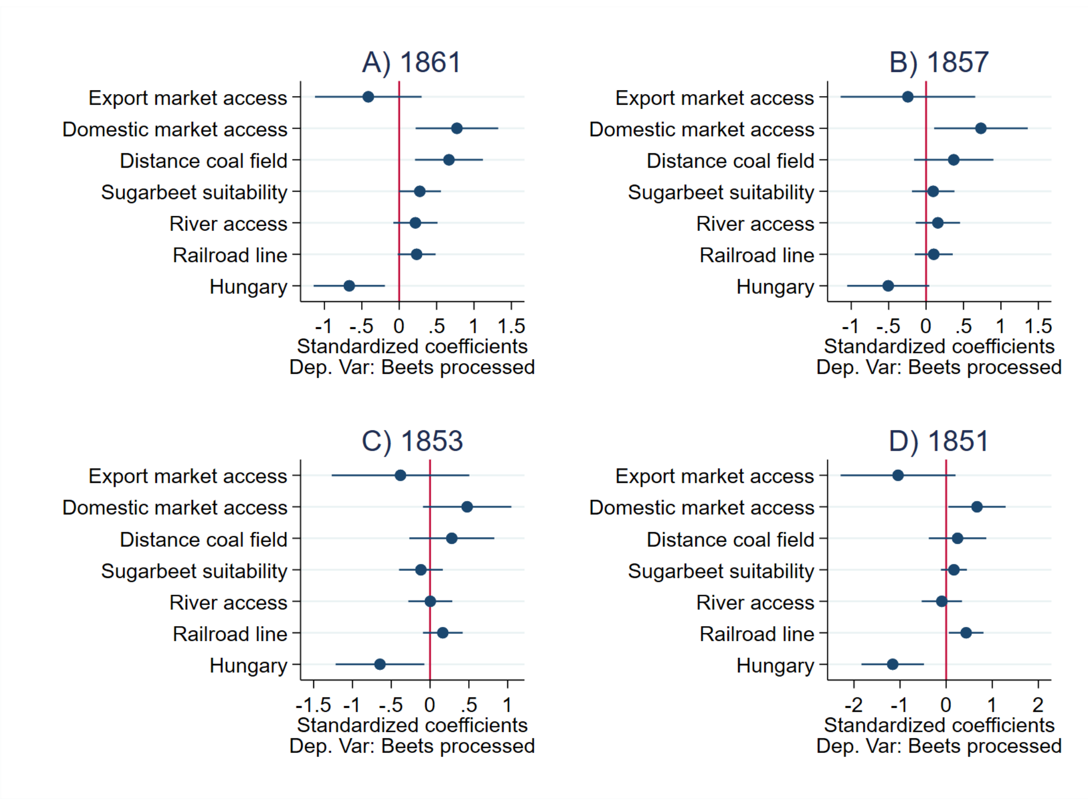


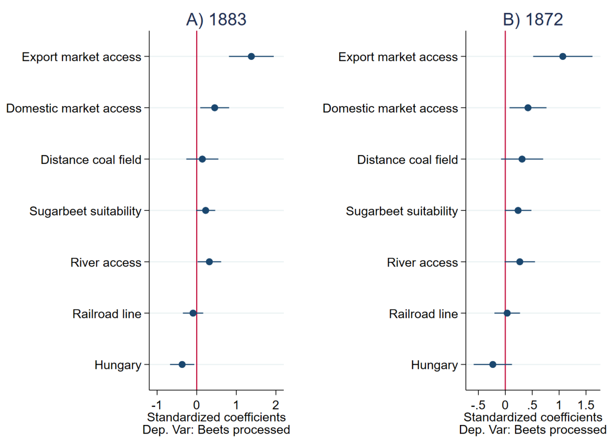
Figure A.5. Map of beet suitability across Austria-Hungary. Notes: Beet suitability calculated as max suitability within a district based on Fischer et al. (2021) Shapefile of 1910 Austro-Hungarian district boundaries from Tomas Cvrcek.

