Labour Scarcity and Productivity: Insights from the Last Nordic Plague

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February 21, 2025

Abstract

This paper studies the relationship between labour scarcity and productivity in the context of a 1710s plague outbreak. While higher wages should have led to an export contraction, exports grew after plagued regions shifted into capital-intensive production. Using a Ricardian model, I show that productivity growth in capital-intensive sectors is best suited to explain this export boom. I argue that labour scarcity incentivises capital-intensive production which raises productivity growth.

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1 Introduction

Does labour scarcity lead to productivity growth? Labour scarcity is considered a significant obstacle to economic growth in many developed economies (OECD, 2024, Caldara, Iacoviello, and Yu, 2024). However, labour scarcity can stimulate innovation (Acemoglu, 2010, Habakkuk, 1962), leading to growth and productivity advances (Voth, Caprettini, and Trew, 2023, Franck, 2022, Allen, 2009). This paper studies the relationship between labour scarcity and productivity in a Ricardian trade model. This allows me to generalise insights on the effects of localised labour scarcity in a general equilibrium framework (Temin, 1966). My paper thereby forms the first test of the Habakkuk thesis on labour scarcity incentivising technological progress in an open economy setting (Habakkuk, 1962). The structure of the model further permits to differentiate the effects of labour scarcity from competing mechanisms such as non-homothetic demand (Voigtländer and Voth, 2012, Fieler, 2011). I also provide a commodity-port-level trade data set uniquely suited to this question. Despite many theories on the relationship between factor proportions and productivity featuring implicit predictions on trade, they have rarely been tested in granular data. I fill this gap by studying trade after an early 18th century plague outbreak in Northern Europe.

This paper documents that plagued regions shift into capital-intensive exports and production. This is predicted by the Rybczynski theorem, as capital became relatively more abundant. Surprisingly, I find that plagued regions' exports expanded along both margins. A third of this expansion is accounted for by goods never exported before. In a Ricardian model, I suggest that labour scarcity and increased capital intensity lead to productivity growth, which explains the observed export expansion. I present historical evidence for capital-induced productivity growth and discuss alternative mechanisms.

I study the Great Northern War plague outbreak of 1708-1712, whose mortality rate was comparable to the 1346 Black Death. A crucial difference lies in their geographical scopes: While the Black Death eventually ravaged the entirety of Europe, the Great Northern War plague outbreak was a Nordic plague, afflicting mostly a few dozen regions around the Baltic Sea. Plagued regions' trading partners on the North Sea were unaffected, leaving foreign demand and trade as a viable survival strategy. This plague outbreak also differs from its predecessor in that Danish toll records permit a uniquely extensive look at trade. This source, which I cleaned and turned into a commodity-port-level trade panel, is uniquely suited to answer my research question. Not only does it differentiate between goods of different factor intensities, it is also geographically granular enough to compare plagued regions from non-plagued ones. I am therefore in a position to track plagued regions' trade patterns for decades while rigorously incorporating the gravity structure of trade.

Between 1429 and 1857, all ships entering or leaving the Baltic Sea were liable to pay duties to the Danish Crown, with their cargoes documented in detail. It was nearly impossible for ships to pass through the Sound unobserved, rendering this a unique data source for trade between the Baltic and North Seas. Origins and destinations were recorded at the level of ports rather than countries and cargoes were disaggregated into individual goods. I map 90,737 spellings to 3,085 unique ports and 143,855 spellings of commodities to 227 unique goods. I construct four aggregate sectors: labour-intensive and capital-intensive agriculture and manufacturing. I assume spatial separation in that agricultural goods are produced in regions' hinterlands and manufacturing goods in their urban cores. Arable farming is labour-intensive, whereas pastoral farming is capital-intensive agriculture; textiles are labour-intensive manufacturing, whereas metal works and ship building are capital-intensive manufacturing. From these records, I build a novel panel data set of Northern European regions' trade at the commodity level over 190 years to track trade after the plague.

I formulate two priors concerning trade. Plague-induced mortality should increase the relative cost of labour as there is no evidence of factor price equalisation. While no data are available for this particular plague outbreak, empirical evidence shows that wages indeed increased substantially after the negative labour supply shock of the Black Death (Jedwab, Johnson, and Koyama, 2022). The plague should then induce factor adjustments, with plagued regions increasing the capital-to-labour ratio within sectors and by shifting production and exports across sectors into capital-intensive goods. For overall exports, a reasonable prior is that exports contract after the plague. Higher wages as a manifestation of labour scarcity should reduce plagued regions' competitiveness and accordingly their exports. I test both priors in the trade panel data set I constructed and establish four novel empirical facts.

First, post-plague factor adjustments are visible in the composition of exports and confirm the adjustment predicted by the Rybczynski theorem. According to the Rybczynski theorem, a rise in the endowment of one factor leads to a more than proportionate output expansion in sectors using that factor intensively. The plague renders capital relatively more abundant, which should lead to an increased share of capital-intensive exports. By shifting the composition of production, trade permits an adjustment without requiring changes in regional factor prices. As I have evidence against factor price equalisation - wages rose in plagued regions - I will work with a Ricardian model instead. This model predicts the shift across sectors into capital-intensive goods as a result of differences in sectors' labour intensities and availability of productivity-enhancing technology. This shift is confirmed in my data. Second, plagued regions expand their market shares abroad and export larger volumes. This finding is surprising, considering that higher wages ought to have reduced competitiveness. I find, third, that this export expansion also takes place along the extensive margin, with plagued regions exporting a larger variety of goods. Finally, I find that a third of the export expansion is attributable to innovative goods which had never been exported before by a region. Thus, the plague shock appears to have induced a pattern of forced experimentation and innovation, contributing to a surprising export boom. I provide robustness results and evidence against mechanical explanations of my findings.

Several existing models struggle to explain this finding. In a Malthusian world, an adverse labour supply shock should increase wages and thus reduce regions' competitiveness. In a world characterised by increasing returns to scale, less populated regions should be less productive, and cities may unravel altogether. To explain these novel findings, I build a multi-sector

Ricardian model based on Eaton and Kortum, 2002, Costinot, Donaldson, and Komunjer, 2011, and Donaldson and Hornbeck, 2016. I model three factors of production: labour, capital, and investment capital, which captures capital upgrading and investments into machinery and innovation.

Crucially, I allow for changes in productivity which I argue to be necessary to explain my findings. Sectoral productivities are drawn from a Fréchet distribution at the variety-level and taken as given by producers. Faced with a higher relative cost of labour, producers in plagued regions employ relatively more capital and investment capital. While on average this increases the investment capital-to-labour ratio, producers in this model do not internalise the external effects this has on the sectoral investment capital-to-labour ratio. I suggest that the sectoral investment capital-to-labour ratio increases the scale parameter of the Fréchet distribution. However, I do not endogenise productivity as the procedure employed in the literature to recover productivities requires me to view them as a fundamental of the model (Costinot, Donaldson, and Komunjer, 2011). These recovered fundamentals have been projected onto observables (Chor, 2010), which I am unable to reproduce due to insufficient data. Instead, I propose a functional form for productivities that could be tested with better data. Importantly, I assume that the efficiency with which sectors translate a higher investment capital-to-labour ratio into productivity growth varies by sector: In arable agriculture, the potential of investments to increase productivities was severely limited by the lack of available technologies in this period (Gallardo and Sauer, 2018, Coleman, 1956). Atack, Margo, and Rhode, 2019 argue the same for labour-intensive manufacturing. Accordingly, investments in capital-intensive sectors should produce larger productivity increases as machines and technologies were more readily available.

I use this model to shed lights on the mechanisms operating to produce the surprising exports expansion. First, I discuss how wages increase in the model. With a labour share of 50% and a trade elasticity of 5, the median mortality rate of 36% increases wages by 5.7%. I present historical evidence on wage increases and population recovery after the plague. Second, I show that the Rybczynski effect operates in this model in that exports are shifted across sectors. The factor adjustment within sectors manifests itself in higher capital-to-labour and investment capital-to-labour ratios. In the absence of firm or input data, this increase is unobservable to the researcher. The factor adjustment across sectors is observable, however, and documented in the first empirical fact: the share of capital-intensive exports expands. This comes down to three channels. The labour cost channel sees exports of more labour-intensive sectors contract relative to less labour-intensive sectors. The productivity channel results in a sector with a greater efficiency at translating investment capital-to-labour gains into productivity growth expanding their exports more. Thus, even if all sectors employed the same production function, the productivity channel would still produce the export shift across sectors and differential productivity growth by sector. Counteracting these two channels are relative price effects as the model passes the relative price decline of capital-intensive goods on to the price index in destination markets. These general equilibrium effects are controlled for in all specifications. I present historical evidence supporting this shift: agricultural production shifted from arable to pastoral farming in post-plague Scania. Data on ship ownership confirms the model-predicted behaviour of capital stocks and the capital-to-labour ratio.

Third, the model predicts productivity growth as a result of an increased investment capital-to-labour ratio, differing by sector. Under the assumption of identical production functions, I back out productivity growth and show that productivities rose after the plague. Capital-intensive agriculture and manufacturing become more productive, whereas their labour-intensive counterparts stagnate. From this relationship, differences in the efficiencies with which productivities increase can be recovered. These confirm that capital-intensive agriculture (manufacturing) is more efficient at using investment capital to produce productivity gains than labour-intensive agriculture (manufacturing). I also discuss historical evidence for post-plague productivity gains, confirming the association between labour scarcity and productivity growth (Broadberry et al., 2014).

As a historical example of a friction on factor mobility, I study how the presence of serfdom shaped post-plague factor adjustments and productivity growth. Serfs were prohibited from moving to cities. Combined with higher mortality rates in cities, this kept cities particularly scarce in labour, whereas their hinterlands were more abundant in labour than they would have been in the absence of serfdom. I show that across all regions, the capital-intensity of manufacturing and agricultural exports increases after the plague. However, the capital-intensity of manufacturing exports increases faster under serfdom, whereas the opposite is true of agriculture. I find evidence for corresponding differences in productivity growth. This historical case study illustrates how policies that limit factor mobility shape adjustments to changed factor proportions.

I continue by discussing alternative mechanisms: directed technical change, venting out, and non-homothetic demand. I discuss their implications and present arguments against them. In the framework of Fieler, 2011, I test formally for the presence of non-homotheticity. I find no evidence for its presence and conclude that the mechanism I propose is best suited to explain my empirical findings. Specifically, I argue that a relative demand-driven explanation produces relative price effects that go in the opposite direction of a supply-driven explanation. In commodity-level price data by Allen and Unger, 2018 I show that prices evolve according to the supply-driven explanation proposed by this paper.

Finally, I present a counterfactual analysis. I establish that in the absence of a productivity channel, exports would indeed have contracted. This confirms the intuitive predictions of Malthusian models and the reasonable prior one may have for trade after a plague outbreak. Therefore, I suggest that the productivity channel is necessary to reconcile theory with empirics.

This paper proceeds as follows. The following subsection places my paper within the existing literature. Section 2 introduces the data and the historical context. Trade results are presented in Section 3. The model is introduced in Section 4. Section 5 presents the mechanism through the lens of the model and provides empirical and historical evidence. Section 6 holds the counterfactual analysis and Section 7 concludes.

1.1 Literature

Labour Scarcity & Technology

My findings relate to a long literature studying how labour scarcity interacts with technological progress. Habakkuk's seminal work studies the 19th century United States, where labour scarcity coincided with labour-saving machinery (Habakkuk, 1962). In a nutshell, the argument is that a high land-to-labour ratio in the United States raised the opportunity costs of labour in manufacturing. This in turn induced the development of machines that substitute capital for labour. Temin, 1966, opposing this mechanism, shows that in general equilibrium capital intensity does not depend linearly on a nation's resource endowment, thus casting doubt over the suggested link between land abundance and labour-saving technological progress. In the original argument, innovations are likelier to be labour-saving when labour is scarce (Habakkuk, 1962), which is formalised in Acemoglu, 2010. From a theoretical standpoint, Acemoglu, 2010 distinguishes technology as strongly labour saving if technological advances reduce the marginal product of labour. Instead, technology is strongly labour complementary if such advances increase the marginal product of labour. Acemoglu, 2010 shows that labour scarcity will encourage technological advances if technology is strongly labour saving, whereas the opposite is true when technology is strongly labour complementary. More generally, Taalbi, 2017 empirically supports that innovation is driven by the need to solve novel problems.

Recent work has sought to add causal identification to this debate. Franck, 2022 exploits plausibly causal variation in summer temperatures to analyse how labour scarcity may lead to technology adoption and innovation. Looking at 19th century cholera outbreaks in France, it is shown that higher cholera mortality had positive effects on technology adoption and innovation in agriculture, but a negative effect in industry. Franck, 2022 suggests that labour scarcity has a positive impact on the formation of human capital. Voth, Caprettini, and Trew, 2023 show empirically that army recruitment correlates with the adoption of labour-saving machines in industrialising Britain. Using geographical variation in warships' access to coastal areas, they identify the positive effect of labour scarcity on technology adoption. Supporting Acemoglu, 2010, they find no significant association with non-labour saving technologies. Finally, there are dynamic gains, as technology improved more rapidly in areas that adopted labour-saving machines.

The relationship between factor proportions, industrialisation, and growth lies at the heart of Allen, 2009. Allen considers Britain as a high wage, cheap energy economy, and argues that the technological innovations which were introduced specifically in Britain at the beginning of the Industrial Revolution were a result of these factor proportions. Labour was relatively scarce and expensive, whereas energy and capital were relatively abundant and cheap. Allen, 2009 argues that these factor proportions explain that the technological breakthroughs were developed and applied in Britain, with the objective to substitute cheap capital and energy for expensive labour. While this characterisation of the British economy and textile industry are subject to debate (Humphries and Schneider, 2020, Humphries and Weisdorf, 2019, Stephenson, 2018), the criticism focuses on the empirical assertion of relatively high wages and less on the economic logic of incentivising labour-saving technologies. Wage increases after plague outbreaks, instead, are well established (Jedwab, Johnson, and Koyama, 2022).

My paper relates to this literature in that the plague as a mortality shock created sudden and localised labour scarcity. I can track the economic consequences of this change in factor proportions through studying granular trade data. This allows me to suggestively link labour scarcity and investment capital-driven productivity gains in a general equilibrium framework. Linking growth to factor proportions in levels is complicated by the fact that fertility and population sizes have deep cultural determinants (Hajnal, 1965). My paper seeks to alleviate these concerns by instead studying a sudden and arguably exogenous decrease in labour supply. I thus contribute the first test of the Habakkuk thesis in an open economy setting.

Recovery After Shocks

The recovery of cities after large shocks is the subject of much academic inquiry. Urban population recovery, as found by Jedwab, Johnson, and Koyama, 2019 and Davis and Weinstein, 2002, may be an artefact of a unique spatial equilibrium and ultimately driven by several factors. In a Malthusian world with a unique spatial equilibrium and without productivity growth, higher wages will lead to higher fertility, predicting population recovery even without migration (Cantoni, 2015). Exports should fall along the intensive and extensive margin as higher wages would have forced selection into goods in which a city is most productive. Sectors employing labour more intensely should see the largest export decreases. As population recovers, wages would fall back to their pre-plague levels as the marginal product of labour falls. Trade patterns would then return, too. The two predictions of this type of model are therefore an export slump followed by recovery and the elimination of wage increases as soon as population recovery is achieved. My findings reject both predictions.

Voigtländer and Voth, 2012 instead suggest the existence of multiple equilibria in a Malthusian framework. Crucially, while their argument implies rising urbanisation rates after the plague, overall population never recovers to pre-plague levels. Their arguments further do not rely on technological progress or capital accumulation. Voigtländer and Voth, 2013 argue similarly for a feedback loop between higher income to more war and diseases to a higher land-labour ratio. Thus, Malthusian dynamics are at play, and it is argued that European particularities relating to fertility and mortality interacted with the political environment of small warring polities to permit lasting income gains (Voigtländer and Voth, 2009). Importantly, this argument suggests multiplicity of equilibria and a switch to an equilibrium with a permanently smaller population. Within this lower population equilibrium, Malthusian dynamics would still operate. An important prediction of Voigtländer and Voth, 2012 is a hump-shaped pattern for the relative price of goods produced in cities. The income effect increases demand for urban goods as wages rise after the plague and supply constraints lead to price increases. Over time, migration eases urban supply constraints and falling wages due to population recovery lower demand for urban goods. As urban goods from plagued cities should have become more expensive, non-plagued destinations should have sourced these goods from other, cheaper suppliers. This would be visible in lower, but recovering exports of urban goods from plagued cities. The adversely affected hinterland of cities should have contributed to this finding by demanding relatively more urban goods. Thus, their model, too, predicts an export slump followed by a recovery, which my data reject. I also directly test their price prediction and show in Table 4 that the plague produced a hump-shaped price pattern that goes in the opposite way: prices of capital-intensive goods decline compared to labour-intensive goods. This is consistent with a productivity growth differential but not with their account of a demand shift. While population recovery is not predicted by Voigtländer and Voth, 2012, plagued cities could return to their pre-plague growth path if technological progress was added and was consistently higher for plagued cities.

Alternatively, one could study this shock through the lens of a non-Malthusian model with multiple equilibria. New Economic Geography models such as Krugman, 1991 maintain that a large negative population shock could lead to cities disappearing entirely. At the lower population level, cities may no longer produce sufficient agglomeration benefits and may begin to slowly unravel, in line with theories of increasing returns to scale in city population (Davis and Weinstein, 2002). For a small enough shock, however, population may also recover in a NEG setting. When studying city populations using data by Bosker, Buringh, and Zanden, 2013, based on Bairoch, Batou, and Chèvre, 1988, I find that by 1800 plagued cities had recovered to their pre-plague growth paths and population levels, both absolutely and relatively to non-plagued cities. I reject that the plague shock may not have been large enough, as the median mortality rate lay at 36%. I therefore do not find support for multiplicity of equilibria.

My paper adds to this literature by stressing that plagued areas did not mechanically bounce back. Instead, they embraced the new factor proportions, innovated, and became more productive. As I find no evidence for multiplicity of equilibria, one might consider that this mechanism ensures uniqueness and plagued areas' return to their pre-plague growth paths.

Economic Effects of the Plague

This study on the Great Northern War plague also relates to previous work on the economic effects of the Black Death. The literature confirms population recovery after the Black Death (Jedwab, Johnson, and Koyama, 2019), a process that took on average about two centuries. The prediction of wage recovery, however, has not been fulfilled by some areas (Jedwab, Johnson, and Koyama, 2022). Following the Black Death, the North Sea area saw permanently higher wage levels, whereas in most of continental Europe wages appear to have dropped again as population recovered. Álvarez-Nogal, Prados de la Escosura, and Santiago-Caballero, 2020 finds that Spanish real wages dropped immediately after the Black Death. In the first two years after the Black Death, Jedwab, Johnson, and Koyama, 2022 find that wages actually dropped. They explain this through Smithian growth going into reverse as societal division of labour and much of economic activity in general came to a standstill.

Dittmar and Meisenzahl, 2019 stress the political economy of plague outbreaks, weakening elites and increasing demand for public goods. This will produce human capital spillovers and set city growth into motion. Voigtländer and Voth, 2012 argue that sustained wage increases were maintained by directly creating downward pressure on urban population, drawing migrants into unhealthy cities and creating trade and conflict that spread diseases.

Gelman, 1982 studies English exports after the Black Death outbreak of the mid 14th century. She uses trade figures to show that exports of both raw wool and finished cloths increased, while imports of cloths decreased. This shows that English agriculture shifted from arable into pastoral farming and thus increased its capital intensity in response to labour scarcity. In this particular case, the more crucial factor was land, which become more available, favouring the land-intensive process of wool production. It further appears that the decline in the domestic population does not account fully for the rise in exports, in line with a potential productivity increase. While I classify the production of woollen textiles as labour-intensive, which makes their export increase surprising, Gelman, 1982 suggests that their export success resulted from the increased production of wool and thus reduced input costs. Madsen, Robertson, and Ye, 2024 estimate the impact of regional plague outbreaks on wheat price differentials in a trade cost model. They find that plague outbreaks were associated with increased trade costs but to a very manageable extent. Regional trade and regional economic integration, therefore, were not severely disrupted by plague outbreaks.

My paper adds to this literature by focusing on granular trade in a general equilibrium framework and establishing novel empirical facts.

2 Context and Data

2.1 The Great Northern War Plague Outbreak

This paper studies the last plague outbreak in Northern Europe (Alfani and Murphy, 2017), which coincided with large-scale warfare. The war that broke out in 1700 affected most countries on the Baltic Sea. The two main factions were Sweden and her allies on the one side and Russia and her allies on the other side. Early campaigns led the Swedish army into the Baltic, later deep into the Polish-Lithuanian Commonwealth. As the war turned increasingly in Russia's favour, Swedish troops receded to Northern Germany. Ultimately, Russian troops marched far into Sweden. This so-called Great Northern War ended in 1721 and marked the end of Sweden as a great power. Swedish territories in the Baltic were lost to Russia, and about half of Swedish Pomerania to Prussia. This war was accompanied by a severe outbreak of the plague with a peak from 1709 to 1712, though the plague was present in Northern Europe until 1714.

The plague mostly followed army routes, reaching East Prussia in 1708, most of the Baltic Sea by 1711 and Hamburg by 1712. At this point, the Swedish army was on their way back from what is today Ukraine and sought refuge and fresh supplies in Swedish Pomerania. Appendix Figure 11 shows digitised army marching routes based on Spruner and Menke, 1880 and Barraclough, 1997 to illustrate how armies spread the plague. This historical evidence speaks towards war, not directly trade, spreading the plague. Figure 1 shows attacked and plagued cities in my sample. Seven cities were both plagued and attacked[1], with most plagued cities catching the plague from their hinterlands through which armies marched. At the beginning of Section 3 below, I will provide more rigorous evidence that this plague outbreak can be viewed as exogenous with respect to trade growth.

Plague & Mortality Data

I collect plague and mortality data, largely from Kroll, 2006 and Kroll and Grabinsky, 2007, presented in Appendix Table 10. While it cannot be ruled out that more cities suffered plague outbreaks than are recorded in these data, I suggest two arguments for why this is not a major issue. First, the secondary literature covers all areas around the Baltic, and it is reasonable to assume that a plague incident will have been recorded.[2] Second, incorrectly coding a plagued city as an unplagued one will only result in my estimates being an underestimate. Given that below I find an export expansion of plagued regions, the estimates would have been even larger had it not been for some plagued cities in the control group which also saw an export expansion.

I restrict myself to coding plagued cities and their mortality rates. While Raster, 2023 presents hand-collected rural mortality data for Northern Estonia, this remarkable data collection effort can hardly be extended to the entire Baltic region. The plagued Estonian ports appearing in the trade data are also recorded as plagued in the original sources consulted by Raster, 2023, and there are no plagued towns in his data that are not coded as plagued in mine. My assumption is therefore that urban mortality rates correlate strongly with mortality rates in the immediate hinterland and that urban plague outbreaks correlate with hinterland plague outbreaks. I consider this a reasonable assumption given that most cities caught the plague from their hinterlands which themselves caught it from armies. In my data, I cannot distinguish cities and their hinterlands, as trade is recorded at the port-level. Thus, mortality in a city's hinterland will be reflected in that city's trade.

For all but three cities, I know in which years the plague hit these cities, and for the three missing cities I set this year to the mode, which is 1710. Mortality estimates are available for half of plagued cities, with the median mortality rate at 36%. For the remaining plagued cities, I form predicted mortality rates by analysing how the timing of the plague, geographical controls, and importantly the proximity to army routes influence observed mortality rates. The proximity to army routes, displayed in Appendix Figure 11, is motivated by the finding that armies spread the plague across Northern and Central Europe. Appendix Table 11 shows the regression results based on which the predicted values are formed. Among plagued cities, mortality rates were significantly higher for cities further East and closer to army routes. In the

[1] These seven cities are Altona, Copenhagen, Narva, Riga, Stettin, Stralsund, and Wolgast. For Copenhagen and the first siege of Riga, there was no association with the plague, as these sieges occurred at the very beginning of the war in 1700 before the plague spread.

[2] Note that even Bremen's mortality rate of 0.7% is recorded, suggesting no omission at the lower end of the intensity scale.

Eastern Baltics, the average death toll for wide areas was up to three quarters of the population, though war, disease, and starvation are hard to distinguish in these numbers.

Below, both mortality estimates and a plague dummy will be used. Figure 1 shows which cities were affected by the war and the plague. Importantly, only 6 out of 676 cities in my sample were directly involved in the war, and three of these (Riga, Narva, Wismar) additionally suffered a plague outbreak. I therefore expect the destruction of physical capital to play only a minor role. Appendix Figure 12 and Appendix Table 12 show that plagued cities' populations were not significantly smaller by 1800 than those of unplagued cities, based on population data by Bosker, Buringh, and Zanden, 2013 and Bairoch, Batou, and Chèvre, 1988. These results also show that plagued cities were not significantly larger before the plague outbreak. The population data underlying these recovery results apply to cities, where mortality rates were higher in general (Voigtländer and Voth, 2012) and particularly so during the plague. Therefore, I interpret the plague as a negative labour supply shock mostly to cities.

Demographic Response

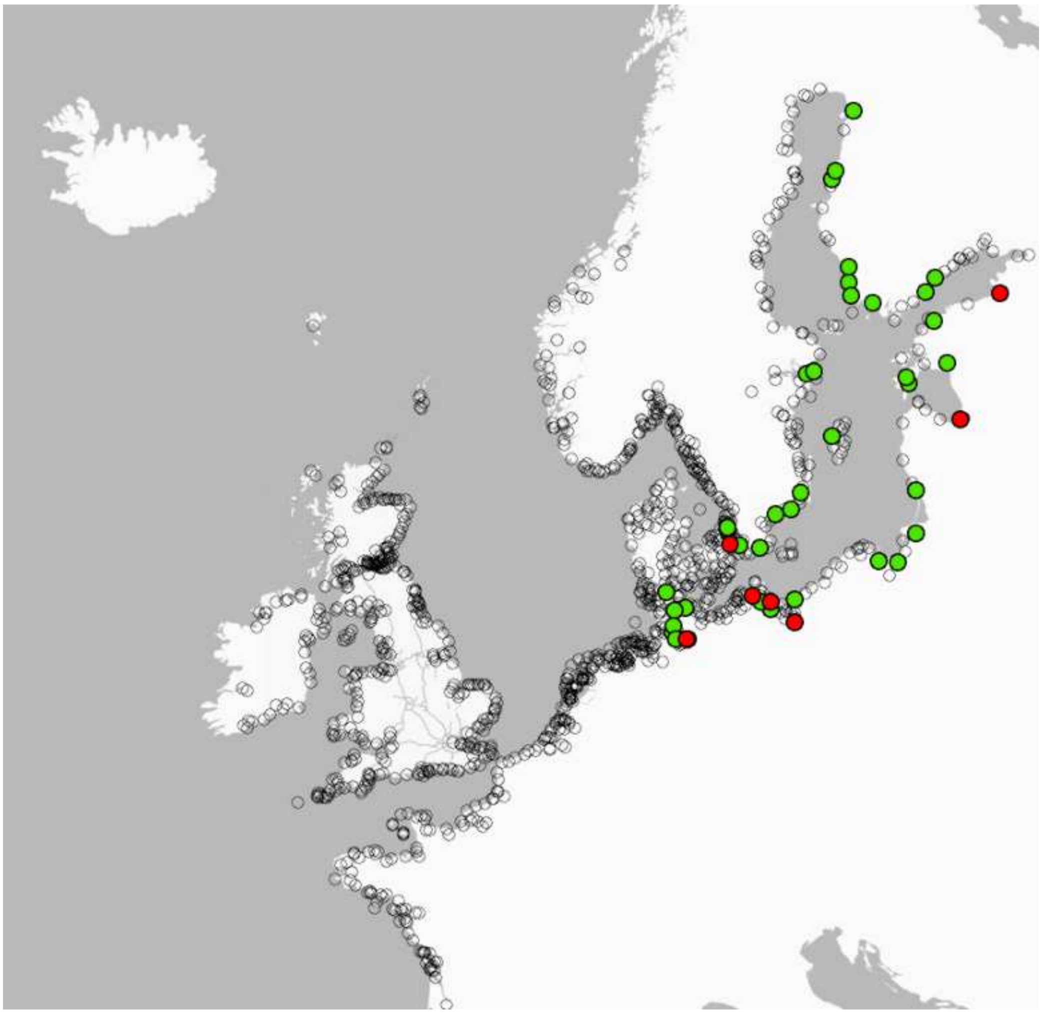
What was the demographic response to this plague outbreak? Theoretically, three main channels could contribute to the recovery of cities. First, an increase in fertility. Guinnane, 2011 argues for a positive elasticity of fertility with respect to income, implying that higher post-plague wages would increase fertility. However, there is reason to doubt the strength and direction of this relationship in the particular area studied here. There is evidence for increased human capital acquisition (Zanden, 2009) and delayed marriage (De Moor and Zanden, 2009) after the Black Death for the North Sea region, both of which may suggest falling fertility. While there is no direct evidence on Baltic cities, this area falls under the European Marriage Pattern in the classification of Hajnal, 1965.

While the effect on fertility is thus debatable, it appears reasonable that population growth accelerated nonetheless due to lowered mortality, the second channel. Waldinger, 2022 shows that higher agricultural productivity was associated with lower mortality in this region. Migration is the third channel through which urban populations may have recovered. Waldinger, 2022 also shows for England that warming increased agricultural productivity and drew in more migrants. While there is limited evidence for such migration across regions, I argue that rural-to-urban migration within regions may be sufficient to produce urban population recovery.

Through rural-to-urban migration, plagued regions' urbanisation rates may have increased. This is a prediction of Voigtländer and Voth, 2012 and explored empirically in Jedwab, Johnson, and Koyama, 2022. They find a range of 0.16-0.24 for the elasticity of the urbanisation rate with respect to mortality after the Black Death. This implies a 5.8-8.6 pp increase in the urbanisation rate in the long run. With median regional (urban) mortality of 20.15% (36%), urban population recovery only through rural-to-urban migration requires a 25% increase in the urbanisation rate[3]. Considering the European urbanisation rate of 11.9% in 1700 (Vries,

[3] The median regional mortality rate sits in the middle between two extremes: assuming no rural mortality

Figure 1: Plagued and besieged cities.



Notes: **Red:** siege & plague. **Green:** plague, no siege. **Empty circles:** neither.

2013), the range based on estimates in Jedwab, Johnson, and Koyama, 2022 is far higher than a 25% increase. This suggests that rural-to-urban migration may be enough to explain urban population recovery.

The Scanian Economic Demographic Database provides a uniquely granular source to answer this question (Bengtsson et al., 2014). Appendix Figure 13 shows annual births, deaths, and marriages for all of Scania. The 1710 peak in deaths is the plague outbreak studied in this paper. It was followed by a slight increase in marriages and births. This suggests a positive fertility response as less inhabitants gave birth to a larger number of children.

I also present results on the fertility channel at the parish level in Appendix Table 14. Births are the only variable in this dataset that is recorded at the parish-level going back to the 17th century. I analyse whether plagued parishes saw changes in the number of births after the plague. While not all parishes' plague status can be ascertained beyond doubt, I conservatively code the five urban parishes of Ystad, Malmö and Domsten as plagued, as their plague outbreaks are established (Kroll, 2006, Kroll and Grabinsky, 2007). I estimate a two-way fixed effects regression and find no significant fertility response at the parish level. As about a third of inhabitants of these parishes vanished, this implies a positive fertility response. However, this result is based on 59 parishes in one particular region of Sweden, limiting the external validity of this finding.

Insights from Other Plague Outbreaks

I conclude the exposition of this plague outbreak by comparing it to the Black Death outbreak of the 14th century. The Great Northern War plague outbreak's mortality rate of 36% is similar to the 40% mortality rate of the Black Death (Jedwab, Johnson, and Koyama, 2022). A crucial difference is the geographical dimension of these outbreaks. While the Black Death affected most of Europe, the Great Northern War plague outbreak was geographically very concentrated. This is a feature of later plague outbreaks also in Southern Europe (Alfani, 2023). Several reasons may have contributed to this, most importantly environmental and epidemiological changes affecting both immunity and transmissibility, and institutional responses (Alfani and Murphy, 2017). Alfani, 2022 stresses that later plague outbreaks did not bring about the sizeable reduction in inequality seen after the Black Death. He argues that local elites shaped institutions such that the distribution of income would be less responsive to mortality shocks. This may also have limited the geographic spread of later plague outbreaks, in particular through the erection of extramural plague houses. It is therefore not atypical for such a late plague outbreak to be geographically concentrated.

The economic consequences of plague outbreaks further depend crucially on how mortality interacts with sex, age, and socioeconomic status. While less is known about the Great Northern War plague outbreak, Alfani and Murphy, 2017 summarises the existing literature

would imply a 4.3% regional mortality rates given prevailing urbanisation rates; assuming identical rural mortality rates situates regional mortality rates at 36%. As in Voigtländer and Voth, 2012, I choose urban mortality rates as an upper bound to rural ones.

on other plague outbreaks. There is no evidence that mortality differed by sex and ambiguous evidence on age. Some studies find that the youngest and oldest were relatively spared, with higher mortality rates for (young) adults. Undoubtedly, crowding and lack of hygiene in poor neighbourhoods will have contributed to higher mortality rates there. For truly large mortality shocks, however, such as the original Black Death and some later plague outbreaks, there is clear evidence that elites, too, suffered high mortality. Pullan, 1992 describes that 17% of the members of the Great Council were killed in the 1630 Venice plague and that 40% of the members of the Great and Low Councils died in the 1656-57 Genoa plague outbreak. Considering the high mortality rates associated with the Great Northern War plague outbreak, I take this summary evidence as suggesting higher mortality rates for working age adults, with no consistent differences by sex or socioeconomic status. Raster, 2023 analyses plague mortality by age, sex, and social status for the Great Northern War plague outbreak. While geographically constrained to Estonia, he finds no significant differences in mortality rates. Frandsen, 2009 shows qualitative evidence confirming this finding. Thus, the compositional effects of the plague outbreak should have been very limited.

Beyond wage increases, the literature on the Black Death confirms increased living standards after the plague. Broadberry et al., 2014 document that the composition of consumed calories in England shifted towards dairy and meat. Consistent with an increased protein intake, Galofré-Vilà, Hinde, and Meera Guntupalli, 2018 show that the average height of Englishmen increased by 6.59 cm between 1348 and 1400. Both findings are suggestive of higher living standards and higher real wages after the plague.

2.2 The Little Ice Age

This paper recovers agricultural productivity estimates to study how economies recovered from a plague outbreak. It has to be noted that the decades during which this recovery occurred coincided with climate warming at the end of the Little Ice Age. As some areas warmed more than others, it is important to account for temperature change. To clean estimates of agricultural productivity, I use temperature data from Luterbacher et al., 2004 and Xoplaki, 2005. They provide quarterly temperatures over 500 years for 0.5° x 0.5° grid cells and I match cities to the four closest weather data observations. I define growing seasons as the average over spring and summer. Temperature is an outcome of heat transfer and thus, as an approximation, an average of nearby temperatures. Therefore, I construct regional temperatures as the average of the four closest points in the grid, weighting by the inverse distance to these grid points. Throughout, I am using growing season temperatures.

Beginning in the late Middle Ages, average temperatures in Northern Europe started falling with significant spatial variation. Northern and North-Western Europe saw particularly steep temperature declines. Waldinger, 2022 studies the effects this climate shock had on land usage, mortality, and aggregate trade volumes. The climate recovery from this Little Ice Age coincided with the recovery from the plague. The plague occurred between 1709 and 1712; by the mid-18th century temperatures in Northern Europe had recovered to their long-run averages.

The mean growing season temperature increase from 1700 to 1750 was 0.114°C, with the 10th and 90th percentiles at -0.031°C and 0.273°C, respectively. Mean annual temperatures increase by 0.117°C, with the 10th and 90th percentiles at 0.021°C and 0.266°C. Appendix Figure 14 shows regions by their quintile of warming over 1700 to 1750. This period of substantial warming coincides with regions' recovery from the plague, which lasted from 1708 to 1714. With a sustained climate recovery beginning in 1718, these two events largely overlapped. Temperature increases in a traditionally cold region marked by long winters raise agricultural productivity and lengthen growing seasons. Accounting for exogenous climate change in productivity estimates will permit me to focus on the plague-induced productivity changes. Note that the documented shift into capital-intensive production also in agriculture actually runs counter to climate warming. Under warmer temperatures, regions were likely to reverse their shift into pastoral farming that had occurred during the Little Ice Age (Degroot, 2018, Degroot et al., 2022). Instead, they would have shifted back into arable farming, in the opposite direction of what I document below.

2.3 Serfdom

I collect data on the presence of serfdom in the Baltic area to shed light on the spatiality of labour scarcity. Serfdom varied greatly over space and time, with the rise of the so-called second serfdom a notable historical development in this region. While Denmark (including Norway and large parts of modern-day Schleswig Holstein) is the only country in this area that re-introduced serfdom in 1733 (Gary et al., 2022), recent work by Raster, 2023 argues that labour coercion increased in Northern Estonia as a result of post-plague labour scarcity. My paper will not seek to disentangle this intensive margin of labour coercion due to insufficient data coverage across the whole region. Instead, I will conceptualise serfdom as a mobility restriction. I thus collect data on the presence of serfdom along the extensive margin, as increased labour coercion would not change the fact that unfree peasants in the countryside could not move to urban areas. While serfs accounted for less than 10% of the population in Estonia and 10-30% in Lithuania (Baten, Szołtysek, and Campestrini, 2016), a significantly higher share of the rural population will have seen their mobility severely restricted as a result of labour coercion (Raster, 2023).

Full labour mobility between a region's rural and urban area implies wage equalisation, at least up to moving costs. Once mobility restrictions are introduced, higher mortality in urban areas should imply that labour scarcity there leads to higher wages that are not equalised to those in the hinterland as peasants can no longer move. Denmark and Norway present a testing ground for this hypothesis of wage equalisation as serfdom was re-introduced in 1733. I use data by Gary et al., 2022 to show that there was no wage gap between unskilled urban and rural workers before the re-introduction of serfdom in Denmark in 1733, consistent with free movement between these areas. After serfdom was brought back, a wage gap appears, with scarcer urban unskilled labour being compensated significantly higher. Appendix Figure 15 compares nominal day wages in Danish skilling for farmhands and unskilled workers in Copenhagen. Specifically, this figure displays the ratio $wage_{ratio} = \frac{wage_{urban} - wage_{farm}}{wage_{farm}}$. While few observations are available before 1733, the picture that emerges is one of a significant post-serfdom urban wage premium, averaging 0.7 farm day wages. With full labour mobility, peasants would have moved to Copenhagen to benefit from these higher wages. Therefore, restricted labour mobility translates into an urban-rural wage wedge.

My main sources for the prevalence of serfdom are Raster, 2023 and Peters, 2022. In cases of disagreement between these sources, I side with Raster, 2023. This concerns three areas: the historical provinces of Estonia and Livonia (corresponding roughly to modern-day Estonia and northern Latvia, but excluding the island of Saaremaa) and Pomerania. While Peters, 2022 agrees with Raster, 2023 that these regions had serfdom throughout the 17th century, she considers them to not have featured serfdom in both 1700 and 1750. I choose to code these areas as having had serfdom, however. Raster, 2023 presents evidence for significant labour coercion in Estonia and Livonia during the 17th century and later. In Estonia and Livonia, the German peasant-owning nobility successfully resisted Swedish attempts to abolished serfdom in 1681 (Tammisto, 2020, Seppel, 2019). Almost a century after the incorporation of these areas into the Russian Empire, several laws were passed in the early 1800s that replaced serfdom with villeinage, ascribing peasants to a parish rather than an individual landowner. This, however, still left peasants without the ability to move. By 1819, Peasant Laws had come into force, abolishing serfdom and permitting freedom of movement. (Blūzma, 2019) There is evidence that even for several decades after this, mobility restrictions remained in place. (Merkel, 1800) Therefore, when judging serfdom from the perspective of mobility restrictions, Estonia and Livonia certainly were areas with serfdom and are classified accordingly. For Pomerania, Millward, 1982 notes that during the 17th century, all peasants were liable for unlimited service. In Swedish Pomerania, legislation permitted the sale of landless serfs as late as the 1780s, suggesting that serfdom was present in Pomerania, too. Appendix Figure 16 shows regions by their serfdom status: regions that did not feature serfdom before and after the plague, regions that did feature serfdom, and those that re-introduced serfdom in 1733.

2.4 The Soundtoll Data

A novel granular trade panel is constructed for this paper. I use Danish toll data, specifically the Soundtoll data. For a discussion of this data set, see also Marczinek, Maurer, and Rauch, 2024. The toll was introduced by the Danish King in 1429 on all ships entering or leaving the Baltic Sea at Helsingor (henceforth “the Sound”). It was nearly impossible for ships to pass through the Sound unobserved. Alternative routes are difficult to navigate and different tolls were applied there. Therefore, it is plausible that almost all trade between the Baltic Sea and the North Sea is recorded in these data. Also ships that were exempt from tolls were recorded. These data are very rich and cover the names of captains, goods transported, various tolls and fees, the home port of a ship, and the precise day of passage.

Classification of Goods

I first translate accounts of goods from Old Danish to English. From unclassified text data, I map 143,855 separate cargo descriptions onto 227 goods. Historical spellings are taken into account when cleaning these data. I then assign these to one of five sectors: labour-intensive agriculture, capital-intensive agriculture, labour-intensive manufacturing, capital-intensive manufacturing, and remaining unclassified goods.

The distinction between agriculture and manufacturing is primarily a spatial one. I assign goods most likely produced in rural settings into agriculture and those most likely produced in urban settings into manufacturing. While this is inevitably an assumption, there is historical evidence to back this up, such as Sweden's town economic policy that restricted textile production and metals processing to cities (Magnusson, 2007). The distinction between capital-intensive and labour-intensive goods follows the principle that capital-intensive goods require a high baseline amount of capital, contained in factories, furnaces, machinery, or tools. Labour-intensive goods, on the other hand, are limited in the degree to which labour can be saved. While factor intensity is a producer's choice in response to relative factor prices, I suggest that technology allows to classify most goods. In short, labour-intensive agriculture is essentially all of arable farming, whereas pastoral farming, mining, and processed foods including alcohols are capital-intensive agriculture. Labour-intensive manufacturing are largely textiles. Capital-intensive manufacturing produces goods such as processed metals, tools, and ship building materials. Figure 2 shows the most common goods for each sector by overall traded value, where the 2% of least common goods have been summarised by 'other' for legibility's sake.

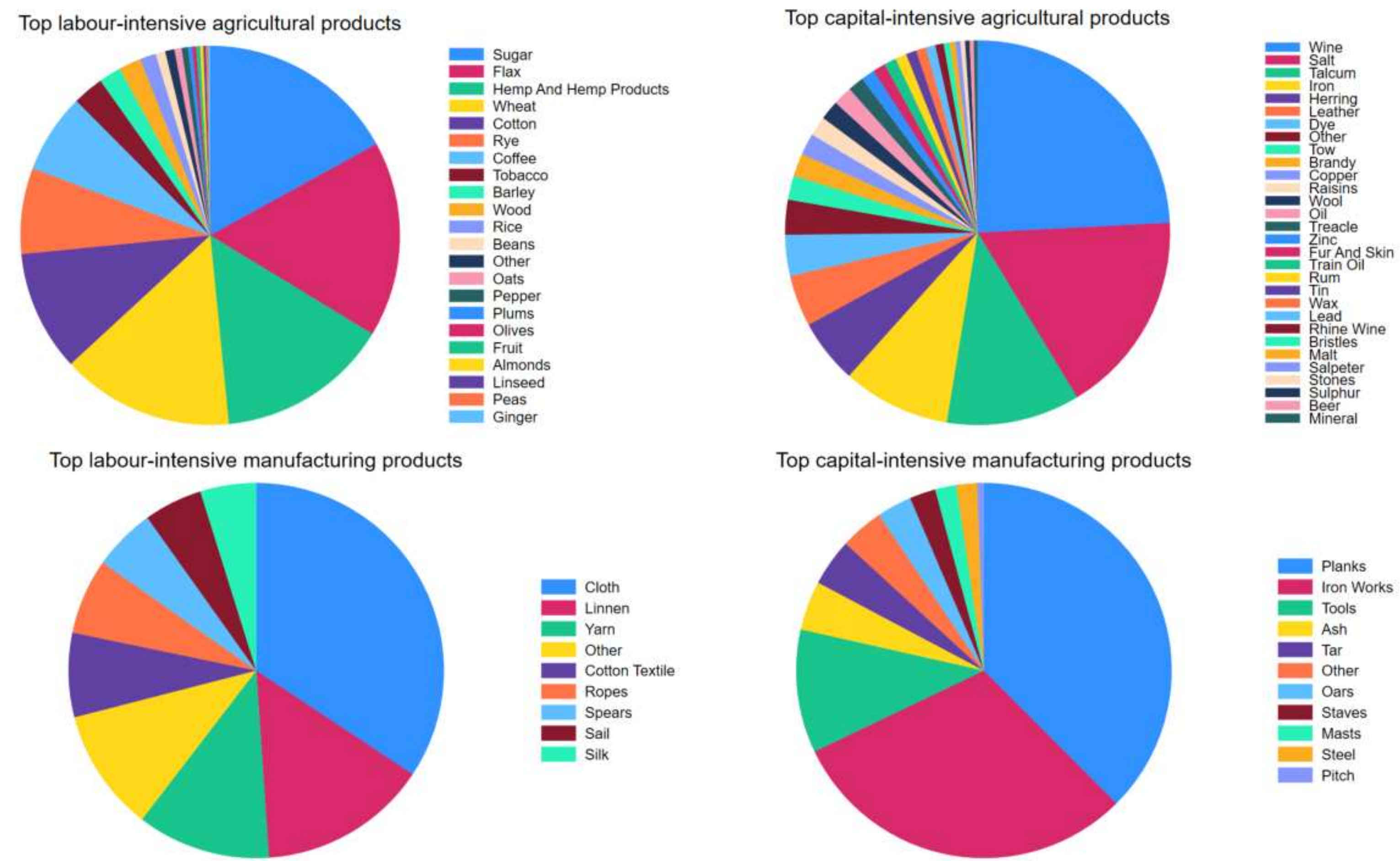
Between 1668-1750, about 55% of traded value is in labour-intensive agriculture, 27% in capital-intensive agriculture, 3% in labour-intensive manufacturing and 13 % in capital-intensive manufacturing. 2% of traded value is in unclassified goods, 99% of which are generic goods and mercery. All details on the classification and grouping of goods are reported in Section A.1.

Classification of cities, duties, and currencies

A second major avenue of data cleaning involves cleaning historical city names. I map 90,737 original city names to 3,085 unique place identifiers and assign them into 68 areas. Section B holds further details.

The Soundtoll data pose selection issues as trade is observed conditional on passing through the Sound. Thus, I only observe trade between the Baltic Sea and the North Sea areas. Due to the almost unavoidability of the Sound as a place of passage, I observe all trade between Saint Petersburg and London, but none between Amsterdam and London, as the latter are both on the same side of the Sound. However, the plague struck in Northern Europe on both sides of the Sound, and further for a lot of Baltic exports, such as agricultural goods and shipbuilding materials, a strong argument can be made in favour of these exports flowing in just one direction, namely to Western Europe, such that I am likely not missing out on a lot of exports. Further, the trade expansion of plagued cities established below would still be a surprising finding even

Figure 2: Goods by sector



Notes: This figure shows the most common goods per sector by overall traded value. The 2% least common goods have been summarised as ‘other’ for legibility’s sake.

if some of the increase came not from higher exports, but from a reallocation of exports from within the Baltic Sea to the North Sea. Given that the North Sea area is further away from the Baltic, exports overcoming larger distances and trade costs must have become more competitive. Finally, I present simulation results in Appendix Figure 34 on a simulated productivity increase in manufacturing. I show that both in the hypothetical full and in the actually observed sample the productivity increase is recovered. Importantly, in both cases the estimates are centred around the simulated effect, suggesting no bias is introduced by only observing trade flows passing the Sound. Thus, I conclude that the geographic particularities of the Soundtoll data do not drive my findings.

The Soundtoll data record duties paid by each passing ship, both fixed and proportional, disaggregated by goods on board. Most authors interpret the proportional duty as a proxy for value (Waldinger, 2022). The variation in proportional duties was quite limited. Suggesting a simple proportionality, the 'hundred money' was introduced in 1548, a 1% duty on value payable by unprivileged nations (Gøbel, 2010). Further, throughout the Soundtoll's existence, the ad valorem duty varied between 1-2%. Therefore, proportional duties are a proxy for value.

The historical literature, however, stresses that duty rates varied along measurable lines. In a robustness check, I flexibly allow for variation in the rate of duty and construct underlying values. Specifically, I postulate a functional form describing how proportional duties as recorded in the Soundtoll register relate to the actual value of a shipment. Details on tolls, duties, and currency conversion are given in Section A.3. I refer to this measure of trade value as underlying value and show robustness results, which are very similar to my main results. All details are held in Appendix A.4.

Currency concerns, as elaborated on in Section A.2, are minor as the vast majority of transactions are carried out in Danish coins. While there are reasons to doubt the accuracy of reported tolls and to suspect corruption, there were also institutions in place to mitigate incorrect reporting. Importantly, the Danish crown implemented a truth telling mechanism: the Crown could choose to purchase goods at the stated (and taxed) value to induce truth telling. One of the great advantages of value data is that they account for empty ships. Their value will be at 0, and the historical literature and my data confirm that a lot of ships entering Baltic ports do not carry exports with them when they leave again.

3 Trade

This Section presents novel descriptives on trade following a plague outbreak. Labour scarcity, resulting from the mortality shock, will have increased the marginal product of labour and accordingly wages, which is confirmed by the literature (Jedwab, Johnson, and Koyama, 2022). Capital, on the other hand, will have become cheaper relative to labour, inducing producers to adjust to changed relative factor prices. While the terms scarcity and shortage are used interchangeably in the literature (Caldara, Iacoviello, and Yu, 2024), I view shortages as an imbalance between supply and demand upheld by a friction or rigidity. Instead, I will speak of scarcity throughout, in the sense that labour became scarcer compared to capital after the plague.

Two adjustments could potentially appear. First, an adjustment *within* sectors. As long as factor prices are not equalised across regions, a higher capital-to-labour ratio will be employed in the production of goods. In the case of arable farming, this might take the form of swapping easily farmed land for more fertile grounds that require drainage, as seen in post-plague Sweden and described in Section 5. In manufacturing, machinery and tools reflect a common way of increasing the capital-to-labour ratio. The historical literature finds that the plague induced higher wages (Jedwab, Johnson, and Koyama, 2022), thus supporting the expectation of a higher capital-to-labour ratio in the absence of factor price equalisation. This adjustment *within* sectors is difficult to observe in trade data, as the researcher observes products but not their production methods. We can observe the second adjustment, however, which is a compositional effect taking place *across* sectors. Labour scarcity should induce regions to increase their production of capital-intensive goods. Some goods present few opportunities to substitute capital for labour and may no longer be produced. A researcher can observe this adjustment as the share of capital-intensive exports should increase after the plague. I note that the observed effect is an understatement as likely many labour-intensive products will have been produced with more capital-intensive methods after the plague. I will occasionally summarise both factor adjustments as capital-intensive production.

This adjustment across sectors is predicted by the Rybczynski theorem in trade theory. At constant relative goods prices, it states that the rise in the endowment of capital, compared to labour, ought to lead to a more than proportional expansion of output in capital-intensive sectors. This change in regional relative factor endowments does not lead to changes in regional factor prices as long as the region is sufficiently small. For agriculture, I classify arable farming as labour- and pastoral farming as capital-intensive, and assume that all agricultural production takes place in the countryside. For manufacturing, I distinguish labour-intensive production of textiles from capital-intensive metal works, ship building, and machinery-intensive production. I assume that all manufacturing production takes place in cities. Details on goods classifications can be found in Section 2.4. Overall, given higher wages, exports should fall, particularly in labour-intensive sectors. While cities saw higher mortality rates than their hinterlands, under full labour mobility this difference should disappear through migration, inducing the same change in labour scarcity and adjustments *within* and *across* sectors within a region.

These adjustments ought to be visible almost immediately after the plague hit a region. This plague outbreak's median mortality rate of 36% is comparable to that of the Black Death at 40% (Jedwab, Johnson, and Koyama, 2022), suggesting a sizeable increase in labour scarcity and at median an increase in the capital-to-labour ratio of 56% on impact. Therefore, the second margin of adjustment to labour scarcity, *across* products, should be visible. What makes this plague outbreak well-suited for a study with trade data is the fact that the Black Death affected all of Europe, whereas the Great Northern War plague outbreak was geographically very concentrated. Neither supply nor demand would have changed in most regions, permitting the researcher to focus on plagued regions' trade responses.