Figure A.6. Determinants of sugar refining



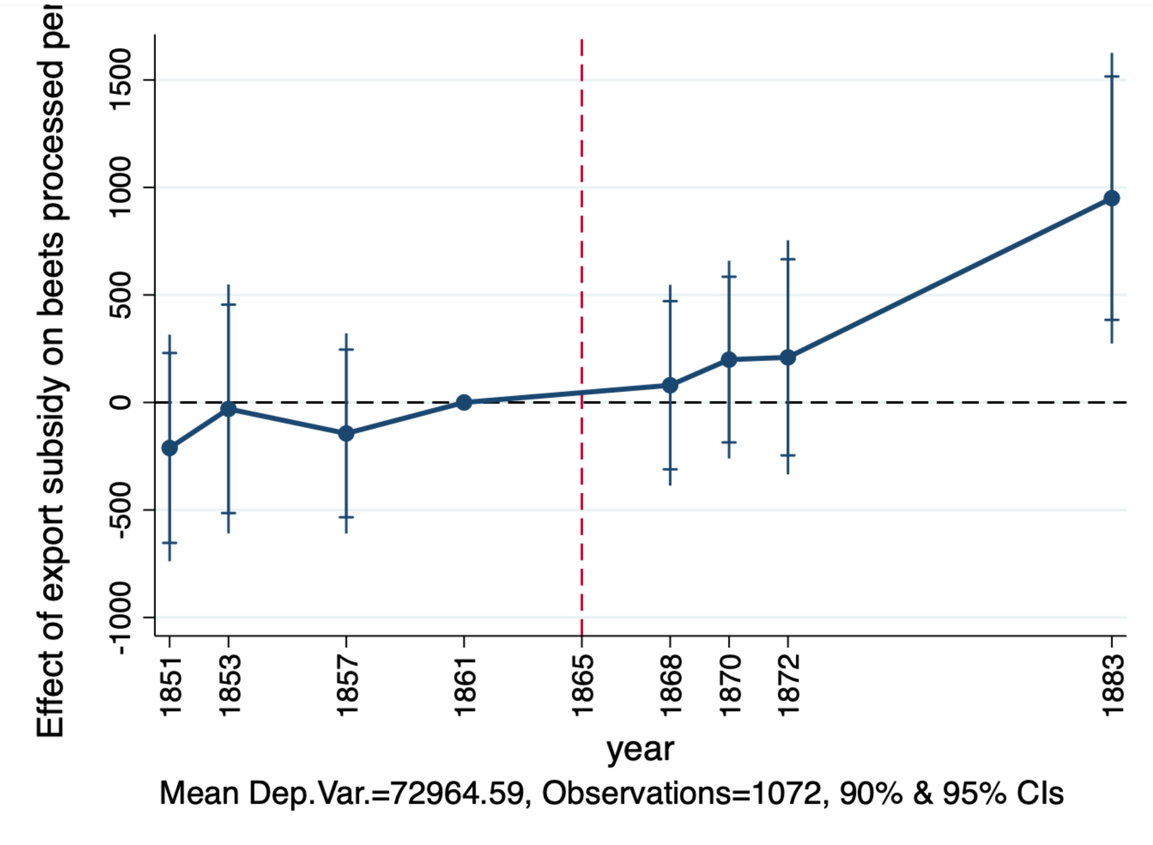
Notes: The figure plots which factors are correlated with the processing of beets before the introduction of export subsidies, namely 1861 (Panel A), 1857 (Panel B), 1853 (Panel C) and 1851 (Panel D). N=171 for each regression.

Figure A.7. Determinants of sugar refining



Notes: The figure plots which factors are correlated with the processing of beets after the introduction of export subsidies, namely 1883 (Panel A), and 1872 (Panel B). N=171 for each regression.

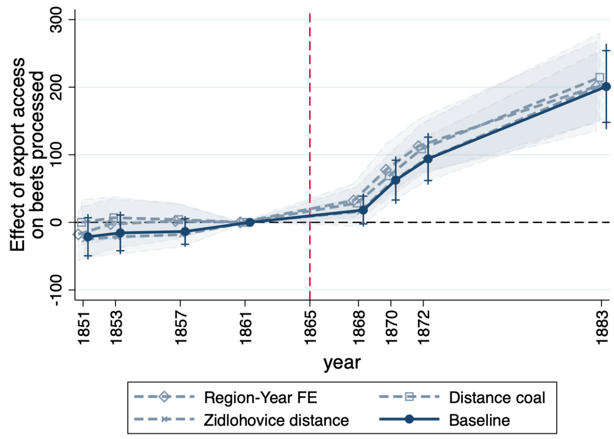
Figure A.8. Effect of export subsidy on processing per firm, incumbents only



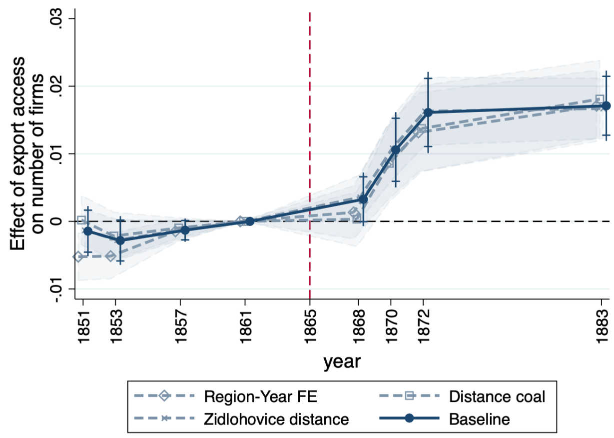
Notes: The figure plots the event-study estimates for the effect of export distance rank on sugar beets processed per firm in a sample restricted to firms that existed before 1868. Estimates are obtained using OLS. Controls: Municipality and year fixed effects. Standard errors clustered at the municipality level.