A key identification challenge in studying the effects of labour scarcity is to rule out that the plague and the associated mortality rate are endogenous to outcomes of interest, such as trade or urban growth. While I cannot fully rule out these concerns, I present some historical evidence and test for different pre-plague trajectories. In the historical literature, it has been argued that armies spread the plague and rarely directly targeted cities or trading hubs. Supporting this, I show in Appendix Table 11 that army proximity predicts plague mortality rates. In the special case of Swedish Pomerania, historians argue that the Swedish army was retreating from Poland-Lithuania to Pomerania to return to mainland Sweden, and only accidentally carried the plague to these lands. There is further no evidence of the plague having been used as a biological weapon. Generally, attacks on cities were rare (see Figure 1). I now present more rigorous evidence for population and trade growth. First, to-be-plagued cities did not differ in population size before the plague, as shown in Appendix Table 15. In levels, I find that to-be-plagued regions traded more. However, a future plague dummy does not predict different trade growth rates at either margin, as shown in Appendix Table 16. This motivates the set up as an event study, estimating on trade growth. The figures below will support my claim with the absence of pre-trends.

I now present novel descriptives on trade following a plague outbreak. These will take the form of an event study incorporating the gravity structure of trade. Specifically, I estimate the following event study:

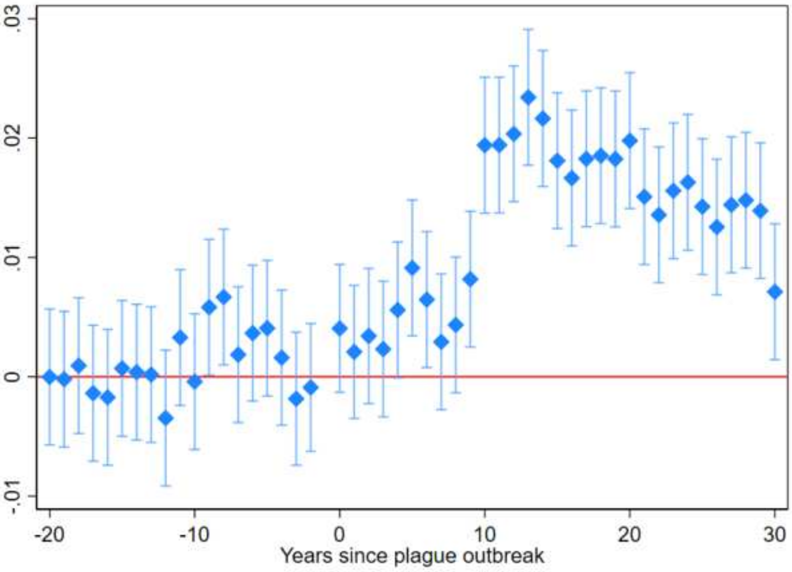
$$T_{ijt} = \alpha_{ij} + \alpha_{jt} + \alpha_{at} + \sum_{l=-20\backslash-1}^{30} \beta_l \cdot \mathbb{1}(K_{it} = l) + x_{it} + \epsilon_{ijt}, \tag{1}$$

where T_{ijt} is one of several outcomes for trade from origin i to destination j in year t. α_{ij} is a bilateral fixed effect, α_{jt} are destination-time fixed effects absorbing the demand side, and K_{it} is the time difference between the current year and the plague shock. ϵ_{ijt} is the error term. α_{at} are area-time fixed effects[4] These permit for different time trends for each area and thus permit heterogeneity by area. x_{it} are time-varying origin controls, in particular growing season temperature, longitude x year, and latitude x year. By controlling for temperatures, I seek to control for the effects of regional warming at the end of the Little Ice Age. Warming, however, should have resulted in a shift out of pastoral and back into arable farming (Degroot, 2018, Degroot et al., 2022) and would thus work against my findings. β_l are the outcomes of interest.

T_{ijt} are trade outcomes that differ across results. For Fact #1, T_{ijt} is the share of i's exports to j in year t that is capital-intensive. For overall trade, it is the share of pastoral farming and capital-intensive manufacturing exports out of all exports. For agriculture, it is the share of pastoral out of all farming exports, and similarly for manufacturing. For Fact #2, T_{ijt} is either the volume of exports from i to j in t, or the export share that origin i captures in destination

[4] 57 areas with 12 regions on average: provinces of Belgium, Finland, Ireland; regions of Denmark, England, France, Norway; states of Germany, each Baltic state, Scotland, and Wales, oblasts of Russia, autonomous communities of Spain, national areas of Sweden, and voivodeships of Poland. Details in Appendix B.

Figure 3: Share of capital-intensive exports.



Notes: Estimation of equation 1 on T_{ijt} as the share of i's export to j in year t that is capital-intensive.

j: $T_{ijt} = \frac{x_{ijt}}{\Sigma_{i \in I} x_{ijt}}$. This formulation of T_{ijt} as the share of exports from origin i in destination j in year t motivates the Ricardian model below, which will predict trade shares. For Facts #3 and #4, T_{ijt} is the number of different goods exported from i to j in t. On occasion, other outcomes may be used, which will be mentioned in the text.

Fact #1: Share of capital-intensive exports increases.

As an adverse shock to labour supply, the plague induced labour scarcity. This will have translated into higher wages and an increased capital intensity of production as long as factor prices were not fully equalised across regions. Figure 3 shows that the share of capital-intensive exports increases after the plague, with the first significant point estimate in the 4th year after the plague. This is predicted by the Rybczynski theorem. Here, T_{ijt} is the share of i's export to j in year t that is capital-intensive.

In the Appendix, I present further results on this fact. First, Appendix Figures 17a and 17b show that the capital-intensive share of exports increases both in manufacturing and in agriculture. However, it increases earlier and more strongly in manufacturing. Similarly, Appendix Figure 18 shows that capital-intensive exports rose relative to labour-intensive exports. This may partially reflect limits to the assumption on full labour mobility between sectors in a region, in that plagued cities, in which manufacturing takes place, remained more labour-constrained than their hinterlands. It may also reflect differences in technology in that factor adjustments *within* sectors may be more difficult in manufacturing, leading to the more visible adjustment *across* sectors. At a more granular level, I analyse the plague's effects on the composition of exports at the goods level in Appendix Figure 19.

Second, the increased share of capital-intensive exports could be caused by a contraction in labour-intensive exports and stagnation in capital-intensive exports. To the contrary, Appendix Figures 17c and 17d show that labour-intensive export volumes stagnated and capital-intensive export volumes increased. These results choose T_{ijt} to be the volume of exports. The fact that labour-intensive exports only briefly decrease and then recover attests to factor adjustments *within* sectors. The production of labour-intensive goods can to some extent take place with a higher capital-to-labour ratio, mitigating some effects of labour scarcity. As only adjustments *across* sectors are observable in these trade data, I regard the results presented here as a lower bound. At the same time, the relative stability of labour-intensive exports suggests a sizeable factor adjustment taking place within these sectors. As an example of a particularly labour-intensive manufacturing good, Appendix Figure 21 shows that exports of yarn dropped significantly after the plague. In Section 5, I present historical evidence relating this finding to data on Swedish farms. I show that after the plague farms switched out of labour-intensive rye and barley production and into raising cattle. These effects are stronger the closer a farm was located to a plagued city, implying that they increase in the mortality rate and thus the degree of labour scarcity. I conclude that the plague induced a shift across sectors as predicted by the Rybczynski theorem: when faced with an adverse mortality shock, regions increased their share of capital-intensive exports almost immediately. In Fact, estimating this relationship using the imputation estimator in Borusyak, Jaravel, and Spiess, 2021 yields an even stronger and indeed immediate shift into capital-intensive exports as shown in Appendix Figure 22.

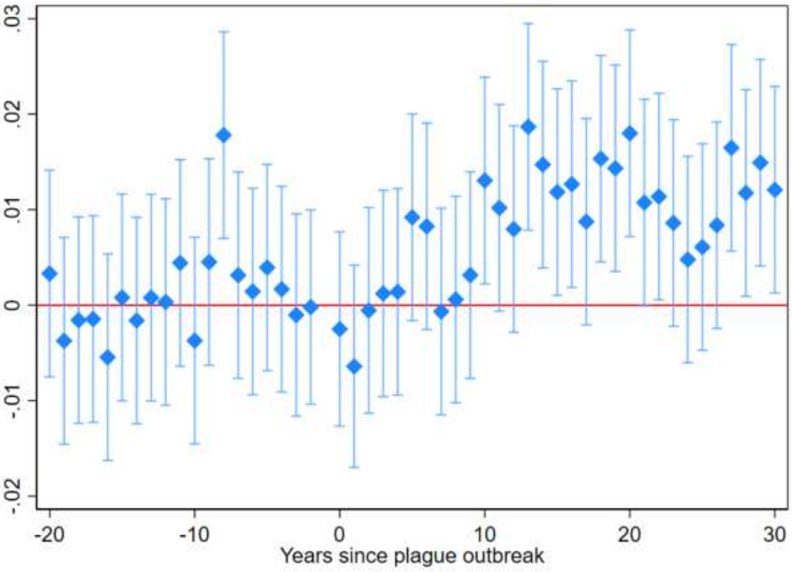
Fact #2: Plagued regions capture larger shares of destination markets.

Higher wages reflecting greater labour scarcity should have reduced plagued regions' competitiveness in destination markets[5]. To test this, I estimate equation 1 on market shares that origin i captures in destination j: $T_{ijt} = \frac{x_{ijt}}{\Sigma_{i \in I} x_{ijt}}$. Contrary to concerns of an export contraction, Figure 4 shows that plagued cities increased their export shares by about 1.5%, which is close to the mean export share of 1.35%.

The export expansion begins 5 years after the plague, though point estimates are insignificant. Ten years after the plague hit regions, which was mostly between 1709 and 1712, these regions captured significantly larger market shares in other regions. This implies a 5-10 year lag between the increase in capital-intensive exports and these larger market shares.

[5]Jedwab, Johnson, and Koyama, 2022 show that due to a collapse in market activity, real wages in England and Spain actually dropped immediately after the Black Death. This was a very short run response, however, lasting only two years. It is likely that if any such market unravelling had happened after the Great Northern War plague outbreak it would have been very brief as institutions were better prepared for a mortality shock.

Figure 4: Market shares in destination.



Notes: Estimation of equation 1 on i's share of j's imports, $T_{ijt} = \frac{x_{ijt}}{\Sigma_{i \in I} x_{ijt}}$.

A prime concern could be that I observe trade bouncing back after the plague. Note that the onset of the export expansion coincided with the end of the Great Northern War in 1721. Nonetheless, these results reject the hypothesis that trade simply bounced back. The war began in 1700 and I show 20 pre-periods before the plague, implying there is at least a decade of peace and normal trade during which cities did not display different export patterns. Appendix Figure 20a extends the pre-period to 40 years and similarly finds no pre-trends. The lack of pre-trends further supports my claim that the plague was largely spread by armies and not by trade, which would imply that cities trading more should have had a higher probability of contracting the plague.

In the Appendix, I present additional robustness results. Appendix Figure 20b implements the estimator by Borusyak, Jaravel, and Spiess, 2021. Chaisemartin and D'Haultfoeuille, 2022 point out that the summation of average treatment effects may involve negative weights, obscuring the relationship between the estimated coefficient and the ATEs. I allow for treatment effects to change over time but maintain the common trends assumption; I find that all weights are positive and conclude that the standard estimator is appropriate. Appendix Figure 20c constructs market shares from cleaned underlying value correcting for duty rates, as introduced in Section 2.4 and detailed in Appendix A.4. Rather than looking at market shares, I regress on T_{ijt} as export volumes in Appendix Figure 20d. The mean point estimate is 40 Danish dalers, with the mean value of exports per year at 13.5 Danish dalers and the mean value of non-zero exports per year at 277.

Appendix Figures 23 and 24 decompose the market share and intensive margin results into sectors. In manufacturing, market shares and export volumes only expand significantly in capital-intensive manufacturing. In agriculture, market shares grow in both capital- and labour-intensive agriculture. Export volumes of capital-intensive agriculture begin an upward trajectory immediately after the plague but are usually not significant, whereas labour-intensive agricultural export volumes dip initially and expand pre-plague levels after 14 years. When relating the export volume expansions by sector to the overall findings, I find that labour-intensive agriculture constitutes two thirds of the volume expansion. Labour-intensive manufacturing plays virtually no role. Capital-intensive agriculture and manufacturing contribute each a sixth of the volume expansion. The outsized role of labour-intensive agriculture is not surprising as it makes up 55% of traded value between 1668 and 1750. At a more granular level, Appendix Figure 25 presents results at the goods level.

Rather than relying on an event study, I also provide results from a panel regression in Appendix Table 17. Defining the plague as a bilateral dummy for whether at least one side suffered an outbreak, I include a full set of bilateral, origin-time and destination-time fixed effects, and regress export levels using both PPML (Santos-Silva and Tenreyro, 2006) and OLS. The results show that trade between cities increased after one side suffered a plague outbreak. Further, Appendix Table 18 shows results for the probability of a region exporting at all in a given year. After a plague outbreak, regions' probability to be active exporters increases significantly.

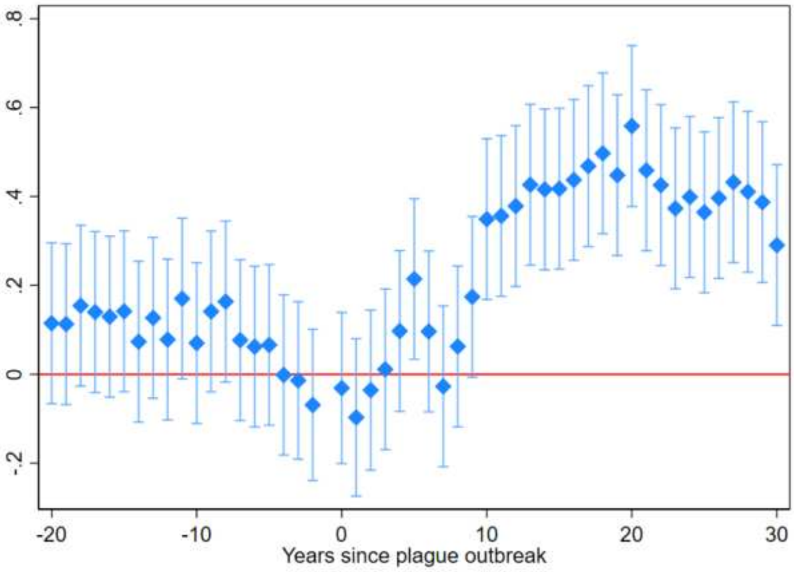
All these results confirm the finding that 5-10 years after the plague had induced a shift into capital-intensive exports, plagued regions captured a significantly larger share of destination markets. This is indicative of a productivity adjustment as plagued regions absolutely and relatively became more competitive compared to other regions exporting to the same destinations. Per capita exports increased even more and faster than export levels, as populations dropped and recovered only by 1800 (Appendix Figure 12).

Fact #3: Plagued regions export a larger variety of goods.

The export expansion documented above could take place along two margins. First, the intensive margin, with plagued regions exporting larger volumes of goods while keeping the number of goods unchanged. Second, the extensive margin, with plague regions exporting a larger variety of goods. I find that the extensive margin plays an important role: Figure 5 shows that plagued regions increased the number of goods they export. The mean number of goods exported per year is at 0.43, which is roughly the average point estimate.

A first significant point estimate appears in the 5th year after the plague but it takes 10 years for a sustained increase in the number of goods exported by plagued regions compared to non-plagued regions. Therefore, this extensive margin expansion does not coincide with the shift into capital-intensive exports documented in Fact #1. In fact, we should not have a strong prior as to the effects of factor adjustments *across* products on the number of exported goods, as some will be dropped and others added to production. Instead, Figure 5 suggests that the

Figure 5: Number of exported goods.



Notes: Estimation of equation 1, where T_{ijt} is the number of exported goods.

extensive margin expansion coincides with the expansion in market shares and export volumes found in Fact #2.

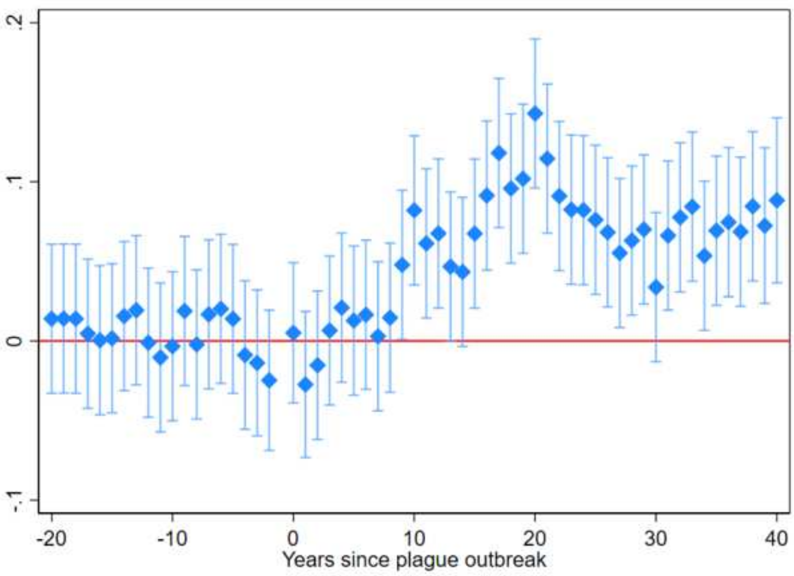
How do sectors contribute to this extensive margin expansion? Appendix Figure 26 decomposes the extensive margin expansion by sector and finds that capital-intensive manufacturing and agriculture and labour-intensive agriculture contribute each 30%, with only 10% of the increased number of exported goods attributable to labour-intensive manufacturing. The extensive margin expansion in labour-intensive manufacturing starts later and is much smaller than in capital-intensive manufacturing. Appendix Figure 27 shows results at the level of goods.

Fact #4: Exports of innovative products increase after the plague.

The extensive margin expansion raises the question whether it is already previously produced or novel goods that are being exported. On the one hand, region may more intensely employ existing knowledge in that they more regularly export goods that previously they would have exported less frequently. On the other hand, regions may create new production knowledge, which I will refer to as innovation below. Innovation would manifest itself in that plagued regions began exporting goods that they had not previously exported. To decompose these two channels, the more intense employment of existing knowledge and innovation, I partial out trade in goods that regions first exported between 1689, the 20 years before first year of the plague in my study area, and 1732, 20 years after the end of the plague.

Figure 6 shows that the number of new goods, not exported before the plague, increased significantly faster in plagued regions than in non-plagued ones. This difference in innovative goods is significant after 10 years, reaches a peak after 20 years, and then settles at a significantly higher level after 30 years. Note that this finding implies that even after 30 years, plagued regions continue to innovate more than non-plagued ones. This suggests that plagued regions began to produce and export a large number of new goods but eventually converged to a subset of the most successful ones. This pattern can be rationalised through forced experimentation, with labour scarcity pushing regions to experiment with new products. Consistent with a time lag in observed novel exports, Juhász, Squicciarini, and Voigtländer, 2024 find that the reorganisation of production takes time to be reflected in higher productivity. They argue for a process of trial and error followed by the diffusion of best practices across firms. In my case, one can therefore suppose an immediate push to experiment with new products that became visible in export data only with a time lag as production knowledge takes time to spread across firms.

Figure 6: New exports at the extensive margin.



Notes: Estimation of equation 1 on the number of exported goods. A new export is defined as a good first exported by a city between 1689, 20 years before the onset of the plague in my study area, and 1732, 20 years after the last plague year in this region.

How much of the intensive margin expansion in Fact #2 is driven by such new innovative exports? Appendix Figure 28 shows that 20 years after the plague, new post-plague goods make up a third of the intensive margin expansion. Two thirds can thus be attributed to more intensely employing existing production knowledge in that this part of the export expansion lies in goods already exported before the plague. Innovation contributes the remaining third of the export expansion.

Appendix Figures 29 and 30 decompose the innovation results by sector. Capital-intensive manufacturing and agriculture are the sectors in which most of the new goods extensive margin expansion takes place, with the other sectors only participating transiently. When tracking the quantities that these new exports constitute, however, it becomes clear that just under half of the export volume coming from new exports are situated in labour-intensive agriculture, with the remaining sectors capturing equal shares of the remaining expansion. This reflects again labour-intensive agriculture's size as a sector. Results at the goods level are shown in Appendix Figure 31. Disregarding time variation and analysing probabilities, Appendix Table 19 shows that plagued regions have a higher probability of beginning to export a good they had never exported before.

For all four facts, I present heterogeneity results in Appendix Table 20. By interacting a post plague dummy with pre plague exports, I find that while the effects are larger for regions that exported more before the plague, they continue to be significant and positive even for regions that had no exports before the plague. These facts all suggest a productivity change. Plagued regions captured a higher market share in destination markets and exported a larger variety of goods to these markets. This suggests that they became the least-cost producer for more markets and more goods. As wages increased due to labour scarcity, this is surprising, and can be rationalised through an increase in sectoral productivities. A third of the export expansion can be attributed to new goods, not previously exported. This is consistent with a narrative of forced experimentation.

3.1 Mechanical Explanations

The finding of export expansion could be driven mechanically by two forces, against both of which I will present evidence in turn. The first one relates to the selective nature of data observation in the Soundtoll data, in which trade is only observed upon passing between the Baltic and North Seas. The observed export expansion might reflect a reallocation of exports from within the Baltic Sea to the North Sea, explained by a severe economic downturn in the Baltics. In this case, regions' trade would appear in the Soundtoll data while it did not use to. There are several issues with this explanation. First of all, heterogeneity within sectors speaks against a simplistic reallocation of trade. Second, competing against existing exporters in new destination markets is not a costless adjustment and raises the question how regions became competitive in these markets. Third, the combination of new markets and longer distances implies that regions in the Baltics would not simply have become the least-cost suppliers of their goods in North Sea regions. They would have had to overcome the cost of distance and higher wages after he plague through higher productivity to be competitive in further away markets. These higher productivity levels would in turn imply that, if anything, I am underestimating trade expansion, as plagued regions would have also exported more to nearby harbours.

To more rigorously address this concern, I show simulation results in Appendix Figure 35 for a simulated productivity increase in manufacturing and its effect on trade outcomes. The simulated productivity increases raises manufacturing exports and should be picked up in trade regressions. I show that both in the hypothetical full and in the actually observed sample, reflecting that only trade flows passing the Soundtoll station were registered, the productivity increase is reflected in significantly higher manufacturing exports. For both samples, the point estimates are centred around the simulated effect, suggesting that no bias is introduced by only observing a subset of trade flows. Appendix Figure 34 runs similar simulations, focussing on whether sample selection affects the recovered productivity growth estimates. I conclude that geographical limitations of the Soundtoll data do not drive my results.

A second mechanical explanation for my finding concerns the role of harbours as export hubs. If a harbour attracts production from the hinterland to export it, some share of these products will be consumed in the city itself. Following a plague outbreak, this local consumption would have dropped, and, assuming constant hinterland production, exports should indeed have gone up. I challenge the notion that the hinterland's production would not have been affected. The plague was spread largely by moving armies, which plundered the hinterland. Mortality rates in cities were without doubt higher (Voigtländer and Voth, 2012, Kroll, 2006) but the hinterland's productive capacity must have been curtailed, too. Supply chains were not particularly long in the pre-industrial era, especially not far into the hinterland given high trade costs. Given the disruptions the plague would have caused in the hinterland, it appears unlikely that consistently high production levels would be exported rather than consumed.

To test whether export hubs may be driving my results, I exclude the top quintile of exporters over the sample period in Appendix Figure 32 and find similar results. This shows that also smaller harbours that are unlikely to have served as hubs saw an export expansion. The alternative explanation also predicts a decline in imports into plagued cities as local demand would have dropped. I show that imports did not drop but expanded in plagued cities along both margins, providing evidence against this alternative explanation.

4 A Ricardian Model

In this Section, I build a Ricardian model leaning on Eaton and Kortum, 2002, Costinot, Donaldson, and Komunjer, 2011 and Donaldson and Hornbeck, 2016. I first present the model in a general form and relate it to the empirical evidence presented before. I then impose additional assumptions and recover productivity growth to argue that labour scarcity was associated with productivity gains that explain the post-plague export expansion.

Throughout, I am dropping the t subscript indicating time for simplicity. There are many regions, i=1,...,I, and three factors of production: labour, L_{ik}, capital, K_{ik}, which is perfectly mobile across regions, and investment capital, I_{ik}, which is also perfectly mobile across regions. There are five sectors indexed by k: labour-intensive agriculture (LA), capital-intensive agriculture (CA), labour-intensive manufacturing (LM), capital-intensive manufacturing (CM), and unclassified goods (U). I begin by discussing my modelling choices.

Unique Spatial Equilibrium: Population recovery is an indicator of a unique spatial equilibrium[6]. I use city population data by Bosker, Buringh, and Zanden, 2013 to show that by 1800, plagued cities had returned to their pre-plague growth paths (Appendix Table 12)[7], which compares to a 200 year recovery after the Black Death (Jedwab, Johnson, and Koyama, 2019). For a small shock, recovery can be consistent with multiplicity, which I reject as median mortality lay at 36%. Thus, my model features uniqueness.

Factors and Sectors: The model features labour and two types of capital: capital, which contains fixed and working capital used in the production of goods, and investment capital, which entails fixed capital used to innovate and improve production processes. In the general part of this model, I will permit each sector k to have a different labour share γ_k and capital share η_k in the production function. Both types of capital are assumed to be freely mobile across regions and sectors. For each sector k=LA,CA,LM,CM,U the production function takes the Cobb-Douglas form:

$$P(L_{ik}, K_{ik}, I_{ik}) = A_{ik} L_{ik}^{\gamma_k} K_{ik}^{\eta_k} I_{ik}^{1-\gamma_k-\eta_k}. \tag{2}$$

A second differentiation assumes cities to produce manufacturing and hinterlands to produce agricultural goods. This assumption finds historical support in policies that restricted manufacturing to cities and viewed crafts and industrial production as purely urban activities. In Sweden, the textile industry was restricted to cities, with rural producers supplying only the input goods; similarly, urban blast furnaces were to be supplied by rural pig iron (Magnusson, 2007). To ensure this separation, a ‘town economic policy’ was introduced in the 17th century, which strictly banned rural trade. In a similar vein, Klein and Ogilvie, 2015 describe how urban institutions hindered rural crafts and industrial production in 17th century Bohemia. Therefore, manufacturing is assumed to take place in cities and agriculture in the countryside. Unclassified goods make up a fifth sector assumed to be produced in the countryside.