Figure A.9. Robustness of main estimates

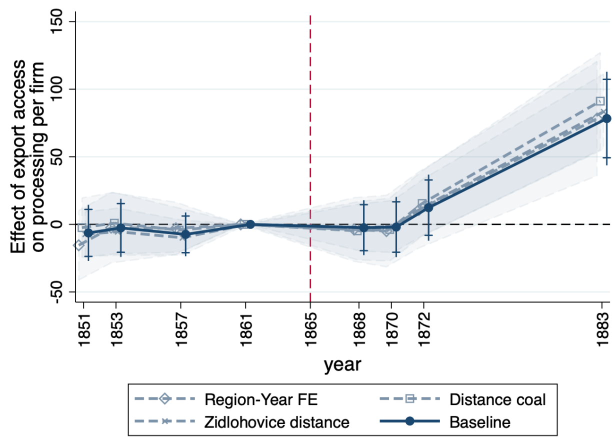
(a) Export access and beets processed



(b) Export access and number of sugar factories



(c) Export access and beets processed per firm



Notes: The figure plots the eventstudy estimates for export access on output, number of firms, and output per factory. Additional controls interacted with year fixed effects: Region fixed effects (Cisleithania/Hungary), distance to coal field, distance to Zidlohovice. Standard errors are clustered at the municipality level.

Table A.3. PPML

	(1) **Total beets processed**	(2) **Number of firms**	(3) **Beets per firm**
1851	-0.00075	0.00025	-0.00091*
	(0.00053)	(0.00033)	(0.00050)
1853	0.00007	-0.00018	-0.00023
	(0.00035)	(0.00023)	(0.00041)
1857	-0.00019	-0.00008	-0.00046**
	(0.00024)	(0.00010)	(0.00023)
1868	0.00076**	0.00015	0.00024
	(0.00032)	(0.00032)	(0.00036)
1870	0.00108***	0.00046	0.00027
	(0.00038)	(0.00037)	(0.00042)
1872	0.00171***	0.00078*	0.00084*
	(0.00047)	(0.00042)	(0.00046)
1883	0.00240***	0.00189***	0.00257***
	(0.00056)	(0.00048)	(0.00063)
Observations	1,352	1,368	1,352
Clusters (municipality)	169	171	169
Pseudo R2	0.7566	0.3083	0.5640

Notes: The table presents the event-study estimates for the effect of export market access on (1) beets processed, (2) number of firms, (3) beets processed per firm, estimated using Poisson Pseudo Maximum Likelihood (PPML). Controls: Municipality and year fixed effects, distance to first use of hot water extraction method×Year and distance to coal×Year. Standard errors clustered at the municipality level.

Appendix B: Spillovers

B.1. Construction of controls

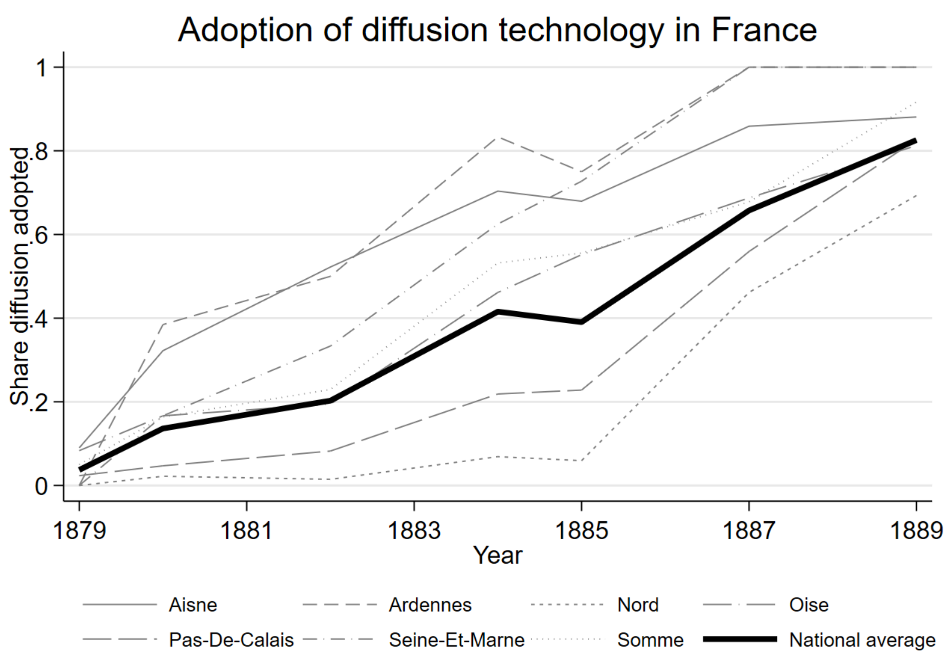
Weather (summer rainfall). Source: Pauling et al. (2006). Construction: annual summer precipitation at the region/municipality level; matched to municipalities; included as level.

Proximity to technology suppliers. Source: *Liste générale* reports machine shops installing hydraulic presses and diffusion batteries. Construction: distance from municipality centroid to nearest shop; included and interacted with year fixed effects.

Export market access. Construction: logarithm of the shortest distance from each municipality to London; included and interacted with year fixed effects.

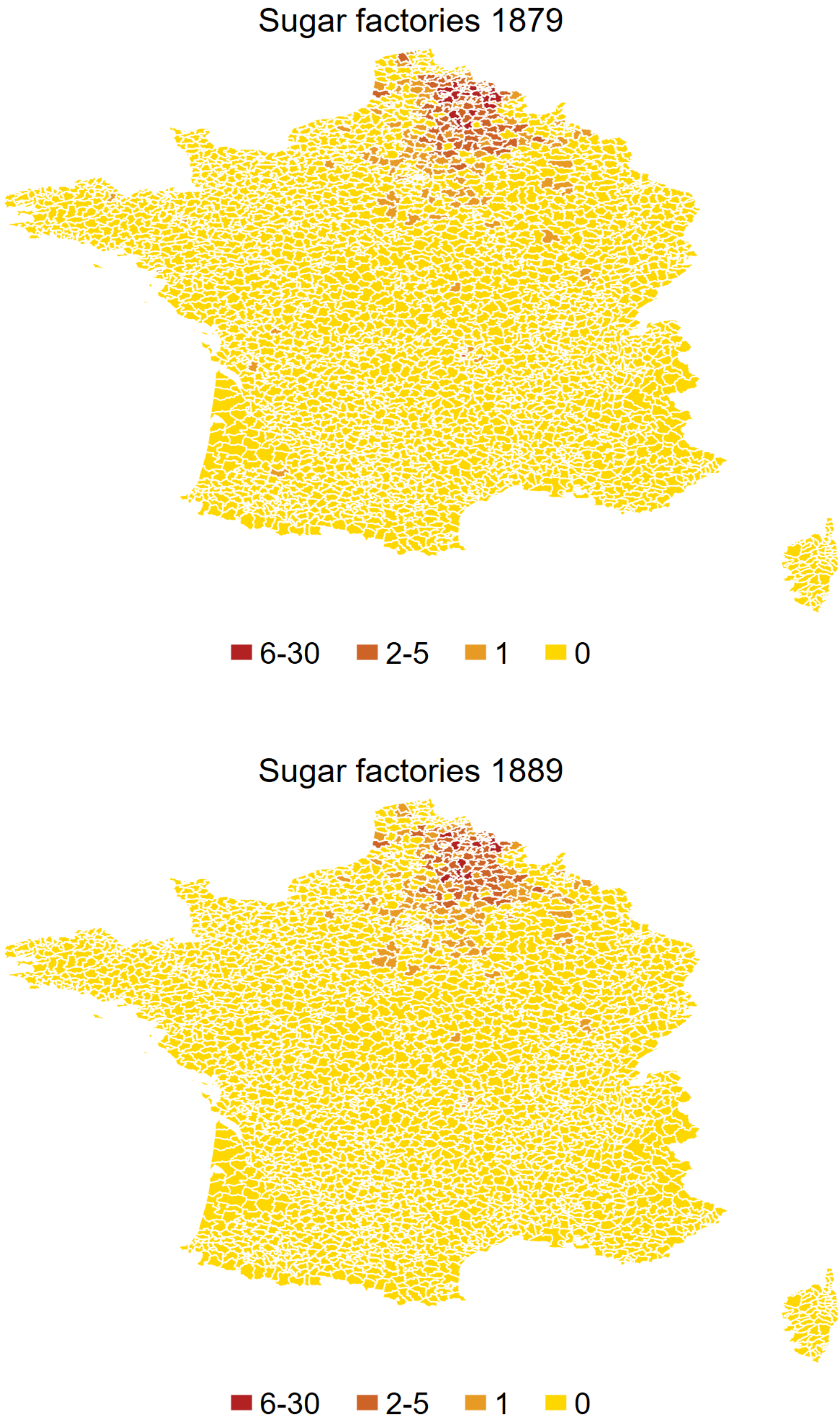
B.2. Extra Figures

Figure B.1. Diffusion adoption share in France 1879-1889



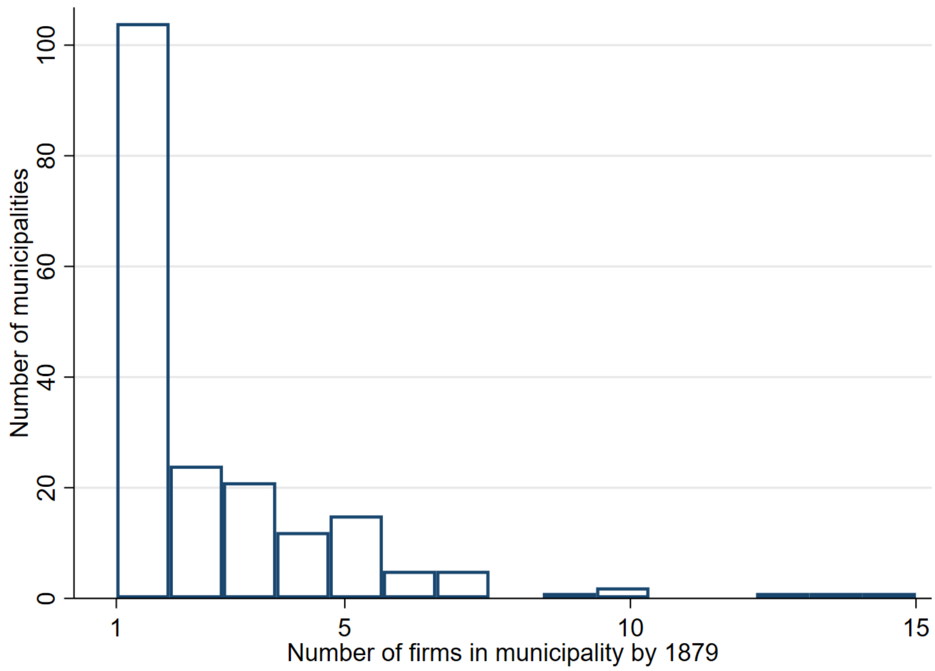
Notes: The figure plots the share of firms that have adopted diffusion in France between 1879 and 1889. National average (bold black line) represents the adoption share for the full French sample. Regional shares (dashed grey-lines) are for departments that had at least 5 firms throughout the sample period.