I define a region as a city and its hinterland. Larger cities on navigable rivers will naturally boast a larger hinterland and I assume that this does not change over the study period. Historical evidence suggests that cities hinterlands were only partially endogenously determined. Swedish cities, for example, enjoyed trade monopolies over their surrounding area, which only changed in 1765 when the Commodity Act was withdrawn (Magnusson, 2007). Throughout my study period, there is accordingly no recorded variation in the extent of these monopolies and the size of the hinterland. All 1,425 cities in the data are coastal or near a coast, and the average diameter of the hinterland is 25 kilometres. Table 1 summarises these assumptions.

[6]See Davis and Weinstein, 2002. Despite the evidence of population recovery after the Black Death in Jedwab, Johnson, and Koyama, 2019, Voigtländer and Voth, 2012 model multiplicity of equilibria in a Malthusian framework.

[7]More frequent population data are not available, so full recovery may have happened earlier.

Table 1: Spatial Separation & Capital Intensity.

		Labour-intensive		Capital-intensive
Region	City	Labour-int. manufacturing (LM)	$\eta_{LM} < \eta_{CM}$	Capital-int. manufacturing (CM)
	Hinterland	Labour-int. agriculture (LA)	$\eta_{LA} < \eta_{CA}$	Capital-int. agriculture (CA)

Notes: Assumptions on spatial separation, sectors, and factor intensities. η_k denotes the capital share in each sector k.

Labour Mobility: The plague induced labour scarcity and increased wages (Jedwab, Johnson, and Koyama, 2022). While the literature uses the terms scarcity and shortage interchangeably (Caldara, Iacoviello, and Yu, 2024), I consider a shortage to be characterised by a friction preventing price adjustments. Price controls, social norms, or nominal rigidities thus permit an imbalance between demand and supply. This model features perfect competition and will therefore speak of labour scarcity, induced by negative shock to labour supply.

Without migration, higher wages increase fertility in a Malthusian model (Cantoni, 2015). I consider this too restrictive. With full labour mobility across regions, higher wages attract migrants until wage differentials are eliminated. One would have to observe an almost immediate population recovery under this assumption, which is surely excessive. In urban population data, I find that population recovery was only achieved by 1800 on average. The literature on plague outbreaks finds significant wage increases (Jedwab, Johnson, and Koyama, 2022), implying local labour scarcity and the absence of factor price equalisation. Accordingly, I model labour as immobile across regions but mobile across sectors within a region. Plagued cities, where mortality rates were higher than in the hinterland, can recover via rural-to-urban migration. This is true in areas without serfdom. Under serfdom, however, peasants could not move to cities and thus a wedge between urban and rural persisted. I suggest that such wage differences can be conceptualised as a mobility friction.

In both settings, workers are assumed to freely move within agriculture and within manufacturing in a given region, implying wage equalisation[8]. Let $w_i^{CM} = w_i^{LM} \equiv w_i^M$ and $w_i^{CA} = w_i^{LA} \equiv w_i^A$. Without serfdom, all four sectors pay equal wages in a region. With serfdom, there are equalised wages within agriculture and within manufacturing. The wedge between urban and rural wages, ϕ_i, will be region-specific and depends, in particular, on mortality differences between the two parts of a region. ϕ_i captures both mobility and other frictions, such as the fact that serfs in the Eastern Baltic did not speak the language of city dwellers (German) and were not permitted to learn a craft, leaving them with little outside options to pursue by moving to cities. Equation 3 summarises the assumptions on labour mobility.

[8]While serfs are not paid wages and cannot move between different agricultural employments, the assumption here is that their lords efficiently allocate them to equalise the marginal products of labour between labour-intensive and capital-intensive agriculture.

Appendix Figure 15 shows that a wedge between urban and rural wages appeared in Denmark after the re-introduction of serfdom.

$$w_{iM} = \begin{cases} w_{iA}, & \text{without serfdom,} \\ (1+\phi_i)w_{iA}, & \text{with serfdom.} \end{cases} \tag{3}$$

Productivity: I argue that productivity growth is required to explain my empirical findings. Malthusian models with fixed productivity predict that an adverse labour supply shock should be followed by an export decline as wages increase. If only Heckscher-Ohlin forces were at play, one should observe only a reallocation to capital-intensive production but no overall increase in exports. As both are inconsistent with my findings, I build a Ricardian model with intra-industry variation in productivity. Each sector's output features in an infinite number of varieties, $\omega \epsilon \Omega$, which is exogenously given. Productivity A_{ik} is modelled as a random variable, drawn independently for each (i, k, ω, t) from a Fréchet distribution as in Donaldson and Hornbeck, 2016:

$$F_{ik}(z) = 1 - exp(-A_{ik}z^{-\theta}), \tag{4}$$

where $A_{ik} > 0$ and $\theta > 1$. A_{ik} captures fundamental productivity of region i in sector k, and encompasses productivity-affecting fundamentals that pertain to all producers in that region and sector. θ reflects intra-industry heterogeneity.[9] In this model, productivity is therefore total factor productivity and not factor biased (Acemoglu, 2002).

Investment & Productivity: Producers take the variety-level draw $A_{ik}(\omega)$ as given when allocating labour, capital, and investment capital. In the typical Cobb-Douglas fashion, factor prices equal marginal products for each factor[10]. Taking ratios reveals that the production of each variety ω becomes more intensive in both types of capital after a plague-induced wage increase:

$$\frac{I_{ik}(\omega)}{L_{ik}(\omega)} = \frac{(1-\gamma_k-\eta_k)}{\gamma_k i} w_{ik},$$
$$\frac{K_{ik}(\omega)}{L_{ik}(\omega)} = \frac{\eta_k}{\gamma_k r} w_{ik}.$$

[9]Costinot, Donaldson, and Komunjer, 2011 elaborate on the implications of assuming $\theta_k = \theta \forall k$.

[10]The first order conditions are:

$$\begin{aligned} \gamma_k P(L_{ik}, K_{ik}, I_{ik}) &= w_{ik} L_{ik}(\omega), \\ \eta_k P(L_{ik}, K_{ik}, I_{ik}) &= r K_{ik}(\omega), \\ (1-\gamma_k-\eta_k) P(L_{ik}, K_{ik}, I_{ik}) &= i I_{ik}(\omega). \end{aligned}$$

The investment capital-to-labour ratio rises also overall, with $I_{ik} = \int_{\omega \in \Omega} I_{ik}(\omega)$. While producers take the variety-level draw $A_{ik}(\omega)$ as given, I suggest that the Fréchet distribution's scale parameters A_{ik}, which govern the average sectoral productivity in region i across all varieties of sector k, are a function of the sector-wide investment capital-to-labour ratio. Importantly, I do not endogenise productivity. The procedure used in the literature to recover productivities requires the assumption of variety-level productivity draws from a given distribution (Costinot, Donaldson, and Komunjer, 2011). The recovered values have then been projected on observables (Chor, 2010). As I have no data on regional capital stocks and other observables, I will instead regress recovered productivity growth on a plague dummy and mortality rates as a measure of the shock to labour supply. The functional form for sectoral productivities suggested here could be tested precisely by projecting them on sector-region factor data.

To be fully consistent with producers taking their productivity draw as given when choosing how much investment capital to use which in turn affects the distribution's scale parameter, one could model a dynamic relationship with a time lag. This would introduce a fairly intuitive temporal shift into the sector shift and the gravity equation. While it ensures consistency, the additional insight from introducing the time lag is very limited. Therefore, I choose to stick to the simpler formulation here and write a repeated static model. I suggest that the efficiency with which investment capital translates into productivity gains varies by sector:

$$A_{ik} = \left(\frac{I_{ik}}{L_{ik}}\right)^{\beta_k}. \tag{5}$$

This reflects the assumption that sectors differ in the degree to which increased investments can move productivities. Technological barriers present the main hurdle here, permitting investment-led productivity growth more to some sectors than to others. In the production of wheat, for example, investment in the early 18th century had limited effects on productivity, as no modern farm machinery was available. According to Gallardo and Sauer, 2018 and Coleman, 1956, the scope for capital investment to increase agricultural productivity was severely limited in this period, with most productivity-increasing devices centuries old. Atack, Margo, and Rhode, 2019 concludes that few technologies were available before the 19th century to increase productivities in labour-intensive manufacturing. In capital-intensive iron and steel making, on the other hand, investments into more efficient furnaces more readily translate into productivity improvements.

Marginal Costs: Returns for both types of capital are equalised across regions, $r_i = r \forall i$ and $i_i = i \forall i$. Production uses Cobb-Douglas technology 2, where $A_{ik}(\omega)$ is drawn from probability distribution 4. Imposing capital returns equalisation across regions, the marginal cost of production in each sector is given by:

$$MC_{ik}(\omega) = \frac{(w_{ik})^{\gamma_k} r^{\eta_k} i^{1-\gamma_k-\eta_k}}{A_{ik}(\omega)}. \tag{6}$$

This is a model of constant marginal costs. My finding relates to the theory of venting out (Almunia et al., 2021), in which a domestic demand slump leading to an export boom is rationalised by non-constant marginal costs of production. In Section 5.2, I discuss how their mechanism fits my empirical results. I argue that one can better rationalise these findings through a mechanism linking factor adjustments to sectoral productivity growth without resorting to assuming non-constant marginal costs. My model will accordingly feature constant marginal costs as shown in equation 6.

Factor Market Clearing: The first order conditions solving the producer's problem at the variety level are virtually identical to the sectoral factor market clearing conditions. Taking ratios yields two capital-to-labour ratios, one for each type of capital:

$$\frac{K_{ik}}{L_{ik}} = \frac{\eta_k}{\gamma_k r} w_{ik}, \tag{7}$$

$$\frac{I_{ik}}{L_{ik}} = \frac{1-\gamma_k-\eta_k}{\gamma_k i} w_{ik}. \tag{8}$$

This result confirms that at a sectoral level, too, increases in wages relative to the constant prices of capital lead to higher capital-to-labour and investment capital-to-labour ratios. This is the theoretical underpinning of the factor adjustment *within* sectors discussed above.

Trade Costs: I assume the standard iceberg form, so for each unit of k sent from region i to j, only $\frac{1}{d_{ijk}}$ units arrive in j. Also, $d_{ii,k} = 1$, and no trade costs apply when transporting goods from the hinterland to the city. Trade costs may vary by sector, $d_{ijk} \neq d_{ijk'}$, but are symmetric, $d_{ijk} = d_{ji,k}$. The no-arbitrage condition $d_{il,k} \leq d_{ijk}d_{jl,k}$ is also imposed. As the time subscript has been suppressed here for legibility, trade costs are allowed to vary by sector and time, thus subsuming any potential tariffs.

Market Structure & Prices: Markets are perfectly competitive, $p_{ijk}(\omega) = c_{ijk}(\omega) = d_{ijk}MC_{ik}(\omega)$. Consumers in region j purchase a variety ω from its cheapest supplier location i:

$$p_{jk}(\omega) = \min_{1\leq i\leq I} c_{ijk}(\omega), \tag{9}$$

where $c_{ijk}(\omega)$ is as above and assumed to be strictly positive. Following Redding and Venables, 2004 and Donaldson and Hornbeck, 2016, consumer market access and firm market access are defined as the price indices[11]:

$$CMA_{jk} = (P_{jk})^{-\theta} = \chi_k \Sigma_{i=1}^{I} A_{ik}(w_{ik})^{-\gamma_k\theta} d_{ijk}^{-\theta},^{12} \tag{10}$$

$$FMA_{ik} = \chi_k \alpha_k \Sigma_{j=1}^{J} d_{ijk}^{-\theta} (CMA_{jk})^{-1} Y_j. \tag{11}$$

[11]Note that the existence of these CES price indices requires the assumption $\sigma_k < 1 + \theta$.

Preferences: The representative consumer in each region has a two-level utility function, where the upper tier is Cobb-Douglas and the lower tier is CES. α_k are the Cobb-Douglas weights in the upper tier and $\sigma_k > 1$ is the elasticity of substitution between differentiated varieties in the lower tier.[13] I assume $\sigma_k < 1 + \theta$. A continuum of these differentiated varieties ω are consumed.

Trade Flows: Following Donaldson and Hornbeck, 2016, trade flows take the gravity form:

$$X_{ijk} = \frac{\chi_k A_{ik}(w_{ik})^{-\gamma_k \theta} d_{ijk}^{-\theta}}{CMA_{jk}} \alpha_k Y_j. \tag{12}$$

Equation 12 implies that region i exports more to region j in sector k if it has a higher labour productivity, A_{ik}, lower trade costs, d_{ijk}, or lower wages, w_i, all relative to all other exporter regions i. Lower relative production and trade costs increase exports from i to j in k, and the Fréchet distribution's shape parameter θ, governing within-location productivity heterogeneity across varieties ω, determines the trade elasticity with respect to these costs. The Ricardian prediction, in essence, is that countries produce and export relatively more in sectors in which they are relatively more productive. Intuitively, if a region conquers large shares of far away markets in a sector, it must be very productive in it. Region i further exports larger volumes to region j if region j spends a lot in a sector and has a high $\alpha_k Y_j$, or low consumer market access in a sector, implying that region i does not face a lot of competition when exporting to region j.

Equation 12 can be used to recover productivity growth. Adding a time dimension to the procedure in Costinot, Donaldson, and Komunjer, 2011, I estimate:

$$X_{ijkt} = exp(\alpha + \delta_{ijt} + \delta_{jkt} + \delta_{ikt}) \times \epsilon_{ijkt}, \tag{13}$$

where all δ parameters are fixed effects and ϵ_{ijkt} is the error term. δ_{ikt} recovers relative productivity growth. All details can be found in Appendix D.1.

Wage Rate & Labour Force: Wages are determined sectorally. Market clearing conditions 7 imply that sectoral wages are determined by $w_{ik} = \gamma_k Y_{ik} L_{ik}^{-1}$. Goods market clear, too: $Y_{ik} = \Sigma_j X_{ijk}$. Combining these two market clearing expressions and plugging in firm market access as in equation 10 yields:

[12] $\chi_k = \left(\Gamma(\frac{\theta+1-\sigma_k}{\theta}) \right)^{\frac{-\theta}{1-\sigma_k}} r^{-\eta_k \theta} i^{-(1-\gamma_k-\eta_k)\theta}$

[13] This is as in Costinot and Rodríguez-Clare, 2014, where the elasticity of substitution can only vary across sectors, rather than as in Costinot, Donaldson, and Komunjer, 2011, where the elasticity can vary across sectors and locations.

$$w_{ik} = \zeta_k \left(\frac{A_{ik} FMA_{ik}}{L_{ik}} \right)^{\frac{1}{1+\gamma_k \theta}}, [14] \tag{14}$$

which implies that wages are inversely proportional to the sectoral labour force. The elasticity of wages with respect to sectoral employment is $-\frac{1}{1+\gamma_k\theta}$. Productivity and firm market access gains, on the other hand, will also increase wages. It is interesting to note how firm market access acts as a weight in this relationship. A given productivity increase in a sector in which a region has high firm market access will produce a larger wage increase than a productivity increase of the same size but in a sector with poor firm market access.

Within regions without serfdom, wages are equalised across sectors. Imposing this wage equalisation and combining labour market clearing conditions with equation 12 allows to write the relationship between sectoral employment L_{ik} and regional employment $L_i = \Sigma_k L_{ik}$ as follows:

$$L_{ik} = L_i \Big(1 + \Sigma_{k' \neq k} \frac{\gamma_{k'} A_{ik'} FMA_{ik'}}{\gamma_k A_{ik} FMA_{ik}} w_i^{-\theta(\gamma_{k'} - \gamma_k)} \upsilon_{k,k'} \Big). [15] \tag{15}$$

In the simplest case, assume $\gamma_k = \gamma \forall k$ and $\beta_k = \beta \forall k$. Assuming no changes in CMA_{jk} or Y_j such that FMA_{ik} is unchanged, equation 15 boils down to L_{ik} equalling a fixed share of L_i. Now, keep these assumptions but allow γ_k to differ by k. The wage term in equation 15 scales sectoral employment shares depending on labour intensity. For a sector k with $\gamma_k > \gamma_{k'} \forall k'$, an increase in wages increases the right-hand side as $-\theta(\gamma_{k'} - \gamma_k) > 0$. Accordingly, the share of regional employment allocated to the most labour-intensive sector rises as other sectors switch away from labour. I will call this channel the **labour cost channel**.

Instead permitting differences in β_k would result in a changed productivities ratio $\frac{A_{ik'}}{A_{ik}}$. Even with $\gamma_k = \gamma \forall k$ and $\eta_k = \eta \forall k$, the proportional shift into investment capital and increased investment capital-to-labour ratio would increase the productivities ratio in equation 15 if $\beta_{k'} > \beta_k$. In other words, even a symmetric labour scarcity increase will shift regional employment, namely into sectors with a high efficiency of translating investment capital into productivity gains. I refer to this as the **productivity channel**.

5 Mechanisms

In this section, I present the mechanisms which I suggest resulted in plagued regions seeing an export expansion. I combine theoretical results from my model with historical evidence.

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[14] $\zeta_k = \left(r^{\eta_k} i^{1-\gamma_k-\alpha_k} \right)^{\frac{-\theta}{1+\gamma_k\theta}}$

[15] $\upsilon_{k,k'} = \left(r^{\gamma_k+\alpha_k-\gamma_{k'}-\alpha_{k'}} i^{\alpha_{k'}-\alpha_k} \right)^{-\theta}$

Step #1: The Plague Induces Labour Scarcity

The Great Northern War plague outbreak reduced urban populations by 36% on average. I assume an average regional mortality rate of 20%.[16] Neither my model nor the empirics below support factor price equalisation. Theoretically, plague-induced labour scarcity increases the relative price of labour. Equation 14 shows that the elasticity of wages with respect to sectoral employment is $\frac{-1}{1+\gamma_k\theta}$. Supposing $\gamma_k = 0.5$ and $\theta = 5$, a 36% decrease in sectoral employment therefore increases sectoral wages by 5.7%.[17] Increased labour scarcity should induce wage increases, which is confirmed by the literature.

Empirical Evidence

Population data only cover a fraction of cities once a century (Bairoch, Batou, and Chèvre, 1988). I propose the number of captains reporting to live in a region as a proxy providing annual data[18]. Figure 7 shows the results of an event study on the number of captains. Considering the pre-plague average of 15 captains per region and year, the point estimates for the plague represent a 50% population drop. Further, the number of captains climbed back to pre-plague levels after 15 years. Thus, this proxy overstates both the population shock and recovery, as captains were highly skilled and mobile. Nonetheless, Figure 7 confirms the drop in population followed by a gradual recovery.

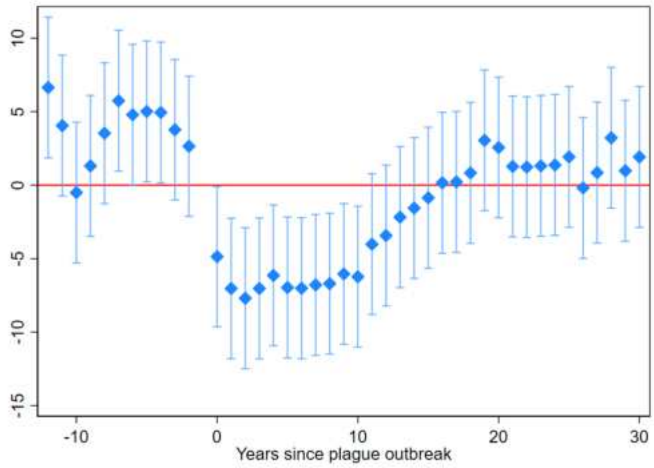
As to wages, model-based wage rises are low compared to what has been found for the Black Death at a similar mortality rate (Jedwab, Johnson, and Koyama, 2022). While the capital-to-labour ratio rose also after the Black Death, Jedwab, Johnson, and Koyama, 2022 caution against concluding immediate wage increases. From a Smithian perspective, high mortality disrupted trade and increased transaction cost. This process of disintermediation should affect those sectors most whose productivity depends on extensive division of labour. They show that real wages in England and Spain dropped immediately after the Black Death. This very short run response lasted only two years, however. Following Alfani and Murphy, 2017, I suggest that market unravelling would have lasted even shorter after the Great Northern War plague outbreak as institutions were better prepared for a mortality shock. I conclude that increased labour scarcity translated almost immediately into higher wages.

[16] This is in the middle between the upper and lower bound. The mortality estimates in Appendix Table 10 pertain to cities, not regions. As Voigtländer and Voth, 2012, I assume that mortality rates where on average lower in hinterlands. Assuming the median urban mortality rate of 36% to hold for regional population L_i is thus an upper bound. Bairoch, Batou, and Chèvre, 1988 finds a European urbanisation rate of 11.4% in 1700, similar to the 11.9% in Vries, 2013. As a lower bound, if there had been no mortality in the hinterland, regional mortality would lie at 4.3%.

[17] Equation 15 displays the equilibrium relationship between sectoral and regional employment and discusses the channels through which labour scarcity affects employment shares.

[18] This is a self-reported variable in the Soundtoll data and interpreted as the home port as in Marczinek, Maurer, and Rauch, 2024. To only count captains once, I omit observations in which first name, last name, and region are duplicates in a given year.

Figure 7: Dynamics of population recovery after the plague: number of captains as proxy for population.



Notes: Event study with area-year and region fixed effects on the number of unique captains' last names living in a region. Captains with the same first and last name from the same region in the same year are assumed to be duplicates and thus dropped.

There is evidence from the Black Death that wage increases were real and increased living standards. Broadberry et al., 2014 show that dairy and meat provided a larger share of calories in England after the plague. Galofré-Vilà, Hinde, and Meera Guntupalli, 2018 document an average height increase of 6.59 cm between 1348 and 1400. Both of these findings are consistent with higher real wages after the plague.

Step #2: Production Becomes More Capital-Intensive

I now discuss how the model relates to the adjustment across sectors into capital-intensive exports. Labour scarcity was followed by an increase in capital and investment capital intensity along two margins. First, higher capital-to-labour ratios were used, which I refer to as a factor adjustment *within* sectors. This is unobservable empirically as I do not observe production methods or input data but is predicted by the model in market clearing conditions 7, restated here:

$$\frac{K_{ik}}{L_{ik}} = \frac{\eta_k}{\gamma_k r} w_{ik},$$
$$\frac{I_{ik}}{L_{ik}} = \frac{1-\gamma_k-\eta_k}{\gamma_k i} w_{ik}.$$

These capital-to-labour and investment capital-to-labour ratios have an elasticity of 1. Thus, a 10% increase in wages translates into a 10% increase in these ratios.

Second, a shift into capital-intensive sectors occurs, which I refer to as a factor adjustment *across* sectors. This shift is predicted by the model. I pick the example of labour-intensive and capital-intensive manufacturing. Taking ratios of gravity equation 12 and plugging in equations 5 and factor market clearing yields:

$$\frac{X_{ijCM}}{X_{ijLM}} = \xi w_{iM}^{-\theta(\gamma_{CM}-\gamma_{LM})} w_{iM}^{\beta_{CM}-\beta_{LM}} \frac{CMA_{jLM}}{CMA_{jCM}}.^{19} \tag{16}$$

Both adjustments produce the adjustment predicted by the Rybczynski theorem: capital and investment capital became relatively more abundant in plagued regions and the sectors that use them more intensely expand their output. The second shift is a result of wage increases through two channels. First, capital-intensive sectors expand as they have smaller labour shares. This is the first term in equation 16, $w_{iM}^{-\theta(\gamma_{CM}-\gamma_{LM})}$, and follows immediately from the fact that the input bundle used in capital-intensive sectors has a smaller labour share. This is the **labour cost channel** discussed above. This channel is switched off when setting $\gamma_k = \gamma \forall k$.

Second, capital-intensive sectors expand as higher wages increase the investment capital-to-labour ratio. This, in turn, increases productivities as per assumption 5. For $\beta_{CM} > \beta_{LM}$, the increased investment capital-to-labour ratio increases productivity in capital-intensive manufacturing more than in labour-intensive manufacturing. This results in the term $w_{iM}^{\beta_{CM}-\beta_{LM}}$ in equation 16. As long as the efficiencies with which increased investment capital-to-labour ratios translate into productivity growth differ between sectors, this **productivity channel** will further increase the expansion of capital-intensive sectors.

In general equilibrium, there is a third channel operating on the demand side in unplagued destination j. The ratio $\frac{CMA_{jLM}}{CMA_{jCM}}$ will decrease, counteracting to some extent the shift into capital-intensive exports. The plague-induced manufacturing wage increase weighs more heavily on the contribution an origin makes to a destination's market access in a labour-intensive sector. Beyond that, differences in β may lead to slower productivity growth in labour-intensive sectors. Both work to decrease the ratio $\frac{CMA_{jLM}}{CMA_{jCM}}$. In other words, plagued regions' labour scarcity and productivity advances increase the relative prices of labour-intensive compared to capital-intensive goods. This **relative price channel** reduces the value of capital-intensive exports to j compared to labour-intensive exports. Importantly, I control for this channel operating on the demand side by estimating equation 1 with destination-time fixed effects. Thus, empirically the first two channels prevail.

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[19] $\xi = \frac{\left(\frac{1-\alpha_{CM}-\eta_{CM}}{\gamma_{CM} i}\right)^{\beta_{CM}}}{\left(\frac{1-\alpha_{LM}-\eta_{LM}}{\gamma_{LM} i}\right)^{\beta_{LM}}} \left(r^{\eta_{CM}-\eta_{LM}} i^{\gamma_{LM}+\alpha_{LM}-\gamma_{CM}-\alpha_{CM}}\right)^{-\theta} \frac{\chi_{CM}}{\chi_{LM}} \left(\frac{d_{ijCM}}{d_{ijLM}}\right)^{-\theta}$

Capital Stocks

How did capital stocks respond to labour scarcity? Combining market clearing conditions 7 and sectoral wages 14 reveals:

$$K_{ik} = \frac{\eta_k \zeta_k}{\gamma_k r} \Big(A_{ik} FMA_{ik} \Big)^{\frac{1}{1+\gamma_k \theta}} L_{ik}^{\frac{\gamma_k \theta}{1+\gamma_k \theta}}. \tag{17}$$

Equation 17 thus confirms that capital stocks drop with sectoral employment, but less than one for one, as the elasticity is $\frac{\gamma_k \theta}{1+\gamma_k \theta} < 1$. While capital stocks decrease - post-plague capital is so abundant that to earn return rate r some of it freely flows to other regions - this elasticity explains why the capital-to-labour ratio increases. The same result can be established for investment capital.