Figure B.2. Number of sugar firms by municipality



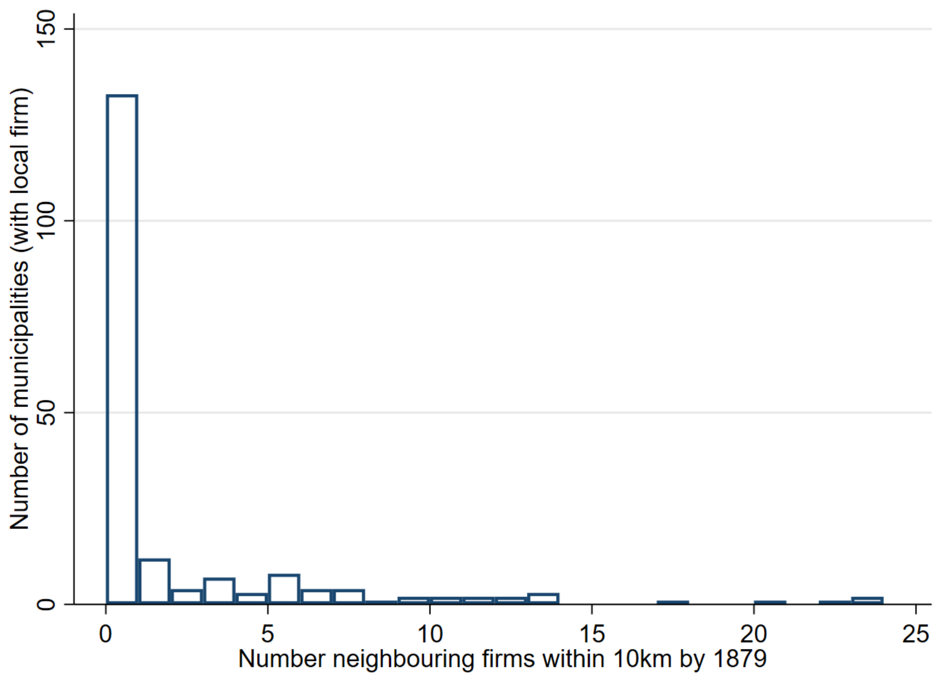
Notes: Number of sugar factories across municipalities by 1879 and 1889.

Figure B.3. Sugar factories across municipalities



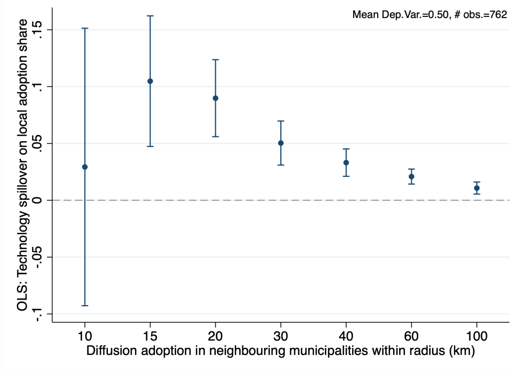
Notes: The figure plots the number of municipalities by number of sugar factories in 1879.

Figure B.4. Sugar factories in neighboring municipalities

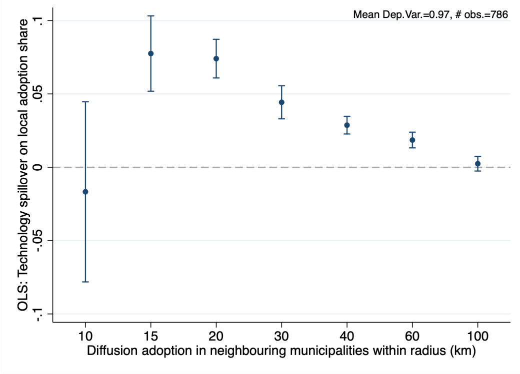


Notes: The figure plots the number of sugar factories in neighboring municipalities (within a 10km radius) for municipalities that had at least one sugar factory by 1879.