While no administrative or firm data are available to test this feature, I employ a proxy for regional capital stocks[20]: the number of ships owned in a region. Ships are an expensive infrastructure investment and highly mobile[21]. Appendix Table 24 shows that the plague led to a larger number of ships registered in a region, which I interpret as an indication of capital accumulation. Focussing on the time path of capital accumulation, Figure 8 shows that for two decades during and after the plague, there were significantly less ships registered in plagued regions' harbours.[22] 50 years after the plague, there were significantly more ships registered in previously plagued regions' harbours, and this higher capital stock remained in place until the mid 19th century when the trade data end. The model showed that capital stocks decline with population, but with an elasticity of less than 1. Indeed, the number of ships declined less and recovered faster than the number of captains, implying an increased capital-to-labour ratio.

Empirical Evidence

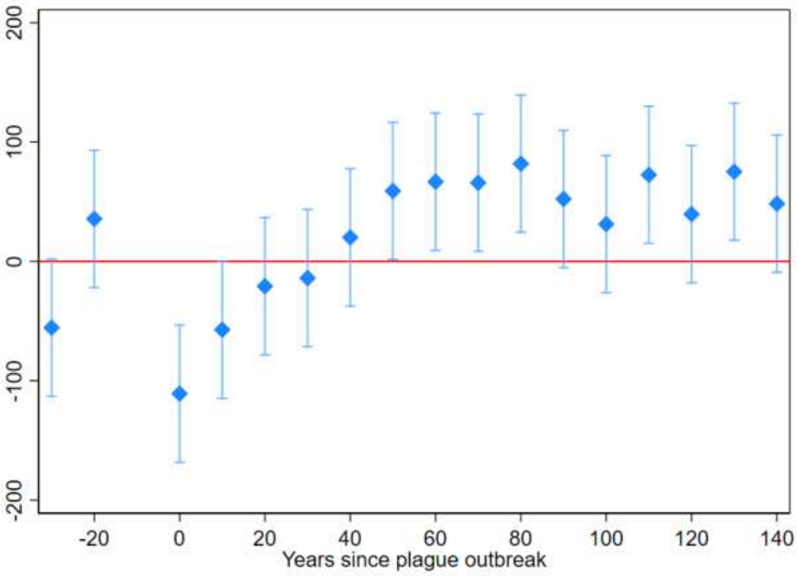
In trade data, the shift *across* sectors is observable: Figure 3 showed that the share of capital-intensive exports overall and within agriculture and manufacturing rises almost immediately after the plague. I find historical evidence from Swedish farm-level data for a factor adjustment *across* sectors: out of labour-intensive agriculture and into capital-intensive agriculture. I present a case study for the province of Scania in Southern Sweden. In 1712, Ystad and Malmö suffered plague outbreaks, with mortality rates of 38% and 35%, respectively. To test for an adjustment *across* sectors, I draw on micro-data by Olsson and Svensson, 2017. Three products are consistently reported: rye and barley, which are labour-intensive, and calves, which are capital-intensive agricultue. Figure 9 shows that in the years after the plague, Scania's farms reduced their production of rye and barley and shifted significantly into raising calves.

[20] I cannot differentiate this by sector. For expositonal clarity, I present theoretical results for sectoral capital stocks. The channels relating the allocation of regional capital stocks across sectors are the same as those for labour. See equation 15.

[21] Note that the export expansion is not mechanically linked to an accumulation of ships. Merchants from other regions could sail to productive locations and ship their goods abroad.

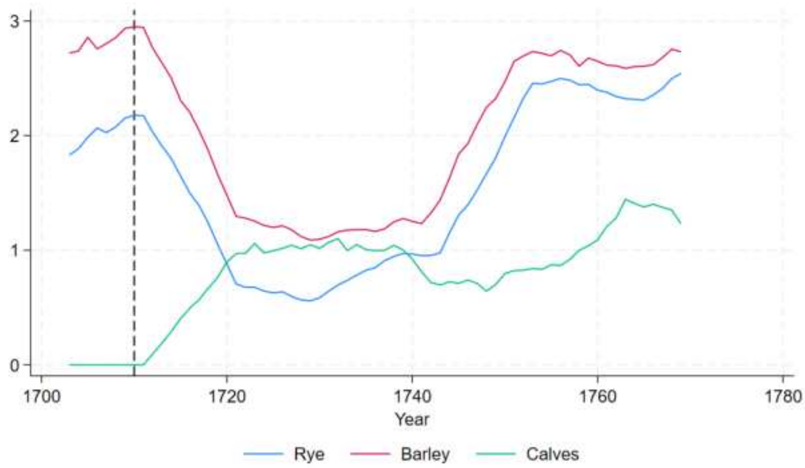
[22] Decade 0, when treatment occurs, covers 1710-1719, with the plague peaking between 1710 and 1712.

Figure 8: Dynamics of capital accumulation after the plague: number of ships as proxy for the capital stock.



Notes: Event study with area-time, region, and decade fixed effects on the number of ships registered in a harbour in levels. Decade -1 is omitted as the reference decade.

Figure 9: Agricultural production in Scania became more capital-intensive.



Notes: Figure 9 covers 119 Scanian farms and the composition of their production.

This shift is predicted by the Rybczynski theorem[23] and also underscores that insights from trade data carry over to production data. To test the link with labour scarcity, I construct for each farm i a measure of distance, $plaguedist_{it}$, to both Ystad and Malmö:

$$plaguedist_{it} = \Sigma_j Distance_{ij} * Plague_{jt}. \tag{18}$$

Farms located closer to plagued Ystad or Malmö will have lower values of $plaguedist_{it}$ after the plague hits. As the plague spread across space, I expect greater proximity to plagued cities to be associated with higher mortality. Accordingly, the shift into capital-intensive agriculture should be increasing in mortality and thus proximity to plagued cities. In Appendix Table 26, I regress production values of calves, rye, and barley on $plaguedist_{it}$ and find that proximity to plagued cities is associated with higher growth in calves production and lower growth in rye and barley production[24] Thus, I find that the shift into capital-intensive production correlates positively with the degree of labour scarcity.

Step #3: Productivity Grows More in High β_k Sectors

I propose that an increased investment capital-to-labour ratio, resulting from a factor adjustment to labour scarcity, raises productivity growth. With both the labour cost and the productivity channels active, I am unable to recover productivity growth. Similarly, serfdom complicates the separation of wages from productivities. In the remainder of this section, I therefore make two assumptions to recover productivity growth as a fixed effect from non-linear regressions of trade values[25]:

1. All sectors have the same labour share, $\gamma_k = \gamma \forall k$.[26]
2. **Either:** There is no time variation in the labour mobility friction, $\phi_{it} = \phi_{it'}$ and $\phi_{i't} = \phi_{i't'}$.
3. **Or:** The labour mobility friction does not vary within areas, such that $\phi_{ikt} = \phi_{jkt} \forall (k, t)$ and i,j within the same area.

My assumption is that sectors differ in the efficiency with which they translate a higher investment capital-to-labour ratio into productivity gains:

[23]The same pattern was also observed in English agriculture after the Black Death (Clark, 2016).

[24]Note that the overall regional trend out of rye and barley and into calves is accounted for by Scania-wide time trends.

[25]Appendix D.1 details how gravity equation 12 can be decomposed into sectoral productivity growth.

[26]An especially strong assumption would be to also let $\eta_k = \eta \forall k$. All sectors would then operate the exact same production function. Capital-intensity as defined above then comes no longer down to different factor shares, but solely to different efficiencies β_k with which sectors turn investment capital-to-labour increases into productivity growth.

$$A_{ik} = \left(\frac{I_{ik}}{L_{ik}}\right)^{\beta_k}.$$

If all sectors operated the exact same production function, proportionate shifts into investment capital would still produce different productivity gains: those sectors with higher β_k efficiencies would see faster productivity growth than those with lower β_k. I expect this efficiency to be higher in capital-intensive than in labour-intensive agriculture and higher in capital-intensive than in labour-intensive manufacturing. At the time, few machines and technologies existed in labour-intensive agriculture and labour-intensive manufacturing that could have led to investments increasing productivity growth (Atack, Margo, and Rhode, 2019, Gallardo and Sauer, 2018, Coleman, 1956). To test the impact of the plague on sectoral productivity growth, I estimate:

$$\text{productivity growth}_{ikt} = \delta_k plague_{it} + \alpha_{ik} + \alpha_{akt} + \epsilon_{ikt}, \tag{19}$$

where productivity growth$_{ikt} = \delta_{ikt}$ are the fixed effects[27] recovered from equation 13. α_{ik} are region-sector fixed effects, absorbing time-invariant region-sector-specific determinants of productivity, such as availability of resources or time-invariant institutions. α_{akt} are area-sector-time fixed effects, absorbing area-wide time variation in sectoral productivity. These absorb sectoral productivity growth across an entire area[28], such that I compare the plague's effects of productivity growth within an area. Example of this are area- and country-wide economic and trade policies. Crucially, if there is time variation in the serfdom-induced mobility friction, these are absorbed by α_{akt} as long as they do not vary within areas. ϵ_{ikt} are the error terms. δ_k is the coefficient on the plague.

Table 2 shows significant productivity growth in capital-intensive sectors after the plague. There are big differences within agriculture and manufacturing depending on their capital-intensities. Capital-intensive agriculture sees significant productivity growth, whereas labour-intensive agriculture stagnates. Labour-intensive manufacturing productivity growth falls significantly[29], whereas capital-intensive manufacturing productivity growth accelerates.

The difference between labour-intensive and capital-intensive sectors is indicative of different β_k values. Different productivity growth effects come down only to differences in β_k under the assumption that all sectors use the same production function and factor shares. In that case, the shift into investment capital in response to wage increases is symmetric across sectors, and can be expressed in terms of wage increases as follows:

[27] As described in Appendix D.1, I pick unclassified goods, London, and the year 1668 as the reference sector, region, and time, such that $\delta_{ikt} = \frac{A_{ikt}A_{LON,k,1668}A_{i,U,1668}A_{LON,U,t}}{A_{i,k,1668}A_{LON,k,t}A_{i,U,t}A_{LON,U,1668}}$.

[28] 57 areas with 12 regions on average: provinces of Belgium, Finland, Ireland; regions of Denmark, England, France, Norway; states of Germany, each Baltic state, Scotland, and Wales, oblasts of Russia, autonomous communities of Spain, national areas of Sweden, and voivodeships of Poland. Details in Appendix B.

[29] As for all values, this is a statement of growth relative to the reference sector of unclassified goods. While productivity in levels is not identified, I suggest that labour-intensive manufacturing saw no overall productivity drop, as its investment capital-to-labour ratio also rose.

Table 2: Impact of plague on sectoral productivity growth, by sector and factor intensity.

	Agriculture				Manufacturing			
	Labour-intensive		Capital-intensive		Labour-intensive		Capital-intensive	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Plague Dummy	0.168		1.000***		-1.306***		0.400*	
	(0.229)		(0.268)		(0.213)		(0.218)	
Mortality Rate		0.331		2.286***		-2.899***		0.969*
		(0.553)		(0.648)		(0.516)		(0.527)
Fixed Effects:								
– Region	✓	✓	✓	✓	✓	✓	✓	✓
– Area x Year	✓	✓	✓	✓	✓	✓	✓	✓
Observations	34,922	34,922	34,932	34,932	34,932	34,932	34,932	34,932

Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The dependent variable is log sectoral productivity growth. The independent variable is first a plague dummy that equals 1 for plagued regions after the plague hit. The second independent variable is the mortality rate, which for half of regions is imputed as the predicted value from regression results presented in Appendix Table 11. Denmark and Norway have been dropped from the sample as they reintroduced serfdom in 1733.

$$log\Big(\frac{A_{ikt}}{A_{ikt'}}\Big) - log\Big(\frac{A_{ik't}}{A_{ik't'}}\Big) = \big(\beta_k - \beta_{k'}\big)log\Big(\frac{w_{it}}{w_{it'}}\Big). \tag{20}$$

Within manufacturing and agriculture, sectoral wages are always equalised. Subtracting the point estimates in Table 2 and supposing a 50% wage increase[30] allows to back out

$$\beta_{CM} - \beta_{LM} = 2.08$$
$$\beta_{CA} - \beta_{LA} = 4.265.$$

Thus, the extent to which capital-intensive agriculture is more efficient than labour-intensive agriculture at turning an increased investment capital-to-labour ratio into productivity gains is more than twice as large as the same comparison in manufacturing. This may come down to technological barriers that are hard to overcome in manufacturing before the Industrial Revolution, limiting how capital-intensive manufacturing could use investment-led productivity gains[31]. The assumption on the time invariance of serfdom implies that Denmark and Norway are excluded in these results as they reintroduced serfdom in 1733. Appendix D.1 details how wage data by Gary et al., 2022 can be used to adjust manufacturing productivities in these areas for this change in serfdom. With this adjustment applied, Denmark and Norway can

[30] This is what Jedwab, Johnson, and Koyama, 2022 find for England 50 years after the 1348 Black Death.

[31] Taking the same ratio between a manufacturing and an agricultural sector requires values for the serfdom-induced mobility friction.

be included in the sample. Appendix Table 25 adjusts for the urban-rural wage wedge that appeared after the reintroduction of serfdom and finds very similar results to Table 2 above.

Empirical Evidence

I will now discuss historical evidence on a productivity increase after the plague. The association between population loss and productivity increases relates to Clark, 2016, who shows in English wage and price data that the Black Death was followed by substantial efficiency gains. Broadberry et al., 2014, too, find that agricultural productivity rose significantly after the Black Death.

For this particular plague outbreak, Appendix Figure 36 shows a brief drop in total agricultural output per farm, adjusting for size, based on Scanian farm-level data by Olsson and Svensson, 2017. However, agricultural production surpasses pre-plague levels after a few years. Given that fewer workers are producing more agricultural products and that the size of farms is accounted for, this is consistent with a productivity effect. In Sweden overall, agricultural output per capita began a sustained increase only in the 1720s, a few years after the plague (Magnusson, 2007). There is evidence of increased adoption of machinery in this period, suggesting an increased investment capital-to-labour ratio. The post-plague decades in Sweden saw the adoption of metal ploughs, early threshing machines and modern farm building designs that improved the efficiency of raising live stock. Further, Swedish agriculture departed from strip farming in an overtly labour saving methodological shift[32]. While the historical literature does not permit to decompose this important shift by region, it is noticeable that plagued Scania again stands out as an early adopter.

An important role is played by land reclamations. Magnusson, 2007 notes that historically, it was not the most fertile land that was farmed in Sweden, but the land that was most easily farmed. In the decades after the plague, historians observe land reclamations and but no overall increase in the amount of cultivated land. Costly drainage systems were put in place to make fertile, yet inaccessible land suitable for farming. This required heavy investments that were not previously possible and may be reflective of a higher investment capital-to-labour ratio. Reclamations of fertile land imply that labour input was shifted onto on average more fertile farm land. The literature believes that this adjustment accounts for a large part of Sweden's observed post-plague productivity increases.

Sweden's industry, too, experienced growth. Textile factories became the biggest employers in Stockholm in the mid-18th century and Norrköping rose to be Sweden's Manchester. Textile schools spread throughout the land, increasing human capital levels in industrially relevant matters. One particular industry that saw important changes was ship building. Using data on ships from the Swedish East India company, I show in Appendix Figure 37 that the vast majority of ship yards built in Sweden after the plague years was built in previously plagued

[32]Previously, farmers had to sustain long commutes to individual strips of land that were intentionally scattered across the land so as to provide insurance to individuals by giving access to different soil types.

regions, indicating high relative amounts of investment capital[33]. These also accounted for the production of the largest ships and the most productive ones, as measured by the number of trips to East Asia that they made successfully.

5.1 Factor Adjustments & Serfdom

This paper proposes an investment capital-driven mechanism that turns a higher post-plague investment capital-to-labour ratio into productivity growth to explain the otherwise surprising export expansion of plagued regions. Sectors adjust to changed factor proportions and employ more capital and investment capital. Importantly, labour scarcity in cities will attract migrants from the hinterland. What are the effects of factor mobility frictions in this framework? To answer this question, history provides us with an institution that severely limited the mobility of one factor in particular, labour, between cities and their hinterlands: serfdom. In this section, I analyse how the mechanism proposed in this paper may differ for regions with serfdom. I classify regions by their serfdom status as described in Section 2.3. Appendix Figure 16 displays this classification.

While serfdom had many facets and varied across both time and space, the aspect I will focus on here is the fact that rural-to-urban migration was severely limited. This came down to several aspects. On the one hand, serfs were usually bound to their lords' lands, either explicitly or implicitly through expected labour contributions. Additionally, serfs were usually not permitted to learn a trade, limiting their outside options as moving to cities was relatively unattractive for unskilled farm workers. Finally, many areas that traditionally featured serfdom, such as modern-day Estonia and Latvia were divided along ethnic lines between cities and their hinterlands. Most cities in this area were founded and populated by German-speaking urbanites, whereas Latvian and Estonian were spoken in the hinterlands. Accordingly, formal institutions and cultural barriers limited the number of rural dwellers that would move to cities in regions with serfdom.

I have previously made an assumption on the relationship between wages in the agricultural sector of the hinterland and those in the urban manufacturing sector. Without serfdom, free movement of workers will equalise these wages; with serfdom, I assume a wedge of ϕ_i between both wages. Appendix Figure 15 shows evidence that after the 1733 re-introduction of serfdom in Denmark, a previously non-existent wage wedge appeared between wages of unskilled workers in Copenhagen and in the hinterland. Accordingly, I assume $w_{iM} = (1 + \phi_i)w_{iA}$.

Mortality rates were surely higher in cities than in rural areas (Voigtländer and Voth, 2012). Without serfdom, mortality differences would quickly have been equalled out through wage equalisation. Labour mobility between sectors within a region accordingly equalises labour scarcity across sectors. I refer to this form of labour scarcity as *absolute* labour scarcity, as for all sectors, labour has become more scarce. With serfdom, however, labour mobility does not

[33]Construction of the Polhemsdockan in Karlskrona began in 1717, five years after the plague hit the city. This dry dock used pumps rather than tides and is considered by some the Eighth Wonder of the World.

equalise labour scarcity. People die in both cities and hinterlands, inducing absolute labour scarcity in both areas. Additionally, however, cities suffered from *relative* labour scarcity. Workers from the hinterland could not equalise wages between sectors. Too many workers would remain in the hinterland and too few would move to cities. Put differently, labour would be artificially scarce in cities and artificially abundant in rural areas. Thus, *relative* labour scarcity manifests itself in a wage wedge that captures precisely this institutionally upheld difference in factual labour scarcity.

Comparing two regions, one with and one without serfdom, with the same mortality rate, we therefore should expect the share of workers in agriculture to be higher in the region with serfdom and the share of workers in manufacturing to be higher in the region without serfdom. Plagued cities in regions with serfdom remain relatively scarcer in labour, whereas their rural counterparts become relatively abundant in labour. The strength of the shift into capital-intensive exports therefore depends on the presence of serfdom. I revisit the result from Step #3 above for both sectors:

$$\frac{X_{ijCM}}{X_{ijLM}} = \xi w_{iM}^{-\theta(\gamma_{CM}-\gamma_{LM})} w_{iM}^{\beta_{CM}-\beta_{LM}},$$
$$\frac{X_{ijCA}}{X_{ijLA}} = \xi w_{iA}^{-\theta(\gamma_{CA}-\gamma_{LA})} w_{iA}^{\beta_{CA}-\beta_{LA}}.$$

With urban wages increasing more with serfdom than without, the ratio $\frac{X_{ijCM}}{X_{ijLM}}$ should increase more in regions with serfdom. Agriculture becomes relatively abundant in labour, leading to lower agricultural wage increases in areas with serfdom than in those without. Accordingly, the ratio $\frac{X_{ijCA}}{X_{ijLA}}$ should increase less in regions with serfdom. I put this prediction to the test and estimate:

$$T_{ijkt} = \delta_{pk} plague_{it} + \delta_{sk} serfdom_i \text{ x } plague_{it} + \alpha_{ijk} + \alpha_{jkt} + \alpha_{akt} + \epsilon_{ijkt}, \quad (21)$$

where T_{ijkt} is the share of i's export to j in year t and sector k that is capital-intensive, α_{ijk} are origin-destination-sector fixed effects, α_{jkt} are destination-sector-time fixed effects, and α_{akt} are area-sector-time fixed effects. ϵ_{ijkt} denotes the error term. δ_{pk} and δ_{sk} are the coefficients on the plague and the plague and serfdom interaction displayed in Table 3.

The results in Table 3 confirm this expectation. The share of capital-intensive exports expands in all sectors as wages rise after the plague. This is the presence of *absolute* labour scarcity in all sectors. Regions with serfdom see significantly larger increases in the capital-intensity of their manufacturing exports and significantly smaller increases in the capital-intensity of their agricultural exports. This reflects *relative* labour scarcity.

One may further contend that differences in wage increases lead to different increases in the capital-to-labour and investment capital-to-labour ratios as per market clearing conditions 7. Per equation 5, different increases in the investment capital-to-labour should also produce different productivity growth. Both manufacturing sectors should see faster productivity growth

Table 3: Impact of plague on share of capital-intensive exports by sector, by second serfdom.

	Manufacturing	Agriculture
	(1)	(2)
Plague	0.022***	0.027***
	(0.002)	(0.003)
Plague & Serfdom	0.009***	-0.009***
	(0.003)	(0.003)
Fixed Effects:		
– Area x Year	✓	✓
– Origin x Destination	✓	✓
– Destination x Year	✓	✓
Observations	488,538	488,538

Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The dependent variable is the share of exports that are capital-intensive. The independent variable is a plague dummy that equals 1 for plagued regions after the plague hit interacted with a dummy for second serfdom.

under serfdom, as they are artificially labour constrained and see larger increases in the investment capital-to-labour ratio. The opposite is true for agriculture, where the incentives for employing more (investment) capital are smaller under serfdom as labour is artificially abundant. Appendix Figures 27 and 28 test this prediction and find no strong evidence supporting this conjecture. Labour-intensive manufacturing sees larger relative productivity losses in areas with serfdom, though this point estimate is only significant in one specification. While artificial labour scarcity in cities may theoretically lead to a higher investment capital-to-labour ratio also in labour-intensive manufacturing, in practice, the limited availability of machinery may simply lead to an even larger productivity loss in textile production. In line with my prediction, productivity growth in capital-intensive agriculture is smaller in areas with serfdom, where labour remained artificially abundant in rural settings.

Some historical evidence confirms different paths for post-plague productivity depending on the presence of serfdom. In particular, the recovery of Russia and the Baltics shows different patterns from Sweden. Broadberry and Korchmina, 2024 note that Russian agricultural output per capita was no different in 1800 than it was in 1700. There is no evidence that strip farming was abandoned in Russia, unlike in Sweden, where this change was made to save labour. Relative labour abundance in serfdom-dominated areas simply may not have necessitated changes to production methods. Crop rotation and new farming machinery also only show up towards the end of the 18th century in Russia, far later than in Sweden. Magnusson, 2007 suggests that this is not driven by the availability of tools through trade, as he shows that all of Sweden could have had access to modern tools but not all areas adopted it. This suggests that for Russia, too, this was a choice and not a result of insufficient access to better tools. The agricultural history of Prussia, which also had serfdom, paints a similar picture of no change after the plague.

I draw two conclusions. First, labour scarcity as induced by the plague increases the share of capital-intensive exports in all regions and sectors. This is a result of what I call *absolute* labour scarcity. Second, areas with serfdom shifted significantly more strongly into capital-intensive manufacturing exports and significantly less strongly into capital-intensive agricultural exports. This reflects what I call *relative* labour scarcity. Overall, studying how serfdom shaped post-plague factor adjustments and productivity growth sheds light on the role any other friction on factor mobility may play.

5.2 Alternative Mechanisms

This section discusses three alternative mechanisms that could produce the observed export boom after the plague. I argue that directed technical change (Acemoglu, 2002) is theoretically compatible with my findings, but present historical evidence against the presence of a factor bias in innovation. I also discuss the phenomenon of "venting out" and conclude that it is unlikely to have been present after the plague. Finally, I test for the presence of non-homotheticity (Fieler, 2011), which is the crucial ingredient in the framework of Voigtländer and Voth, 2012.

Directed Technical Change

A long literature discusses the factor bias of technical change. As a recent example, Alfaro et al., 2024 study a policy-induced scarcity of rare earths and its effects on downstream industries. They document a rise in patents seeking to counteract this scarcity by using less of the now scarcer inputs. Surprisingly, downstream industries in affected countries see faster TFP growth than their counterparts in China, where export quotas for rare earths had been cut beginning in 2010. In a framework of directed technical change (Acemoglu, 2002), they argue that rare earths scarcity directed innovation to save this input. This resulted in TFP growth and an export expansion of affected downstream industries outside of China.

Acemoglu, 2002 shows that the factor bias of technical change is governed by the relative strength of two effects. First, a price effect leading to technological improvements favouring scarce factor. Second, a market size effect leading to innovation complementing the abundant factor. A low elasticity of substitution between factors renders the price effect more powerful. In the model I presented above, production is Cobb-Douglas and the elasticity of substitution between factors is therefore equal to 1. Thus, these two channels cancel out and technology is not factor biased. Acemoglu, 2010 extends this framework and shows that labour scarcity increases the rate, rather than the bias, of technological progress if technological change is strongly labour saving in that it reduces the marginal product of labour. Under perfect competition, labour scarcity would therefore increase technological progress if technological change reduces wages.

I now discuss how factor bias might have played out after the plague. The plague changed the relative abundance of factors. While labour became scarcer, capital became more abundant. The price effect shifts technological improvements towards using more labour; the market size effect shifts technological improvements towards using more capital, both compared to the pre-plague factor bias. If the market size effect had prevailed, innovation would have taken on a labour-saving bias. While it is hard to prove or rule out this shifting factor bias, I note that the finding of increased TFP growth in Alfaro et al., 2024 is consistent with the mechanism suggested in this paper. The difference lies in how precisely changed factor proportions translated into TFP growth, with both mechanisms leading to similar results.