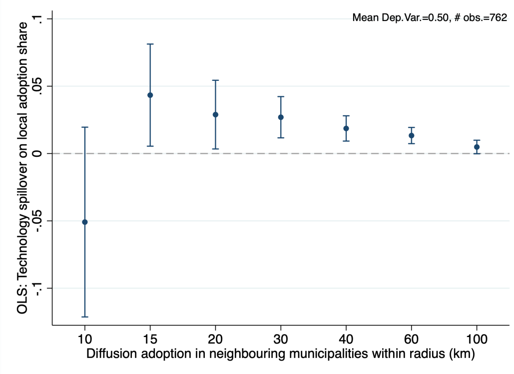
Figure B.5. Technology spillovers (Robustness)



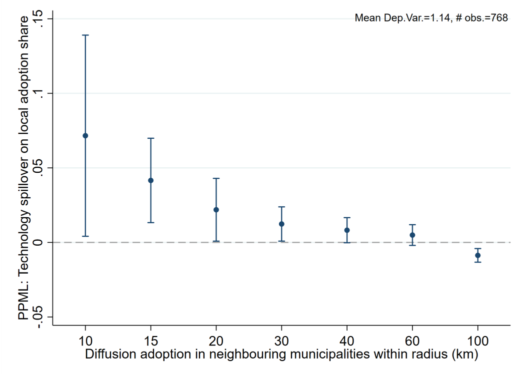
(a) No controls



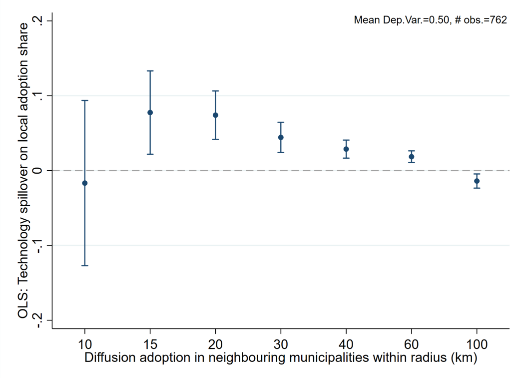
(b) Conley std. errors



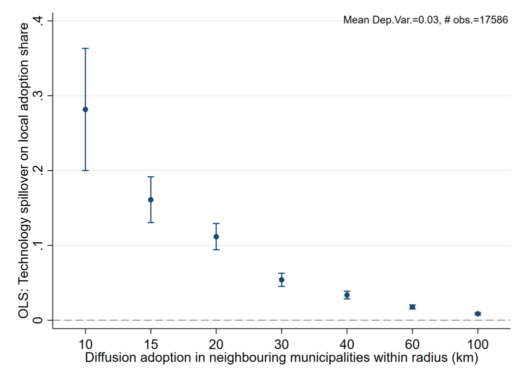
(c) Previous firms & diffusion



(d) PPML



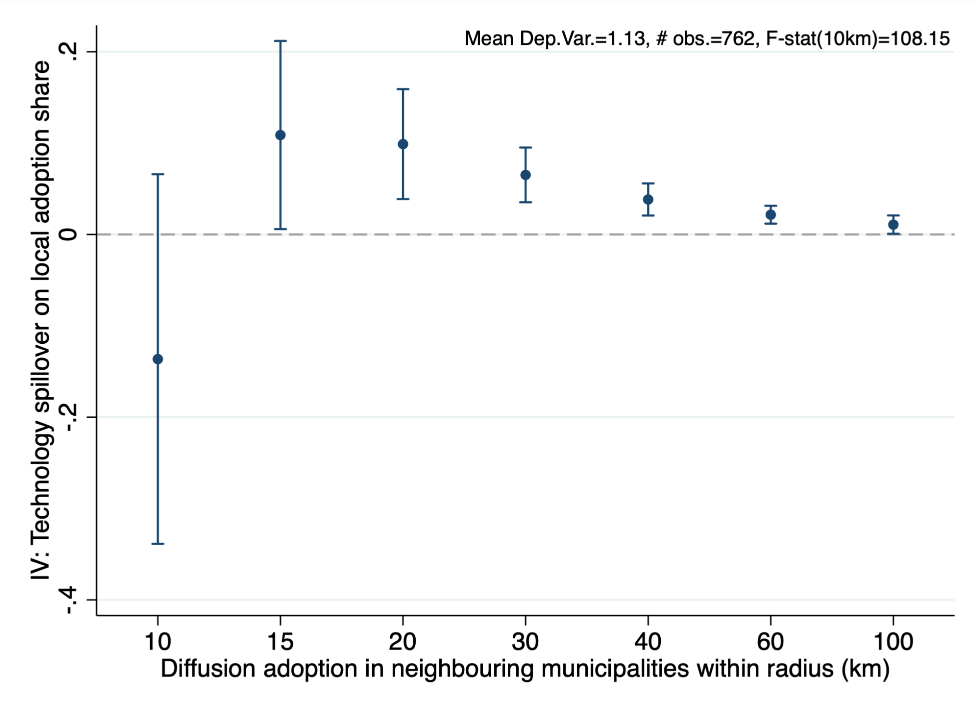
(e) Grid-year FE



(f) Full sample

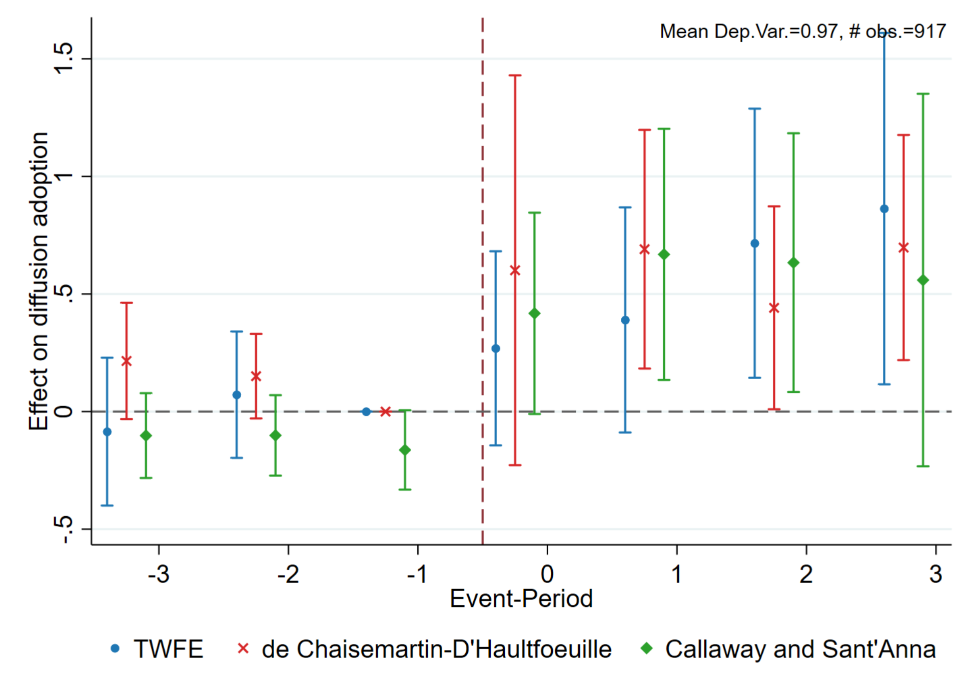
Notes: The figure shows the robustness of estimates of technology adoption spillovers for: i) no controls (apart from municipality and year fixed effects), ii) Conley clustered standard errors, iii) controlling additionally for lagged nr. of firms and lagged nr. of diffusion adopters, iv) PPML estimator, v) controlling for 1-degree-grid-cell-year fixed effects vi) using the full municipality sample including areas that zero firms throughout the whole sample period. 90% confidence intervals clustered at the municipality level.

Figure B.6. Technology spillovers (IV)



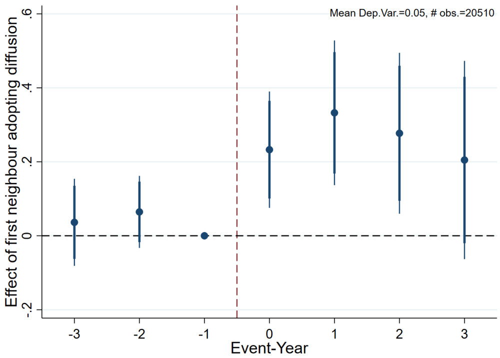
Notes: The figure plots the IV estimates for lagged number of firms with diffusion in neighboring municipalities on diffusion adoption in the municipality. Lagged neighboring diffusion adoption instrumented with number of neighboring firms by 1879×leave-one-out national adoption (diffusion adoption in the rest of France). Controls: Municipality fixed effects, distance to manufacturer of presses×Year, distance to manufacturer of diffusion×Year, distance to UK export market×Year, and summer-rainfall (from Pauling et al. 2006). 