Despite this theoretical ambiguity permitting directed technical change, I argue that history does not support the presence of this factor bias in the period studied. Gallardo and Sauer, 2018 review the historical evidence on labour-saving technologies in agriculture. They conclude that labour-saving mechanisation in crop agriculture began succeeding only in the 19th century. An early example of a crop harvesting machine that explicitly substituted labour for capital was the cotton gin by American inventor Eli Whitney, patented only in 1794. Focusing on the 17th century in England, Coleman, 1956 argues that labour-saving technologies in agriculture were practically non-existent. Those that existed, such as mills, spinning wheels, and water-powered blast furnaces, were centuries old and not a testament to a changed factor bias in technological improvements. In manufacturing, Atack, Margo, and Rhode, 2019 document how innovative machinery consolidated multiple hand tasks into a single machine task. They consider this the most labour-saving type of technological transition, which, however, only came to bear during the 19th century. Coleman, 1956 further argues for a political determination to absorb rather than substitute labour in this period, resulting in opposition to the development of labour-saving devices in agriculture and manufacturing alike. Thus, I consider the historical evidence to point towards unbiased technical change.

Venting Out

Almunia et al., 2021 document a striking pattern: a domestic demand slump during the Great Recession was accompanied by increased exports. They show in Spanish firm-level data that the larger a firm's domestic sales decline, the larger was their increase in exports. They term this phenomenon "venting out". Under constant marginal costs, as in my model, venting out cannot be explained. Instead, they suggest a model with flexible inputs, whose usage Spanish firms reduced as domestic demand fell. Using less flexible inputs reduced short-run marginal costs, permitting an increase in exports. In this setting, export markets can counteract a negative local demand shock.

I compared the Great Northern War plague outbreak to the Black Death in Section 2. While the Black Death hit all of Europe with varying intensity, the 1708-1714 plague outbreak left most of Europe unscathed. This presents an ideal setting for unperturbed export markets to counteract the local demand shock of the plague. Translating venting out to my setting, regions would have reduced their short-run marginal costs by using less of flexible inputs such as temporary workers. This drop in short-run marginal costs would have implied higher competitiveness in destination markets. This paper's finding of increasing exports could therefore indeed be rationalised by reduced short-run marginal costs.

I suggest the time dimension as a crucial difference, however. Almunia et al., 2021 find an almost immediate response of exports to domestic demand, this paper documents a five year gap between the plague and the export expansion. Further, while Almunia et al., 2021 track Spanish exports for four years after the onset of the Great Recession, this paper studies trade for 30 years after the plague. Short-run marginal costs are unlikely to explain this persistent export boom. Over the long-run, an additional force would have been required to keep marginal costs from rising again. I postulate that productivity growth is precisely this force and is kicked off by an increased capital intensity. The shift into capital-intensive exports, unlike the export expansion, indeed appears in the data almost immediately after the plague struck. I argue, therefore, that the plague did not lead to a phenomenon of venting out.

Non-Homotheticity

Voigtländer and Voth, 2012 tell a story of non-homotheticity. The plague increased wages, which shifted demand relatively into more income-elastic goods. They assume these to be urban manufactured goods. In essence, this would represent a positive demand shock for manufactured goods coinciding with a negative labour supply shock. This increased demand may have spurred productivity advances. In my four sector world, it seems reasonable to assume that capital-intensive agriculture (manufacturing) is more income-elastic than labour-intensive agriculture (manufacturing). In product-level price data by Allen and Unger, 2018, I test a key empirical prediction in Voigtländer and Voth, 2012: a hump-shaped pattern of prices for plagued regions, with prices of capital-intensive goods increasing relative to those of labour-intensive goods. To test the behaviour of relative prices, I assemble price data for both labour- and capital-intensive agricultural and labour-intensive manufacturing products from Allen and Unger, 2018[34]. For plagued Danzig and non-plagued Amsterdam, their dataset holds annual prices on 77 products, which I classify according to Appendix Table 7. I show in Table 4 that labour-intensive agricultural prices rose after the plague and capital-intensive agricultural prices fell. To a lesser extent, the same is true of labour-intensive manufacturing. This may reflect both the labour cost and productivity channels. Plague-induced labour scarcity increased the cost of labour-intensive goods, whereas productivity advances in capital-intensive goods lowered their price. I suggest that pastoral farming is more efficient than arable farming at translating a higher investment capital-to-labour ratio into productivity gains. While these effects were also passed on to Amsterdam through trade in general equilibrium, Amsterdam itself was not affected by the plague and faced higher trade costs to the regions that were plagued and saw the prices of capital-intensive agricultural goods fall as their productivities in that sector rose.

This finding fits well with the story of this paper, a supply side-driven response to factor scarcity, but not well with a demand side-driven response. This relative price effect provides empirical evidence against the hump-shaped price prediction in Voigtländer and Voth, 2012.

[34]No data on goods I classify as capital-intensive manufacturing are containted in the data set and few for labour-intensive manufacturing.

Table 4: Product-level prices by sector and year in Danzig and Amsterdam.

	Labour-int. Agriculture			Capital-int. Agriculture			Labour-int. Man.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Post Plague	10.53	32.82	114.2***	-41.24***	-59.72***	-16.44***	0.665
	(15.09)	(21.40)	(15.05)	(8.040)	(12.56)	(6.242)	(2.137)
Fixed Effects:							
– City	✓	✓	✓	✓	✓	✓	✓
– Year		✓	✓		✓	✓	
– Product			✓			✓	
Observations	4140	4140	4140	5116	5116	5116	191

Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The independent variables are prices of products by sector in Amsterdam and Danzig. The dependent variable is 1 after the plague in Danzig in 1709. The second and third specification cannot be estimated for labour-intensive manufacturing due to lack of observations. No data on capital-intensive manufacturing products are contained in the data set.

If demand shifted relatively into capital-intensive agriculture - dairy, meat, and eggs - as a result of higher incomes, this should have increased the relative price of capital-intensive agriculture. Instead, Table 4 reflects the effects of the labour cost and productivity channels under trade in general equilibrium. These price findings also reconcile the evidence that after the plague consumers received a higher share of their calories from meat and dairy (Broadberry et al., 2014) with my assumption of homothetic demand. As capital-intensive agricultural prices dropped, under homothetic consumption and constant consumption shares consumers mechanically demand higher quantities of meat and dairy as their prices have dropped. Accordingly, non-homotheticity is not required to justify this finding.

Despite this evidence, higher incomes after the plague may have led to an increased spending share on dairy rather than wheat. Thus, under non-homotheticity, demand shares should have shifted into capital-intensive goods in plagued regions. I test for evidence of non-homotheticity and find no evidence to support this plague-induced shift in demand shares. Fieler, 2011 provides a generalised trade model with non-homotheticity which allows a neat mapping onto my model under the assumption that $\theta_k = \theta \forall k$. This implies a fixed intra-industry heterogeneity in the Fréchet distribution. Her paper shows that even under non-homothetic preferences, her trade model then breaks down to an Eaton and Kortum, 2002 model. Preferences alone do not alter the structure of trade as long as the distribution of technologies is equal across sectors. The gravity equation with sectoral productivities under non-homotheticity becomes:

$$X_{ijk} = \frac{\chi_k A_{ik} (w_{ik})^{-\gamma_k \theta} d_{ijk}^{-\theta}}{CMA_{jk}} X_{jk}, \tag{22}$$

where I no longer assume $X_{jk} = \alpha_k Y_j$. I proceed in two steps. First, I show that when permitting non-homotheticity, I still find significant productivity growth effects after the plague. In a second step, rather than controlling for different demand structures, I test directly for non-homothetic demand.

For the first step, I form ratios of equation 22 between a sector k and the reference sector of unclassified goods. This mirrors the referencing procedure employed when recovering sectoral productivity growth. When assuming $w_{ik} = w_{iU}$ and $\gamma_k = \gamma_U$[35], I find:

$$\frac{X_{ijk}}{X_{ijU}} = c\frac{A_{ik}}{A_{iU}}\frac{X_{jk}}{X_{jU}}\frac{CMA_{jU}}{CMA_{jk}},$$

where $c = \frac{\chi_k}{\chi_U}$. I then estimate:

$$\frac{X_{ijkt}}{X_{ijUt}} = \delta_k plague_{it} + \alpha_{ik} + \alpha_{jkt} + \epsilon_{ijkt}, \tag{23}$$

where α_{ik} are origin-sector fixed effects that, among others, control for the baseline ratio of the left-hand side. α_{jkt} are destination-sector-time fixed effects absorbing any changes in relative market access and, crucially, in j's demand ratio $\frac{X_{jk}}{X_{jU}}$. ϵ_{ijkt} are the error terms and δ_k the coefficients of interest, measuring the association with the dummy $_{it}$ that switches to 1 once the origin region has been hit by the plague.

Table 5: Relative export growth under non-homotheticity.

	(1)	(2)	(3)	(4)
Plague Dummy	0.948***	1.315***	0.192***	1.038***
	(0.275)	(0.156)	(0.051)	(0.166)
Fixed Effects:				
– Origin	✓	✓	✓	✓
– Destination x Year	✓	✓	✓	✓
Observations	481,161	478,263	486,936	482,796

Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The dependent variable is the ratio of exports from i to j between the respective sector and unclassified goods. The independent variable is a plague dummy that equals 1 for plagued origin regions after the plague hit.

Table 5 shows significantly positive estimates for relative export growth. Through the lens of the model, this corresponds to productivity growth. This result establishes productivity growth effects even under non-homothetic preferences. The question is therefore not whether there is one or the other but whether there is both productivity growth and non-homotheticity.

[35]Additionally, one requires that trade costs are the same between k and k' or that their proportional difference is time-invariant.

For the second step, I form the ratio of the gravity equation between any two sectors k and k', for which I need to asssume $w_{ik} = w_{ik'}$ and $\gamma_k = \gamma_{k'}$. This yields the following ratio:

$$\frac{X_{ijk}}{X_{ijk'}} = c\frac{A_{ik}}{A_{ik'}}\frac{X_{jk}}{X_{jk'}}\frac{CMA_{jk'}}{CMA_{jk}}, \tag{24}$$

where $c = \frac{\chi_k}{\chi_{k'}}$. Equation 24 shows that the ratio of i's exports to j in sector k to sector k' depends on the ratio of i's productivities in these sectors, j's demand in these sectors, and j's market access in these sectors. In my model, the ratio of j's demands equals the ratio of Cobb-Douglas weights and is time-invariant by assumption. Thus, if $\frac{X_{ijk}}{X_{ijk'}}$ moves over time and preferences are homothetic, this can only be attributed to either changes in relative productivities of the exporter or in relative market access of the importer.

Permitting for non-homotheticity, changes in j's relative demand can directly affect relative trade flows. If after the plague income-elastic k goods see a demand increase at the expense of k's goods, the demand ratio changes. As I test for non-homotheticity in plagued regions j, note that the observed trade of j in my data is with regions i on the North Sea, which (apart from Hamburg and Bremen) were not plagued. These regions' wages, productivities, and trade costs to j should not have changed in the short-run. I therefore assume that j's market access ratio does not change within a small window around the plague: $\frac{CMA_{jk't}}{CMA_{jkt}} = \frac{CMA_{jk't'}}{CMA_{jkt'}}$, where I choose 10 years to be a sufficiently small window. While it simplifies the demand side of equation 24, this assumption actually works against me, in that any changes in relative demand will be seen as evidence for non-homotheticity, even if they arise from relative market access changes. This is because I do not hold a prior over the direction of the shift in demand shares. The only possibility would be for a shift in demand shares that is offset by a shift in relative consumer market access.

I define the baseline period as the years before the actual or median plague outbreak, depending on a region's plague status. Then, I take endline over baseline ratios of equation 24 and first absorb changes in the productivity ratio in exporter i with an origin fixed effect. Finally, I regress the residuals on a plague dummy for importer j to see if any origin-unrelated changes in j's relative imports vary by the importer's plague status.

Table 6 shows the results of these regressions for all pairs of sectors. None of the point estimates are significant, suggesting that plagued regions did not change their demand composition in excess of potential universal demand shifts. Therefore, I find no evidence supporting the competing mechanism of non-homothetic demand.

6 Counterfactuals

In this paper, I show that labour scarcity induces a shift into capital-intensive production and suggest that this causes differential productivity growth across sectors. This productivity growth contributes to the observed export boom in Fact #2 before. In a counterfactual analysis,

Table 6: Testing for plague-induced relative demand shifts.

	(1)	(2)	(3)	(4)	(5)	(6)
Plague Dummy	-0.085	-0.212	-0.320	-0.756	-2.197*	0.974
	(0.057)	(2.665)	(0.645)	(0.776)	(1.333)	(1.268)
Sectors	CM & LM	CA & LA	CM & CA	LM & LA	CM & LA	CA & LM
Observations	5,392	5,170	5,131	5,362	5,333	5,072

Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The dependent variable is the ratio of exports from i to j between the two sectors noted below the results. The independent variable is a plague dummy that equals 1 for plagued destination regions after the plague hit. The number of observations varies due to zeros in the sectoral export data.

I shut down this productivity channel and model the effects of labour scarcity in exports in the absence of a productivity response. I find that market shares of plagued regions would have contracted rather than expanded.

Shutting Down The Productivity Channel

How would trade have responded to the plague in the absence of the productivity channel? In this counterfactual scenario, only Malthusian forces would be at play, increasing wages and reducing plagued regions' competitiveness. I abstract from factor adjustments *across* sectors by focusing on one sector.

The outcome are market shares, as defined in equation 1 for empirical fact #2, where I plug in gravity equation 12, equation 14 for wages and equations 10 for firm and consumer market access to arrive at an equation defining market shares as a function of productivities, sectoral employment, trade costs, wages, and total income. In this counterfactual exercise, I shut down the productivity channel. Thus, A_{ik} is fixed[36]. Counterfactual market shares t years after the plague can then be decomposed into a time-invariant term, s_{ijkPRE}, that contains productivities, trade costs, and incomes, and a time-varying component reflecting sectoral employment changes:

$$s^c_{ijkt} = \frac{L_{ikt}}{L_{ikPRE}}^{\frac{\gamma_k \theta}{1+\gamma_k \theta}} s_{ijkPRE}. \tag{25}$$

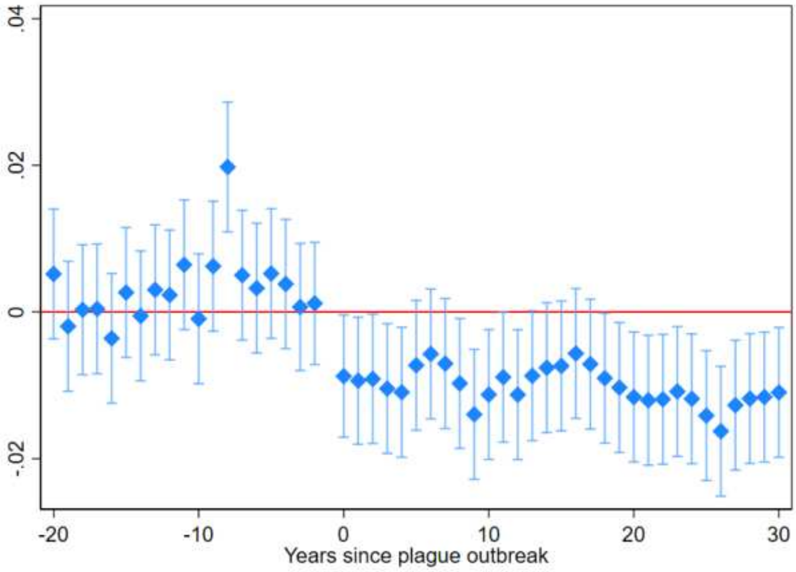
As no annual population estimates are available, I suppose an upper bound for population recovery and impose exponential population growth[37].

[36] All other assumptions and justifications are in Appendix F.

[37] I show in Appendix F that for mortality rate m_i and 90 years as the upper bound:

$$s^c_{ijkt} = (1 - m_i)^{\frac{\gamma_k \theta}{1+\gamma_k \theta}} \left(\frac{1}{1 - m_i}\right)^{\frac{\frac{\gamma_k \theta t}{1+\gamma_k \theta}}{90}} s_{ijkPRE}. \tag{26}$$

Figure 10: Counterfactual market shares without productivity channel.



Notes: Counterfactual export shares, shutting down productivity channel. Estimate equation 1 on counterfactual export shares after the plague and observed export shares before the plague.

In Figure 10, I repeat the event study in equation 1 but replace post-plague export shares of plagued regions by the counterfactual shares calculated above. Not surprisingly, I find significantly lower export shares as a smaller population led to labour scarcity, higher wages, and lower competitiveness in destination markets. This stands in a stark contrast to my empirical findings but supports the prediction of Malthusian models.

7 Conclusion

This paper studies the relationship between labour scarcity and productivity growth in granular trade data. The historical setting is the 1708-1714 plague outbreak during the Great Northern War that afflicted regions around the Baltic Sea. With a median mortality rate of 36%, plagued cities' populations had returned to their pre-plague trends by 1800. From the Danish Soundtoll data, I build a novel trade data set and establish four empirical facts.

First, exports became more capital-intensive in that the share of capital-intensive exports out of all exports increased in plagued regions. This is predicted by the Rybczynski theorem. Second, plagued regions expanded their market shares in destination markets, and similarly exported larger volumes. Third, plagued regions expanded their exports along the extensive margin and shipped a larger number of goods abroad. Fourth, exports of innovative products, never before exported by a region, expanded faster in plagued regions. About a third of the intensive margin expansion derives from this innovation.

I show that these results are robust to different specifications and estimators. I also reject the alternative explanation that plagued export hubs consumed less and mechanically exported more. Similarly, I argue that plagued regions did not simply reallocate exports from unobserved to observed destinations. My trade findings suggest productivity gains, as exports expanded despite wage increases in the aftermath of an adverse labour supply shock. They further suggest an important role for capital as capital-intensive manufacturing sees particularly pronounced export increases.

To conceptualise these findings, I build a three-factor and five-sector Ricardian model following Eaton and Kortum, 2002, Costinot, Donaldson, and Komunjer, 2011, and Donaldson and Hornbeck, 2016. The three factors are labour, capital, and investment capital, where the latter contains any capital investments used to upgrade machinery or innovate new products. Sectors differ in their factor intensities and all produce using Cobb-Douglas production functions. The five sectors are a sector of unclassified goods, labour-intensive agriculture and manufacturing, and capital-intensive agriculture and manufacturing. I parametrize sectoral productivity - more specifically, the scale parameter of the Fréchet distribution of sectoral productivities - as the investment capital-to-labour ratio in a sector to the power of a sectorally varying β_k parameter. This value measures the efficiency with which increases in the investment capital-to-labour ratio translate into productivity growth.

Within this model, I first show that labour scarcity leads to wage increases. I then show that the prediction of the Rybczynski theorem can be decomposed into two channels: a labour cost channel, inducing relative export gains in sector that use labour less intensely, and a productivity channel, increasing exports depending on how β_k scales up increases in the investment capital-to-labour ratio. In some sectors, new machinery and infrastructure investments may be available and may produce significant productivity gains, whereas other sectors are more technologically constrained and cannot benefit similarly from a higher investment capital-to-labour ratio.

In the next step, I shut down the labour cost channel by imposing the same production function on all sectors. Therefore, the increased cost of labour relative to capital and investment capital leads to producers employing a higher capital-to-labour and investment capital-to-labour ratio, but proportionately across sectors. As a result, only differences in β_k drive differential productivity growth. Under a few additional assumptions, I back out sectoral productivity growth. I show that labour-intensive agriculture stagnates, whereas productivity growth in capital-intensive agriculture accelerates. Similarly, labour-intensive manufacturing productivity drops after the plague, whereas it increases in capital-intensive manufacturing.

To support this mechanism, I present empirical and historical evidence. I show that wages increased after earlier plague outbreaks and that agricultural production in Sweden became more capital-intensive after the Great Northern War plague outbreak. I also present evidence of major capital investments in industry and ship building. I show that the number of ships owned in plagued regions dropped less and recovered faster than the number of captains living in these regions, consistent with the model and suggesting an increased capital-to-labour ratio.

I also discuss alternative mechanisms, namely directed technical change, venting out, and non-homothetic demand. I discuss their implications and present arguments against them. I formally test for the presence of non-homotheticity and find no evidence supporting its presence.

In counterfactual analysis, I shut down the productivity channel. Labour scarcity then increases wages and renders exports less competitive. Contrary to the export expansion I established above, in this counterfactual exports decline. Wage increases simply reduce competitiveness without inducing productivity gains through an increased investment capital-to-labour ratio. The difference between this counterfactual export contraction and the observed export expansion adds plausibility to the missing channel, namely productivity gains.

To summarise, this paper establishes two main empirical points. Labour scarcity produces measurable factor adjustments. Second, plagued regions see an export expansion briefly after the plague. It should surprise the reader that plagued regions increased their market shares abroad. I propose a theoretical link between the two findings: an increased investment capital-to-labour ratio that increases sectoral productivities. I show that productivity growth explains the surprising export expansion and present a counterfactual export contraction when shutting down productivity growth.

Several avenues for future work appear. Chief among them is the need to expand on localised historical evidence. Further, more work is required in different settings and period. The important difference between sectors in the degree to which investment capital can render them more productive is linked to technological constraints which surely differ across space. While the Baltics in the 1700s could not become much more productive through machinery in arable farming, the modern world knows tractors and harvesting machines that can increase productivities manifold.

This paper, studying granular trade flows after a plague outbreak, has several implications for rich countries today faced with labour scarcity. I confirm factor adjustments towards more capital-intensive production and document a surprising export expansion of plagued regions. I suggest that productivity increases can reconcile this finding with the reality of labour scarcity and higher wages. Therefore, basic economic mechanisms - changes in relative factor prices - are clearly operating when economies are faced with a sudden increase in labour scarcity. This should support the role of our field in a discussion held increasingly politically.

Further, the importance of trade is evident in my findings. As long as goods and services can be traded between countries, factor shocks in one country need not ruin its economy. Quite to the contrary, trade permits not just an efficient factor adjustment, but opens the door to productivity growth consistent with the post-shock factor relations. Accordingly, labour scarcity also in modern economies may be surmountable despite persisting worries (OECD, 2024). This result, however, hinges on a willingness to embrace changed factor proportions and to pursue a different composition of outputs. The historical case study of serfdom illustrates how limits on factor mobility, for example, shape and limit adjustments to changed factor proportions. Finally, this result depends on trade openness. Moves towards autarky inevitably limit regions' ability to adjust, specialise, and thrive.

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A Data Appendix

A.1 Commodities

This Appendix details how goods are constructed and classified. The Soundtoll data do not provide researchers with cleaned information on commodities. Instead, the variable 'soort' denotes the type of commodity simply in words, and specifically in the words of the custom official at the time. A total of 143,855 separate goods descriptions is reported. The data are documented in Danish, specifically in Old Danish which is further changing over time. I am using two sources to translate goods: first, the Soundtoll Project provides researchers with a list of proudcts, which holds 44 pages of (theoretically appearing) goods translated into English, Dutch, French, and Frisian. Many of them are very specific and do not actually exist in that spelling in the data. This document forms the basis of good classification, and the second source consulted are etymological dictionaries for Danish to ensure, as much as possible, that correct classifications are made. However, the list of products only classifies a small fraction of goods due to the variety in spelling and unstructured nature of the goods variable. Standard text analysis is not suitable for this cleaning task, as these data are in a time-varying version of Danish and a lot of similar sounding words introduce a lot of complexity and require intuition, as closest neighbour matching can be highly misleading. I now explain how I approach the manual classification of goods. I clean spellings and create unified 'goods' as outlined below. These goods will also be aggregated up into five sectors.

Most goods are denoted in a large variety of ways, which introduces some issues to the cleaning process, as it not only requires the researcher to determine closest matches, but also asks of them to apply prudent risk management so as not to accidentally classify goods into a wrong, similar sounding category. An example of this will be provided below. There are a couple of general issues with these text data, which lead me to specific approaches when cleaning the data and classifying goods.

1. The Danish special characters 'ø' and 'æ' are more often than not coded incorrectly. **Cleaning needs to take account of special characters.**

2. The data are unstructured and not concise. While sometimes 'wheat' is denoted, usually it is something like 'wheat from Livland' or 'two tons of wheat'. **Cleaning cannot use just perfect matches, but needs to look for matching substrings.**

3. Good names are contained within each other. For example, I can distinguish apples from apple juice, or iron ore from iron and iron works. The more general category should be searched for first, therefore, so that iron works are not accidentally classified as iron. **The order of substring matching matters.**

4. Whenever a good name is part of another, I either apply only exact matches for classification, or, as mentioned above, work with the order of substring matches. **In some cases, only exact matches can be considered.**

5. Goods vary greatly in their specificity. While sometimes just 'goods' or 'fish' is denoted, I also regularly find 'goods from Greenland' and specific types of fish. When the distinction carries meaning, I distinguish these. **Some goods are bundled and others are highly specific.**

6. Goods are spelled in a great variety of ways. This concerns similar vowels, double or single consonants, and also language-specific terms. **A variety of close matches needs to be considered.**

7. Goods sometimes cannot be distinguished. Plums, 'pruneller', are very close to a type of textile, 'prynellen'. **Discretion needs to be applied at points.**

Following these approaches, I arrive at 227 goods, 8 out of which only exist in the early trade data without bilateral coverage, and which therefore are never part of the analysis. In total, 143,855 goods descriptions are mapped onto 219 goods, so the average commodity appears in 9,000 variations. An example of different spellings is sturgeon, appearing in four variations: Stor, Større, Støre, and Stører. An example of varieties of goods and spellings is iron, of which there are six variations: jerren, jeern, jern, jeren, osmundt jern, and osmunds jern, where the latter two denote specifically Swedish iron. Many variations in fact contain information on value or amounts: lead oxide appears in 15 variations, six of which specify value, e.g. 'gleide 3 ort' and 'gleide a 6 skilling'.

An example for close words is 'olie' for oil and 'øl' for beer. I classify as beer what contains: øll, Ãel (incorrectly digitised character), oill, oell, Ãell, oll, oel, øell, Ãl, and øl. As oil: olly, ollj, olli, olie, olhie, oliue, and ollio.