90% confidence intervals clustered at the municipality level.

Figure B.7. Technology spillovers (Event-study: Robustness)

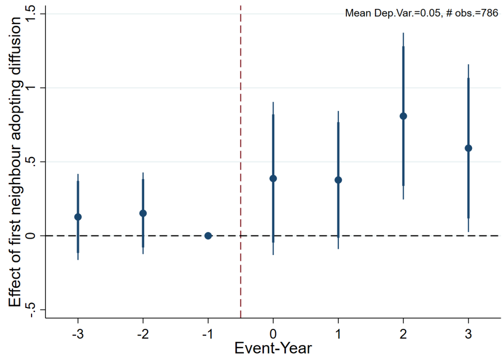


Notes: The figure plots the event-study estimates for the first neighboring firm using different estimators. Controls: Municipality fixed effects, distance to manufacturer of presses×Year, distance to manufacturer of diffusion×Year, distance to UK export market×Year, and summer-rainfall (from Pauling et al. 2006). 90% confidence intervals clustered at the municipality level.

Figure B.8. Incumbents & lagged adoption



(a) Full sample (0-firms)



(b) Lagged diffusion & firms

Notes: The figure shows the robustness of event-study estimates of technology adoption spillovers when a) restricting the sample to areas that have at least one firm throughout the whole sample period, b) when controlling for local lagged adoption of diffusion and number of firms. Controls: Municipality fixed effects, distance to manufacturer of presses×Year, distance to manufacturer of diffusion×Year, distance to UK export market×Year, and summer-rainfall (from Pauling et al. 2006). 90 & 95% confidence intervals clustered at the municipality level.