Sometimes, a number of goods is reported, e.g. 'wheat and chestnuts'. This is surprising, as usually a tax official would note goods line by line. In fact, it only applies to 100,000 out of over 3.5 million shipments, so about 2.8%[38]. These shipments capture 2.57% of shipped value. The issue this introduces is, like in the case where several cities are reported, that the researcher cannot discern which value accrues to either of the goods. While I can see that 30 Daler of wheat and chestnuts were transported, I cannot ascertain what the split across goods was. Besides the relative uncommonness of this, there are two more reasons to be little concerned here: for one, these two goods are usually within the same category, as in the example above, where two agricultural goods are reported. This may have been one of the reasons for simply reporting them at once. The other reason is that these goods were regarded as substitutes by tax officials, that is, they carried the same relative duties, and only for this reason were reported together in one line rather than separately.

There are some goods which appear both in an aggregated and in a disaggregated form in the data: there are both 'textiles' and 'woollen textiles'. Rather than aggregating them up, I code goods as granularly as I can. Evidently, when aggregating into agricultural or manufacturing goods, both textiles and woollen textiles will be in the same category. The most important

[38]Counting as double whenever 'og' (also) or 'etc' are contained in a goods description.

bundled categories in the original data are textiles, fish, and goods. The latter is simply not further specified, and thus distinguishing English goods from French goods captures the only difference, and I accordingly code these as different goods, even though I will later aggregate them into a group of unspecified goods. For fish, I find that often the data just speak of fish, and on occasion they are very specific, e.g. 'lings'. The approach I follow is to code as specific as I can, so individual types of fish are their own good, and the compound category of fish contains all types that are not further specified in the original data.

For textiles, I distinguish raw materials (cotton, linen, wool) from processed textiles (band, gaze, ribbon, yarn, tissue, stockings), luxury textiles (flannel, satin, silk, velours, velvet) and naval textiles (sail/canvas, flag cloth). In cases where the data are insufficiently specific, I use compound categories (cloth, cotton textile, woollen textile). The compound categories distinguish, if possible, at least by cotton and wool. The good 'clothes' contains all types of fabric, textile, and clothes which are not further distinguishable, either by material or by degree of processing.

As mentioned above, the order of partial matching matters: as one example, 'haardug' is a woollen textile. For this specific case, 'haardug' contains 'haar' and is thus first classified as hair. I then classify all goods containing 'dug' into the compound category of cloth, so 'haardug' moves from hair to cloth. Then, when a perfect match of 'haardug' is encountered, the good is instead classified as a woollen textile, which is the correct match.

To summarise the commodities data at a high level, I now report the top commodities with their share of total traded value: sugar and flax (9%), hemp and wheat (8%), wine and cotton (6%), planks and salt (5%), iron works, rye, and coffee (4%), and talcum and iron (3%). These top 13 commodities make up 73.3% of total traded value.

I then construct five sectors: labour-intensive agriculture, capital-intensive agriculture, labour-intensive manufacturing, capital-intensive manufacturing, and the remaining sector of unclassified goods. I distinguish agricultural from manufacturing goods based on their likely location of production, namely the countryside rather than the city. Capital-intensive goods require a high amount of capital that cannot be swapped for labour. This capital may consist of factories, furnaces, machinery, or tools necessary to produce the good. Labour-intensive goods are limited in the degree to which labour can be saved in their production. Labour-intensive agriculture is all of arable farming, whereas pastoral farming, mining, and processed foods including alcohols are capital-intensive agriculture. Labour-intensive manufacturing are largely textiles. Capital-intensive manufacturing produces goods such as processed metals, tools, and ship building materials. All 227 goods, accompanied by an assignment into the four sectors, are reported in Table 7. 2% of traded value is in unclassified goods, 99% of which are generic goods and mercery. This implies that 98% of traded value is assigned into goods.

Table 7: Goods Classification.

Animals	Capital-int. ag.	Rhine Wine	Capital-int. ag.	Ship Nails	Capital-int. man.	Tea	Labour-int. ag.
Arrack	Capital-int. ag.	Rum	Capital-int. ag.	Soda	Capital-int. man.	Tobacco	Labour-int. ag.
Beef	Capital-int. ag.	Salmon	Capital-int. ag.	Staves	Capital-int. man.	Trees	Labour-int. ag.
Beer	Capital-int. ag.	Salpeter	Capital-int. ag.	Steel	Capital-int. man.	Wheat	Labour-int. ag.
Bones	Capital-int. ag.	Salt	Capital-int. ag.	Swords	Capital-int. man.	Wood	Labour-int. ag.
Brandy	Capital-int. ag.	Seed	Capital-int. ag.	Tar	Capital-int. man.	Baize	Labour-int. man.
Bread	Capital-int. ag.	Sekt	Capital-int. ag.	Tiles	Capital-int. man.	Band	Labour-int. man.
Bristles	Capital-int. ag.	Soap	Capital-int. ag.	Tools	Capital-int. man.	Bay	Labour-int. man.
Buckling	Capital-int. ag.	Sprat	Capital-int. ag.	Turpentine	Capital-int. man.	Bowls	Labour-int. man.
Butter	Capital-int. ag.	Starch	Capital-int. ag.	Almonds	Labour-int. ag.	Chests	Labour-int. man.
Caviare	Capital-int. ag.	Stockfish	Capital-int. ag.	Amber	Labour-int. ag.	Cloth	Labour-int. man.
Chalk	Capital-int. ag.	Stones	Capital-int. ag.	Anise	Labour-int. ag.	Confectionaries	Labour-int. man.
Cheese	Capital-int. ag.	Sturgeon	Capital-int. ag.	Apples	Labour-int. ag.	Cotton Textile	Labour-int. man.
Cidre	Capital-int. ag.	Sulphur	Capital-int. ag.	Barley	Labour-int. ag.	Flag Cloth	Labour-int. man.
Coal	Capital-int. ag.	Talcum	Capital-int. ag.	Beans	Labour-int. ag.	Flannel	Labour-int. man.
Codfish	Capital-int. ag.	Tartar	Capital-int. ag.	Bushel	Labour-int. ag.	Folio	Labour-int. man.
Copper	Capital-int. ag.	Tin	Capital-int. ag.	Capers	Labour-int. ag.	Furniture	Labour-int. man.
Downs	Capital-int. ag.	Tow	Capital-int. ag.	Cardamon	Labour-int. ag.	Gaze	Labour-int. man.
Dye	Capital-int. ag.	Train Oil	Capital-int. ag.	Chestnuts	Labour-int. ag.	Gloves	Labour-int. man.
Eal	Capital-int. ag.	Treacle	Capital-int. ag.	Cinnamon	Labour-int. ag.	Hat	Labour-int. man.
Feather	Capital-int. ag.	Vetch	Capital-int. ag.	Cloves	Labour-int. ag.	Lace	Labour-int. man.
Fish	Capital-int. ag.	Vinegar	Capital-int. ag.	Cocoa	Labour-int. ag.	Lamps	Labour-int. man.
Flounders	Capital-int. ag.	Vitriol	Capital-int. ag.	Coffee	Labour-int. ag.	Linnen	Labour-int. man.
Flour	Capital-int. ag.	Wax	Capital-int. ag.	Cork	Labour-int. ag.	Mats	Labour-int. man.
Fur And Skin	Capital-int. ag.	Wine	Capital-int. ag.	Cotton	Labour-int. ag.	Paper	Labour-int. man.
Gin	Capital-int. ag.	Wool	Capital-int. ag.	Cucumbers	Labour-int. ag.	Ribbon	Labour-int. man.
Grass	Capital-int. ag.	Zinc	Capital-int. ag.	Dates	Labour-int. ag.	Ropes	Labour-int. man.
Gymsum	Capital-int. ag.	Alkali	Capital-int. man.	Dodder	Labour-int. ag.	Sail	Labour-int. man.
Haddock	Capital-int. ag.	Anchors	Capital-int. man.	Figs	Labour-int. ag.	Satin	Labour-int. man.
Hair	Capital-int. ag.	Ash	Capital-int. man.	Flax	Labour-int. ag.	Silk	Labour-int. man.
Ham	Capital-int. ag.	Barrels	Capital-int. man.	Frankincense	Labour-int. ag.	Spears	Labour-int. man.
Herring	Capital-int. ag.	Bells	Capital-int. man.	Fruit	Labour-int. ag.	Spokes	Labour-int. man.
Honey	Capital-int. ag.	Black Powder	Capital-int. man.	Ginger	Labour-int. ag.	Stockings	Labour-int. man.
Horn	Capital-int. ag.	Bottles	Capital-int. man.	Grapes	Labour-int. ag.	Tissue	Labour-int. man.
Horses And Horse Products	Capital-int. ag.	Bowsprits	Capital-int. man.	Groats	Labour-int. ag.	Trousers	Labour-int. man.
Iron	Capital-int. ag.	Brass	Capital-int. man.	Hemp And Hemp Products	Labour-int. ag.	Velours	Labour-int. man.
Lead	Capital-int. ag.	Brass Works	Capital-int. man.	Hops	Labour-int. ag.	Velvet	Labour-int. man.
Leadoxide	Capital-int. ag.	Bullets	Capital-int. man.	Ivory	Labour-int. ag.	Woollen Textile	Labour-int. man.
Leather	Capital-int. ag.	Cannons	Capital-int. man.	Juniper	Labour-int. ag.	Yarn	Labour-int. man.
Lings	Capital-int. ag.	Caps And Helmets	Capital-int. man.	Lemons	Labour-int. ag.	Ballast	Unclassified
Liquorice	Capital-int. ag.	Cement	Capital-int. man.	Linseed	Labour-int. ag.	Chinese Goods	Unclassified
Mackarel	Capital-int. ag.	China	Capital-int. man.	Millet	Labour-int. ag.	Comm	Unclassified
Malt	Capital-int. ag.	Glass	Capital-int. man.	Muscade	Labour-int. ag.	English Goods	Unclassified
Marble	Capital-int. ag.	Glue	Capital-int. man.	Nuts	Labour-int. ag.	Faroer Goods	Unclassified
Mead	Capital-int. ag.	Hoes And Shovles	Capital-int. man.	Oats	Labour-int. ag.	French Goods	Unclassified
Meat	Capital-int. ag.	Iron Works	Capital-int. man.	Olives	Labour-int. ag.	Goods	Unclassified
Mineral	Capital-int. ag.	Masts	Capital-int. man.	Peas	Labour-int. ag.	Icelandic Goods	Unclassified
Mustard	Capital-int. ag.	Medicine	Capital-int. man.	Pepper	Labour-int. ag.	Luggage	Unclassified
Oil	Capital-int. ag.	Nails	Capital-int. man.	Plums	Labour-int. ag.	Mercery	Unclassified
Ox Products	Capital-int. ag.	Oars	Capital-int. man.	Potatoes	Labour-int. ag.	Norwegian Goods	Unclassified
Oysters	Capital-int. ag.	Pipe Tools	Capital-int. man.	Resin	Labour-int. ag.	Provisions	Unclassified
Paint	Capital-int. ag.	Pipes	Capital-int. man.	Rice	Labour-int. ag.	Sailors	Unclassified
Pimento	Capital-int. ag.	Pistols	Capital-int. man.	Rubber	Labour-int. ag.	Ship Sully	Unclassified
Pollock	Capital-int. ag.	Pitch	Capital-int. man.	Rye	Labour-int. ag.	Soldiers	Unclassified
Quicksilver	Capital-int. ag.	Planks	Capital-int. man.	Safran	Labour-int. ag.	Swedish Goods	Unclassified
Raisins	Capital-int. ag.	Powder	Capital-int. man.	Spices	Labour-int. ag.	Waste	Unclassified
Rays	Capital-int. ag.	Sheet Metal	Capital-int. man.	Sugar	Labour-int. ag.		

Notes: List of 227 goods and classification into capital-intensive and labour-intensive agriculture and manufacturing, and unclassified goods.

A.2 Currencies

In principle, the Soundtoll Data contain a variety of coins in which toll transactions are recorded. Over all recorded passages, there are 40 types of coins, out of which 48.88% are Daler and 50.88% Skilling. These two are Danish coins, leaving only 0.24% of transactions to non-Danish currency. The use of non-Danish currency is, reassuringly, focused on earlier years, for which I lack destination information and which are therefore not included in the analysis. My data of bilateral trade flows start in 1668 and cover 3.7 million coin transactions, as an individual passage usually requires payment of an amount in full Daler and in fractions of a Daler, calculated in Skilling. From 1668 onwards, 49.2% of coin transactions are recorded in Daler and 50.8% are in Skilling. Out of 3.7 million transactions, 294 use the Ort and one uses the Rosenobel. An Ort is a quarter Daler, so 24 Skilling, and a Rosenobel is an English gold coin. When converting it based on its gold content compared to the Danish daler, I find that one Rosenobel corresponds to roughly 3.94 Daler or 378 Skilling. Given that only 0.008% of transactions in my data are recorded in non-Danish currencies, it is safe to declare foreign currency a non-issue in this data set. Table 8 records the conversion rates across the four currencies actually in use in these data.

Table 8: Currency conversion rates.

	Daler	Skilling	Ort	Rosenobel
Daler	1	0.0104	0.25	3.94
Skilling		1	24	378
Ort			1	15.76
Rosenobel				1

A.3 Duties

I now turn to explaining the way in which duties are recorded in the data. For every passage, the type and amount of duty is recorded, and usually there are several duties payable, some fixed and some proportional. As an example, I picked passage number 304. This ship paid 4 Daler of fire money ('fyrpenge', a fixed fee for the maintenance of the lighthouse) and passed the Sound on April 27, 1790. Its captain, Daniel Wendlandt, citizen of Windau, received a captain's compensation of 1.5 Daler, which was deducted from the total duty payable. This is a proportional tax free allowance. The first sub-total is 37.5 Daler and a function only of proportional duties. I therefore call it proportional duty from now on. When subtracting the captain's allowance, the second sub-total comes to 36 Daler, and the total duty payable is 40 Daler, which is the net proportional duty plus the fire money of 4 Daler. The ship is going from Windau to Rotterdam with 75 last of rye; the recorded tax amount is 37.5 Daler, which equals the proportional duties, rather than the payable duties which account for the allowance and the fixed fee, and which is the basis for my value calculations. Table 9 shows the summation exercise.

Table 9: An example from the Soundtoll Data to show the different duties and sub-totals.

Proportional duty	37.5 Daler
First sub-total	37.5 Daler
Captain's allowance	-1.5 Daler
Second sub-total	36 Daler
Fixed duty (fire money)	+4 Daler
Total payable duty	40 Daler

I now turn to describing the way in which the duty data are recorded. The Soundtoll team digitised the toll books in setting up three separate files.

1. The first one, called 'belastingen' or duties, records for each passage and good the name of the applied duty and the amount payable. This captures fixed duties that vary at most by the number of goods, but not by their value. The most common fixed duty is the fire money, or 'fyrpenge', at about 80% of all fixed duties. 64% of fire duty payments amount to 4 Daler and 24% to 2 Daler.

2. The second file, called 'ladingen' or carriage, records for each passage and good the origin and destination, the goods transported, and the overall amount of duty paid per good. The amount of duty given here corresponds to a sub-total of all duties, to be explained below. Importantly, I am using this sub-total for my value calculations, as it captures the cleanest function of true value, abstracting from fixed duties, which are by nature uninformative about shipped value, and from allowances and reductions.

3. The third data set is called 'doorvaarten', or passages. For every passage, it records the day of passage through the Sound, information on the captain, discounts (or 'korting') applied to the duty, and two sub-totals and a total. A 'korting' is a discount, 87% of which are 'føring', a compensation for the captain in terms of a tax free allowance at their disposal.

The duty amount I use as a proxy for value is the proportional duty, or the first sub-total. Waldinger, 2022, using the same data, focuses on the same proportional duty. It corresponds to the duty amount recorded in 'ladingen' and forms the basis of my value calculations, abstracting from both fixed duties and the 'korting'. The latter should not be taken off the sum as it reflects goods' value. When subtracting it from the proportional duty, however, we arrive at the second sub-total recorded in the books. The recorded total, on the other hand, equals this second sub-total plus the fixed duties, usually the fire money. This is the least suitable measure of value and captures the actual financial transaction in terms of paid duty. For the above arguments, the proportional duty (first sub-total) will be used for all value calculations. Gøbel, 2010 elaborates on the mechanics of the proportionality of this duty, which is summarised in Waldinger, 2022 as a duty of 1-2% of cargo value. In order to discourage understating cargo value, a truth-telling mechanism was put in place: the toll official could purchase the cargo at the total value indicated in the customs forms. As outlined in Section 2 and detailed in Section A.4 below, I use the information on duty variation in Gøbel, 2010 to back out underlying values from toll data by specifying a functional form for duty rates. This exercise produces virtually identical results, suggesting that it is appropriate to focus on the proportional duty, here the first sub-total.

A.4 Recovering underlying value

In this section, I will lay out how I recover underlying shipped value from duty data. Underyling value, rather than the amount of duties paid, is a measure of value which I will use as a robustness check. Gøbel, 2010 notes that the rate at which proportional duties were applied varied by flag, with Danish ships paying lower tax rates, by good, with e.g. salt facing an additional duty, and also by time, with Swedish cargoes taxed at a lower rate only until 1720. Importantly, the origin and destination were not important for the determination of the proportional duty rate.

Motivated by this finding, I assume that taxed value, $\phi_{ijo,kt}$ is the product of a proportional duty $\psi_{o,kt}$, varying by flag o, sector k and time t, and underlying value $v_{ijo,kt}$. In particular, I assume the following:

$$\phi_{ijo,kt} = \psi_{o,kt} v_{ijo,kt} = \psi_{o,kt} p_{ijkt} q_{ijo,kt}, \tag{27}$$

such that the duty rate paid for shipping k goods from i to j under the flag of o in time t depend on the value of these goods multiplied by a proportional duty, $\psi_{o,kt}$, which varies only by flag o, sector k, and time t.

Turning equation 27 into logs and absorbing log proportional duties by $d_{o,kt}$, I can recover proportional duties by estimating:

$$ln\phi_{ijo,kt} = d_{o,kt} + lnv_{ijo,kt}. \tag{28}$$

When estimating equation 28, I use manufacturing and agriculture as two tradable sectors and keep unclassified goods as a reference sector. Non-tradables, which are used as the reference sector for productivity growth, cannot be used here as by definition no trade data for this sector exist. I construct 13 countries, allowing some variation within larger countries such as the Russian Empire[39], group colonies and dependencies with their metropolis, and assign all

[39]The main countries are Sweden, Russia, the German states, Denmark, the Netherlands, France, and Britain.

remaining countries, which rarely show up in the data, into a reference category. This estimation effectively recovers differences-in-differences-in-differences. I set Denmark as the reference flag o, unclassified goods as the reference category k, and the 1670s as the reference decade in order to turn these differences into levels of proportional duties.[40] This procedure imposes that there are no time trends in the proportional duty rate of unclassified goods shipped under Danish flags, but similarly one could fit the recovered differences around a historical time series of duties for Danish merchants at the Sound. While the differences contain the economically meaningful relations, levels allow a more intuitive understanding of underlying value. Choosing Denmark as the reference is motivated by the fact that Danish merchants paid on average the lowest tax rates.

Further, I can recover prices. The underlying value is composed of a price variable p_{ijkt}, which does not vary by flag o, and a quantity variable that does. I impose that bilateral prices in k at time t are the same for all flags, whereas merchants sailing under specific flags may select themselves into certain bilateral connections by shipping higher quantities. Prices of k vary by origin i and destination j to capture varieties which may differ across bilateral pairs. This estimation requires data on quantities, which is not always recorded, and imposes reference categories, thus reducing the number of observations for which underlying value is recovered.

From equations 27 and 28, it can be seen that per unit duties relate to underlying prices as follows:

$$ln(\phi_{ijo,kt}/q_{ijo,kt}) = ln\psi_{o,kt} + lnp_{ijkt} = d_{o,kt} + lnp_{ijkt}, \tag{29}$$

where $d_{o,kt}$ is a flag-sector-time fixed effect absorbing differences in proportional duties. Copenhagen will be fixed as the reference origin and destination, unclassified goods as the reference category and the 1660s as the reference decade. [41] Quantity will be introduced as a control[42],

Within these larger states, I also allow Norway, Belgium, Estonia, Lithuania, Latvia and Finland to potentially have different duty rates.

[40]Differences-in-differences-in-differences are recovered. Using $d_{o,kt} = ln\psi_{o,kt}$ and writing in terms of $\psi_{o,kt}$, estimating equation 28 recovers:

$$\frac{\psi_{ikt}\psi_{i'kt'}\psi_{ik't'}\psi_{i'k't}}{\psi_{ikt'}\psi_{i'kt}\psi_{ik't}\psi_{i'k't'}}.$$

[41]Differences-in-differences-in-differences-in-differences are recovered:

$$\frac{p_{ijkt}p_{i'jkt'}p_{ijk't'}p_{i'jk't}p_{ij'kt'}p_{i'j'kt}p_{ij'k't}p_{i'j'k't'}}{p_{ijkt'}p_{i'jkt}p_{ijk't}p_{i'jk't'}p_{ij'kt}p_{i'j'kt'}p_{ij'k't'}p_{i'j'k't}}.$$

This procedure to create levels effectively removes time trends in Copenhagen's unclassified goods prices for own consumption, which are set to equal 1 throughout. As above, one could similarly fit the recovered differences around a historical price series.

[42]Historical units are difficult to unify, which is why I run this separately by the dimension of units: volume, weight, length, and count. Units are converted to litres, kilograms, metres, and counts, and by running it separately, I allow for differences in the per unit price of a litre or a kilogram of the same good. Usually, the vast majority of a commodity is recorded in units of the same dimension, but for cases when a good k is measured in, say, both volume and weight units, I allow for this flexibly.

so it will be on the right-hand side, and log prices will be recovered as fixed effects.

Any potential tariffs will, in the eventual estimation of the trade model, be subsumed by iceberg transport costs d_{ijkt} as they vary by sector and time.

B History and Geography Appendix

Observing a ship in the data depends on it passing through the Oresund. Thus, trade flows between cities on either side of the Sound will not be observed: trade between Danzig and Stockholm or London and Amsterdam will not be observed in this dataset. For these flows, I do not impose zero trade, but rather will not include these. It is highly unlikely that any trade between Danzig and London occurred other than through the Sound. Other straits, such as the Little Belt between Jutland and Funen, were difficult and dangerous to navigate for larger ships such as the ones used for trading with the West. Note further that trade over land faced a high number of tolls, too, in that many more borders would have to be crossed when compared to simply passing through the Sound.

The main alternative to passing the Sound, between Sweden and Denmark's main island Zealand, was sailing through the Great Belt, between Zealand and Funen. Degn, 2017 makes a number of arguments against this being an issue for these data. The Danish king introduced a prohibition on sailing through the Belt, directed specifically against the Prussian towns, extending this prohibition later on to all foreign nations. This was precisely because the Great Belt potentially allowed merchants to circumvent the Sound Toll. Only expert skippers possessed the specific knowledge required to pass through the Great Belt, a route usually taken in case of storms. Degn, 2017 concludes that skippers only reluctantly avoided the Sound. Finally, toll records from the Great Belt reveal that the number of passages was small. This implies only a small number of unobserved vessels in my data. Importantly, there is no reason to believe that these would be high value trade flows I am missing: according to Gøbel, 2010, the toll revenue from the Great Belt and the Little Belt combined equalled but a few percent of the Sound Toll revenues.

My source for identifying cities in the trade data are two files provided by the Soundtoll team: one maps every mentioning of a city, for all spellings and versions appearing in the toll records, to a unique identifier, the "soundcoding", and the other one links these unique identifiers to a unified way of naming the city. (So 'Dantzig', 'Dannzig', and 'Danzig' all become 'Danzig'.) This converts 90,737 original city names to 3,085 unified city names. My sample are coastal cities (less than 25 kilometres distance to the coast, or those along a major river up to 100 kilometres from the coast) between Ireland to the West, Saint Petersburg to the East, the Arctic Circle to the North, and Bayonne to the South. 1,425 cities are in this sample, though only 676 will be actively trading during the main period I study.

In order to find the lowest cost route connection two cities, I compute cost distances for each city pair in the dataset using a raster approach and the CostDistance tool in ArcGIS similar to Bakker et al., 2021 or Nunn and Puga, 2012. As in the latter paper, my pixel resolution is 30 arc-seconds, corresponding to square cells of about 1 km side length (in fact, the longitudinal dimension is even less than that given the latitude of Northern Europe). I compute bilateral distances over sea between all cities. Including land transport is motivated by some large ports slightly inland, such as Thorn or Bordeaux.

The trade regressions in Section 3 include area-time fixed effects. These areas are different from European NUTS regions as their granularity is not suitable for my purposes. NUTS 1, for example, is far too aggregate for Northern Europe, with Finland and Denmark as each only one region. NUTS 2 is sufficiently granular in Northern Europe, but far too granular in Western Europe, prompting most areas to only contain one city. Therefore, I construct similarly sized areas from current country's administrative borders. When aggregating areas below, this is always to ensure that no area has only one city. The United Kingdom is disaggregated into Scotland, Wales, and the Channel Islands, with England disaggregated into her nine regions, where I pool the East Midlands with the East of England, London with the South East, and the Isle of Man with the North West. Ireland's four provinces are aggregated to three together with Northern Ireland, with Connacht pooled with Ulster. The Netherlands are made up of their 5 provinces by the North Sea. Belgium's areas are her three provinces by the North Sea, where Antwerpen is grouped with East Flanders. Denmark has 5 regions and the Faroe Islands are pooled with the main country. For Finland, I pick the provinces of Finland as of 1997, pooling Oulu and Lapland as Northern Finland and Aland with Western Finland. France's areas are the five regions on the Atlantic Coast and Channel. For Germany, I pick the current states. The three Baltic states are separate areas. Norway is disaggregated into five traditional regions, though Nord Norge never shows up in the data. For Russia, I choose oblasts, pooling Arkhangelsk with Leningradskaya Oblast. Eight national areas are chosen in Sweden, corresponding to the NUTS 2 areas, though I pool Northern Sweden. The few ports in Northern Spain, specifically in Asturias and Galicia, are pooled as one area. Finally, the areas in modern-day Poland are the three voivodeships on the Baltic Sea.

Figure 11 shows digitised army marching routes. As armies spread the plague across Europe, regions' proximity to these routes is used in Table 11 to predict mortality rates when this information is not known.

Table 10 shows information on plague outbreaks in my sample and provides an overview of timing and mortality rates. For plagued cities whose mortality rates were not observed, I form predicted mortality rates from regressing geographical covariates, the timing of the plague, and the proximity of army marching routes on observed mortality routes. These results are shown in Table 11 and used to form predicted mortality rates. Army marching are digitised based on maps by Spruner and Menke, 1880 and Barraclough, 1997.