Appendix C: Quantification

C.1. External calibration: spillover

In order to estimate the elasticity of cost of upgrading to share of local adopters, we run a variant of the specifications used in Section 5 that is consistent with our model. We begin by taking a stance on the timing of spillovers in equation (3). In particular, we assume that the regional cost of upgrading this year is a function of the share of upgraders in the last year

$$\lambda_{r,t} = \lambda_r {m^u_{r,t-1}}^{-\lambda^s}.$$

Additionally, we allow the costs of upgrading to vary across regions: λ_r. The share of upgraders is determined by the equilibrium condition (6):

$$m^u_{r,t} = \left((\gamma_t^{\sigma-1} - 1)\lambda_r^{-1} {m^u_{r,t-1}}^{\lambda^s} \left(1 + {m^x_{r,t}}^{\frac{\sigma-1}{\beta}} f\right)\right)^{\frac{\beta}{\sigma-1}} \tag{C.1}$$

Next, equilibrium conditions (11), (13) and (14) can be used to show that the regional exporter shares can be expressed as a function of iceberg trade costs from the region and some common factor $\overline{m}^x_t$ which varies over time but not across regions: $m^x_{r,t} = \overline{m}^x_t \tau_r^{-\beta}$. Finally, we allow the marginal cost improvement associated with upgrading to change over time: $\gamma = \gamma_t$. Under these assumptions, equation (C.1) can be approximated as

$$\ln m^u_{r,t} \approx \alpha \ln m^u_{r,t-1} + \sum_s \beta_s D_{t+s} \ln \tau_r + \delta_i + \delta_t \tag{C.2}$$

where $\beta_t = \frac{\beta}{\sigma-1} \ln\left((\gamma_t^{\sigma-1} - 1)\left(1 + {\overline{m}^x_t}^{\frac{\sigma-1}{\beta}} f\right)\right)$, $\alpha_i = \frac{\beta}{\sigma-1} \ln \lambda_r$, and $\beta_s = -\beta \frac{{\overline{m}^x_s}^{\frac{\sigma-1}{\beta}} f}{1+{\overline{m}^x_s}^{\frac{\sigma-1}{\beta}} f}$. We estimate equation (C.2) using Poisson Pseudo-Maximum Likelihood regression. As in Section 5, we use lagged adoption share in the neighbor municipalities that fall withing 10-kilometer-radius $m^{u,10}_{r,t-1}$, control for municipality and year fixed effects, distance to manufacturers of presses, distance to manufacturers of diffusion batteries and export market access, all interacted with time, as well as summer-rainfall variation. Our coefficient of interest, α, estimates the compound parameter $\alpha = -\frac{\beta}{\sigma-1}\lambda^s$.

Our estimates of α are reported in Table C.2. The point estimate is $\alpha = 0.66$, implying an elasticity of the cost of upgrading with respect to upgrader share of $\gamma^s = \frac{\sigma-1}{\beta} \times 0.66 = 0.14$.

Table C.1

Variable	Symbol	Value / Formula	Source
Panel A: Sugar			
Employment, Bohemia	L_{bs}	18633	*Nachrichten über Industrie, Handel und Verkehr, 1873*
Employment, rest of Austria–Hungary	L_{rs}	19178	*Nachrichten über Industrie, Handel und Verkehr, 1873*
Output	Y_s	43772	*Nachrichten über Industrie, Handel und Verkehr, 1873*
Output share of GDP	Y_s/Y	0.0099	Komlos (2014)
Exports	X_s^x	X_s^x	*Austro-Hungarian Foreign Trade Returns, 1864*
Imports	X_s^m	322.546	*Austro-Hungarian Foreign Trade Returns, 1864*
Domestic sales	X_s^d	$Y_s - X_s^x$	
Import tariff	t_s^m	1.57	*Austro-Hungarian Foreign Trade Returns, 1864*
Panel B: Non-sugar			
Employment, Bohemia	L_{bn}	1820192	*Census of Industry and Commerce, 1880*
Employment, rest of Austria–Hungary	L_{rn}	2889855	*Census of Industry and Commerce, 1880*
Output	Y_n	$(1 - Y_s/Y)(Y_s/Y)^{-1}Y_s$	
Exports	X_n^x	272537	*Austro-Hungarian Foreign Trade Returns, 1864*
Imports	X_n^m	$X_s^x + X_n^x - X_s^m$	*Austro-Hungarian Foreign Trade Returns, 1864*
Domestic sales	X_n^d	$Y_n - X_n^x$	
Import tariff	t_n^m	1.05	*Austro-Hungarian Foreign Trade Returns, 1864*

Table C.2. Neighbor Adoption and Local Diffusion (PPML)

	(1)
Lagged neighbor diffusion share (10km)	0.658***
	(0.192)
Controls	Y
Municipality FE	Y
Year FE	Y
Observations	768
Clusters (id)	128
Pseudo R^2	0.188

Notes: The table reports the PPML estimates for lagged share of adopters in 10-kilometer-radius neighbor municipalities on adopter share in the municipality. Controls: Municipality & year fixed effects, distance to manufacturer of presses×Year, distance to manufacturer of diffusion batteries×Year, export market access×Year, and summer-rainfall variation (Pauling et al., 2006). 90% confidence intervals clustered at the municipality level. Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.