Table 11 regresses geographical controls, the timing of the plague, and proximity to army marching routes on observed mortality rates for the subset of plagued cities. For half of these cities, I form predicted mortality rates based on the results presented in this table, as no mortality estimates are available.

Figure 12 uses population data by Bosker, Buringh, and Zanden, 2013 to establish popula-

Figure 11: Army marching routes, 1706-1714.

Notes: Map of army marching routes between 1706 and 1714, when the plague was recorded to have spread across Eastern and later Northern and Central Europe. No distinction is made between armies, as both allied and Russian troops are known to have spread the plague. I base these routes on maps by Spruner and Menke, 1880 and Barraclough, 1997 which I digitised.

Table 10: List of plagued cities and mortality estimates.

City	Modern Country	Plague	Time	Population	Mortality	Source
København/Copenhagen	Denmark	1	1711	60000	.283	Kroll and Grabinsky, 2007, Kroll, 2006
Helsingør	Denmark	1	1710 - 1711	4000	.408	Frandsen, 2009
Flensburg	Germany	1	not specified			Ulbricht, 2004
Frederiksort	Germany	1	1712			Ulbricht, 2004
Kiel	Germany	1	1712			Frandsen, 2009
Rendsburg	Germany	1	1712			Ulbricht, 2004
Altona	Germany	1	1712			Frandsen, 2009, Winkle, 1983
Glückstadt	Germany	1	1712			Frandsen, 2009
Pinneberg	Germany	1	1712			Winkle, 1983
Itzehoe	Germany	1	1712			Frandsen, 2009
Schleswig	Germany	1	1712			Ulbricht, 2004
Helsinki	Finland	1	1710		.66	Engström, 1994
Rauma	Finland	1	1710 - 1711			Vourinen, 2007
Turku	Finland	1	1710 - 1711	6000	.33	Vourinen, 2007
Raseborg	Finland	1	1710			Kroll and Grabinsky, 2007, Kroll, 2006
Pori	Finland	1	1710 - 1711			Vourinen, 2007
Oulu	Finland	1	1710 - 1711			Vourinen, 2007
Borgå	Finland	1	1710			Vourinen, 2007
Pietarsaari	Finland	1	1710 - 1711			Vourinen, 2007
Kokkola	Finland	1	1710 - 1711			Vourinen, 2007
Uusikaupunki	Finland	1	1710 - 1711			Vourinen, 2007
Enköping	Sweden	1	1710			Frandsen, 2009
Stockholm	Sweden	1	1710 - 1711	53750	.378	Kroll and Grabinsky, 2007, Kroll, 2006
Visby	Sweden	1	1710 - 1711	2375	.233	Kroll and Grabinsky, 2007, Kroll, 2006
Karlskrona	Sweden	1	1710 - 1712			Persson, 2011
Karlshamn	Sweden	1	1710 - 1712			Persson, 2011
Jönköping	Sweden	1	1710 - 1711	2500	.374	Kroll and Grabinsky, 2007, Kroll, 2006
Ystad	Sweden	1	1712	1950	.385	Kroll and Grabinsky, 2007, Kroll, 2006
Blekinge	Sweden	1	1710			Persson, 2011
Malmö	Sweden	1	1712	5000	.35	Kroll and Grabinsky, 2007, Kroll, 2006
Linköping	Sweden	1	1710 - 1711	1500	.295	Kroll and Grabinsky, 2007, Kroll, 2006
Domsten	Sweden	1	1711			Kroll and Grabinsky, 2007, Kroll, 2006
Narva	Estonia	1	1710 - 1711	3000		Kroll and Grabinsky, 2007, Kroll, 2006
Tallinn/Reval	Estonia	1	1710	9900	.661	Kroll and Grabinsky, 2007, Kroll, 2006
Kuressaare	Estonia	1	1710			Frandsen, 2009
Saaremaa	Estonia	1	1710			Frandsen, 2009
Riga	Latvia	1	1710 - 1711	10477	.651	Kroll and Grabinsky, 2007, Kroll, 2006
Pärnu	Estonia	1	1710	2350	.529	Kroll and Grabinsky, 2007, Kroll, 2006
Kaliningrad/Königsberg	Russia	1	1709 - 1710	36250	.239	Kroll and Grabinsky, 2007, Kroll, 2006
Klaipeda/Memel	Lithuania	1	1709 - 1710			Kroll and Grabinsky, 2007, Kroll, 2006
Sovjetsk/Tilsit	Russia	1	1709 - 1710			Kroll and Grabinsky, 2007, Kroll, 2006
Gdansk/Danzig	Poland	1	1709	50000	.533	Kroll and Grabinsky, 2007, Kroll, 2006
Elblag/Elbing	Poland	1	1709 - 1710		.3	Frandsen, 2009
Kamien Pomorski/Cammin	Poland	1	not specified			Wieden, 1999
Stargard	Poland	1	1710 - 1711	7000	.041	Kroll and Grabinsky, 2007, Kroll, 2006
Szczecin/Stettin	Poland	1	1709 - 1711	11250	.171	Kroll and Grabinsky, 2007, Kroll, 2006
Wolin	Poland	1	1710 - 1711			Wieden, 1999
Anklam	Germany	1	not specified			Wieden, 1999
Greifswald	Germany	1	1711			Wieden, 1999
Wolgast	Germany	1	1710 - 1711		.4	Wieden, 1999
Stralsund	Germany	1	1710 - 1711	7250	.314	Kroll and Grabinsky, 2007, Kroll, 2006
Goleniow/Gollnow	Poland	1	1709			Schöning, 1837
Hamburg	Germany	1	1712 - 1714	70000	.130	Kroll and Grabinsky, 2007, Kroll, 2006
Stade	Germany	1	1712			Frandsen, 2009, Winkle, 1983
Bremen	Germany	1	1712 - 1713	28000	.007	Frandsen, 2009

Notes: Sources are indicated in the last column. Population and mortality estimates, in the case of several available sources, denote the mean estimate. The modern names and countries of cities are used here.

Table 11: Determinants of urban mortality.

	Mortality rate
	(1)
Year of plague outbreak	-0.000
	(0.001)
Latitude	0.010
	(0.022)
Longitude	0.017**
	(0.007)
Distance to closest army	-0.062**
	(0.023)
East of the Sound	0.160**
	(0.055)
Observations	19

Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The dependent variable is the median urban mortality estimate. The independent variables are the year of the plague outbreak, latitude, longitude, distance to the closest army route between 1706 and 1714, and a dummy for the city being to the East of the Sound. The rationale for including army marching routes is that armies spread the plague.

tion recovery of plagued cities by 1800.

Table 12 shows that plagued cities were not larger or smaller than other cities, taking into account time trends and locational fundamentals by including time and city fixed effects. The source for these city-level populations is Bosker, Buringh, and Zanden, 2013. As the closest data point after the plague is in 1800, I conclude that cities' populations and population shares out of the entire urban population had recovered to the common trend after at most nine decades. Note also that Table 12 implies that plagued cities were not significantly larger before the plague.

Figure 13 shows a graph of annual births, deaths, and marriages in Scania. Table 14 presents parish-level results on birth rates' responses to the plague.

Figure 14 shows regions by quintile of warming between 1700 and 1750.

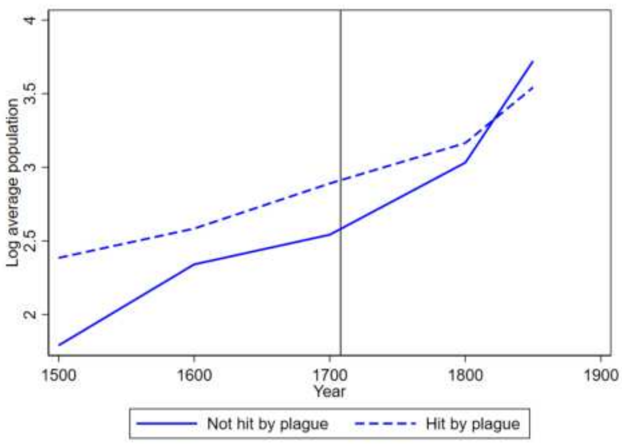
Figure 15 shows that the re-introduction of serfdom in Denmark was associated with a wedge in wages between urban and rural areas that had previously not existed. Figure 16 shows regions by their serfdom status.

Table 12: Impact of plague on city population in Bosker, Buringh, and Zanden, 2013.

	Population		Standardised Population		Share of entire urban population	
	(1)	(2)	(3)	(4)	(5)	(6)
Plague Dummy	-4.538		-0.0837		0.000477	
	(7.222)		(0.133)		(0.00404)	
Plague x Year=900		0.0550		0.00101		7.45e-11
		(13.21)		(0.244)		(0.00738)
Plague x Year=1000		-0.440		-0.00812		4.66e-11
		(13.21)		(0.244)		(0.00738)
Plague x Year=1100		-0.513		-0.00945		0.00127
		(13.21)		(0.244)		(0.00738)
Plague x Year=1200		0.475		0.00876		0.00578
		(13.21)		(0.244)		(0.00738)
Plague x Year=1300		2.097		0.0387		0.00824
		(13.21)		(0.244)		(0.00738)
Plague x Year=1400		1.940		0.0358		0.00721
		(13.21)		(0.244)		(0.00738)
Plague x Year=1500		4.528		0.0835		0.00796
		(13.21)		(0.244)		(0.00738)
Plague x Year=1600		2.418		0.0446		0.00596
		(13.21)		(0.244)		(0.00738)
Plague x Year=1700		4.674		0.0862		0.00651
		(13.21)		(0.244)		(0.00738)
Plague x Year=1800		2.092		0.0386		0.00542
		(13.21)		(0.244)		(0.00738)
Plague x Year=1850		-8.121		-0.150		0.00412
		(13.21)		(0.244)		(0.00738)
Fixed Effects:						
– Year	✓	✓	✓	✓	✓	✓
– City	✓	✓	✓	✓	✓	✓
Observations	2,748	2,748	2,748	2,748	2,748	2,748

Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The independent variable are city population, standardised city population (mean 0 and standard deviation 1) and the share of a city's population in the entire urban population. The dependent variable is first a plague event dummy which is defined to equal 1 in cities that got hit by the plague of 1708-1712, for observations in 1800 and 1850, i.e. after the event. Alternatively, the dependent variable are time-interacted plague dummies, where I omit the year 800 as the reference category. Results are virtually identical when centring historical population data around London in 1700, as done for all model-implied population values.

Figure 12: Log average city population for the two groups, plagued cities and non-plagued cities.



Notes: Population recovery based on population data by century in Bosker, Buringh, and Zanden, 2013. The only plagued city whose population had not surpassed its 1700 population in 1800 is Danzig. Among non-plagued cities, there are more of these: Alkmaar, Haarlem, Leiden, Middelburg and Vlissingen in the Netherlands; Brest, Eu, Le Croisic and Saint-Malo in France; Arkhangelsk in Russia.

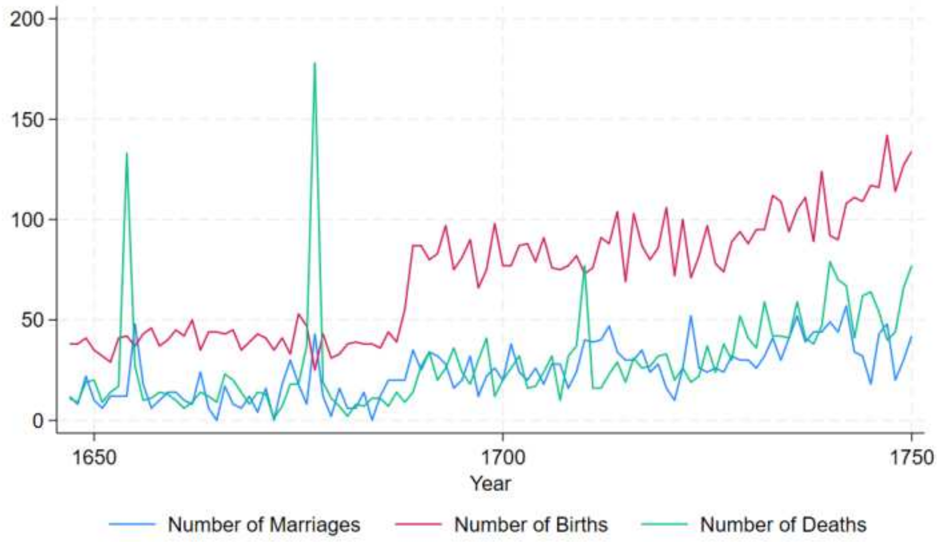
C Trade Appendix

This Appendix holds all additional and robustness results for trade. To begin with, Tables 15 and 16 test whether future plague dummies correlate significantly with trade in levels or growth rates at either margin. Figures 17a, 17b, 17c, 17d, and 18 corroborate the increase in the share of capital-intensive exports by dissecting it by sector and showing results on export volumes by factor intensity. Figure 19 shows the result by goods. Figure 21 shows the export decline in labour-intensive yarn.

I also present robustness results for the post-plague export expansion. Figure 20a extends the pre-period to 40 years and again finds no pre-trends. Figure 20b repeats the main analysis on trade shares using the imputation estimator by Borusyak, Jaravel, and Spiess, 2021. I also show results from cleaned values following the decomposition of duty records into underlying value as outlined in Section A.4 in Figure 20c. Instead of regressing on export shares, Figure 20d regresses on export volumes. Figures 23 and 24 decompose the market share expansion and the intensive and extensive margin results into sectors, whereas Figure 25 shows the market share expansion by goods. Results from gravity regressions with origin-time, destination-time, and origin-destination fixed effects are displayed in table 17. Table 18 shows that the plague increased regions' probability to export.

Robustness results for the extensive margin expansion follow. Figure 26 shows that all four sectors participated in the expansion, with labour-intensive manufacturing contributing the

Figure 13: Number of births, deaths, and marriages in Scania, 1647-1750.



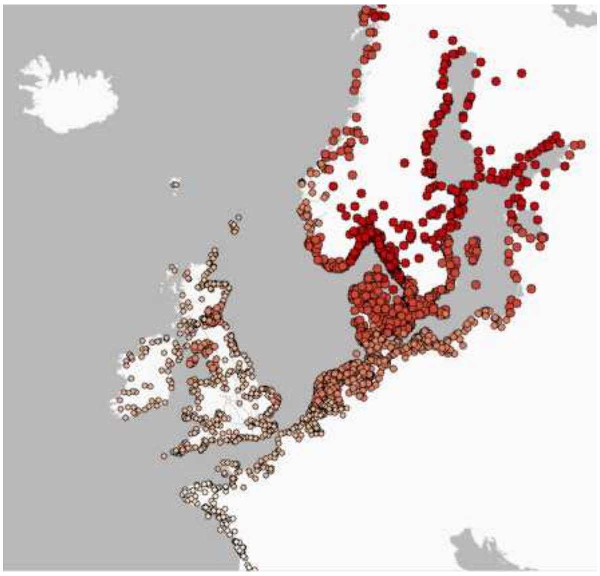
Notes: The 1650s peak in deaths marks the Second Northern War and the 1670s peak the Scanian War.

Table 13: Impact of plague on number of births in 59 Scania parishes.

	Births		Log Births	
	(1)	(2)	(3)	(4)
Post Plague	0.174	-0.376	-0.065	-0.104
	(0.725)	(0.735)	(0.068)	(0.083)
Fixed Effects:				
– Origin	✓	✓	✓	✓
– Year	✓	✓	✓	✓
Years	All	1647-1750	All	1647-1750
Observations	1,015	591	973	578

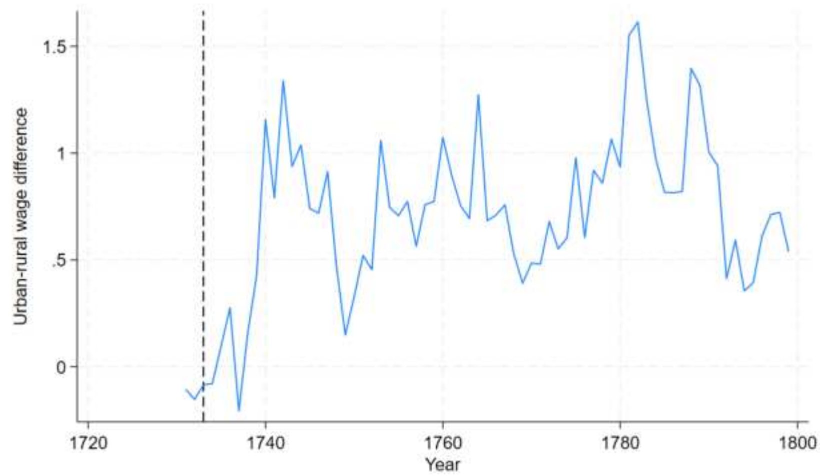
Table 14: *Notes:* Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The independent variable is a the (log) number of births per year and parish. The dependent variable is a plague dummy, equal to one after the parish suffered a plague outbreak.

Figure 14: Regions by quintile of warming.



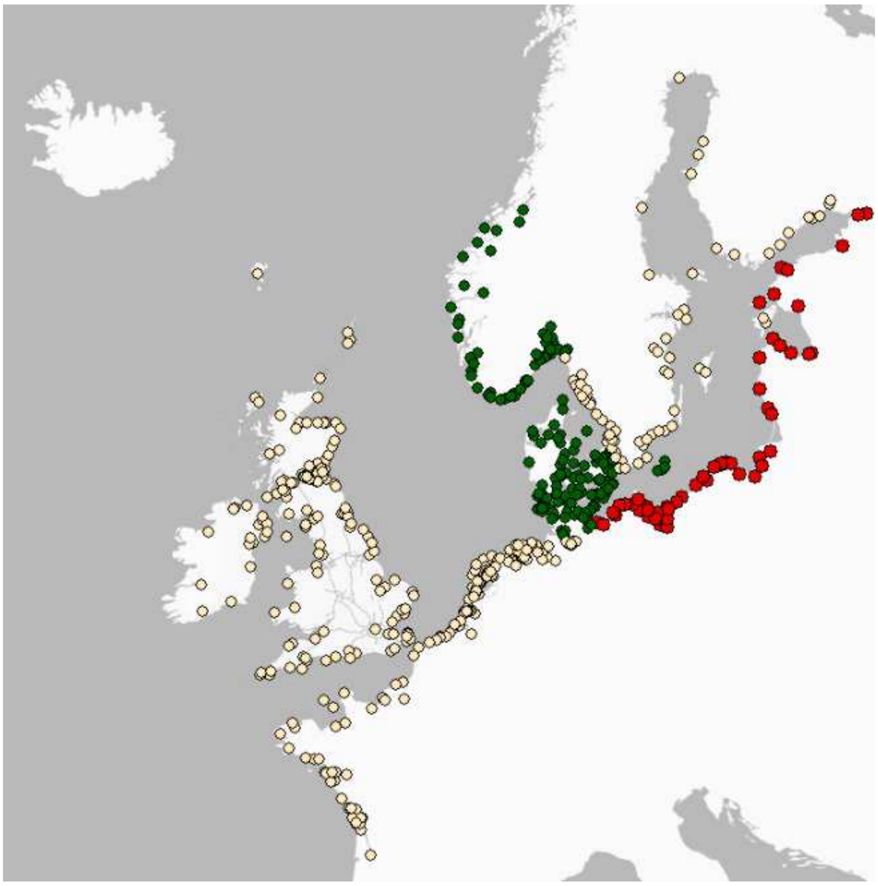
Notes: Red and larger dots show the top 20% in the distribution of warming from 1700 to 1750.

Figure 15: Urban-rural wage differential in Copenhagen.



Notes: Difference between urban and farm day wages divided by farm day wages. Data by Gary et al., 2022. The dotted line signifies the 1733 re-introduction of serfdom.

Figure 16: Regions by serfdom status.



Notes: This map classifies regions by their serfdom status according to the above discussion. Yellow regions did not feature serfdom before and after the plague, whereas red regions did. Green areas re-introduced serfdom in 1733.

least. Figure 27 shows results at the goods level.

Further results for innovation are presented in Figure 28, which shows the contribution of new goods, not exported before the plague, to the intensive margin results. Figures 29 and 30 repeat this for each sector and Figure 31 by good. Dropping the time dimension, Table 19 regresses the probability of exporting a new good or to a new destination on a plague dummy.

Finally, Figure 32 presents evidence that my finding is not driven by export hubs whose reduced local consumption pushed more goods into exports.

Table 15: Pre-plague balancedness checks.

	Population		Export Share		# Exported Goods		# Export Markets	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Plague in Origin	9.047	12.24	0.0112***		0.475***		4.996***	
	(8.716)	(13.31)	(0.000661)		(0.0176)		(0.0916)	
Plague in Destination				0.00544***		0.530***		7.220***
				(0.000696)		(0.0178)		(0.135)
Fixed Effects:								
– Area x Year		✓	✓	✓	✓	✓	✓	✓
– Origin x Year				✓		✓		
– Destination x Year			✓		✓			
Estimator	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS
Observations	1,145	1,105	241,080	239,604	241,080	239,604	24,272	20,336

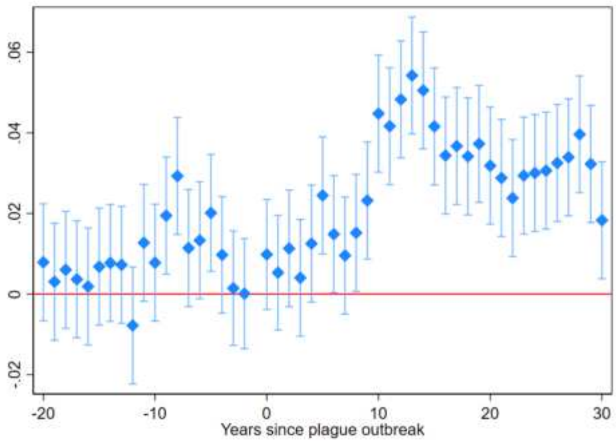
Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The independent variable are population, export share, the number of exported goods and the number of export markets. The dependent variable is a future plague dummy. Data are only before 1708, i.e. before the first plague outbreak.

Table 16: Pre-plague balancedness checks.

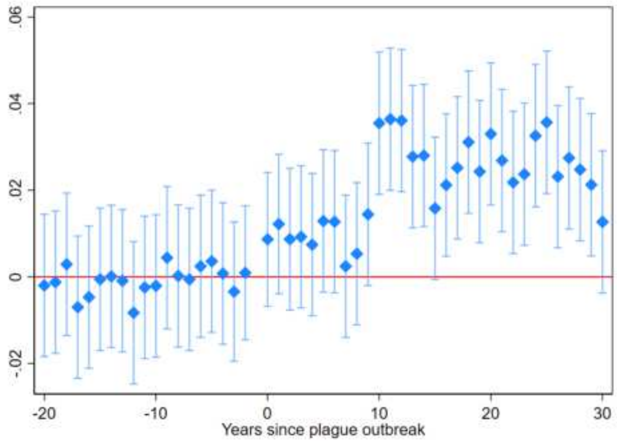
	Growth in Export Volume		Growth in # Exported Goods	
	(1)	(2)	(3)	(4)
Plague in Origin	0.426		0.00382	
	(0.875)		(0.0100)	
Plague in Destination		0.529		0.0186*
		(0.914)		(0.0105)
Fixed Effects:				
– Area x Year	✓	✓	✓	✓
– Origin x Year		✓		✓
– Destination x Year	✓		✓	
Estimator	OLS	OLS	OLS	OLS
Observations	241,079	239,603	241,079	239,603

Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The independent variable are growth of export volume and growth of the number of exported goods. The dependent variable is a future plague dummy. Data are only before 1708, i.e. before the first plague outbreak.

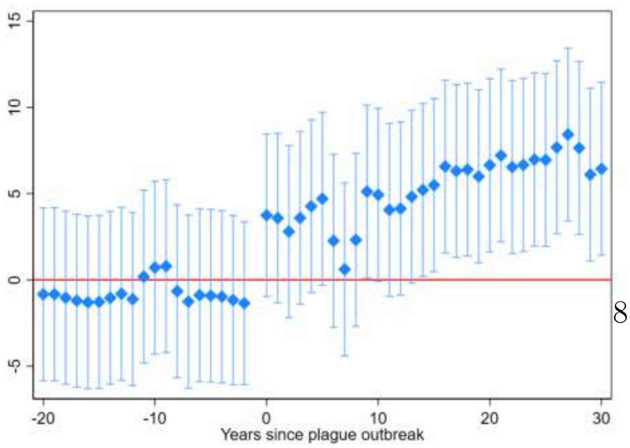
Figure 17: Further results for Fact #1: Capital-intensive shares by sector and volumes by factor intensity.



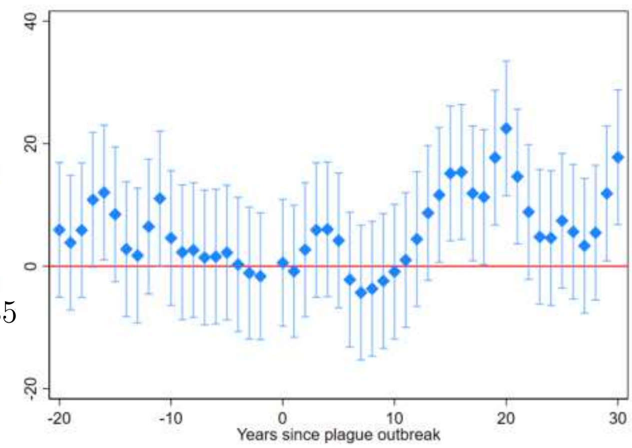
(a) Share of capital-intensive exports in manuf.



(b) Share of capital-intensive exports in agriculture.



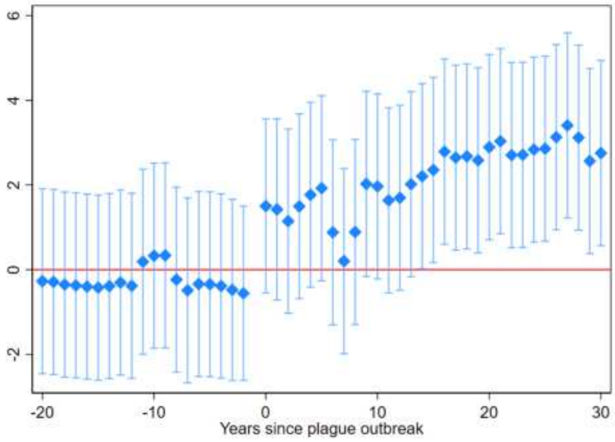
(c) Capital-intensive export volumes.



(d) Labour-intensive export volumes.

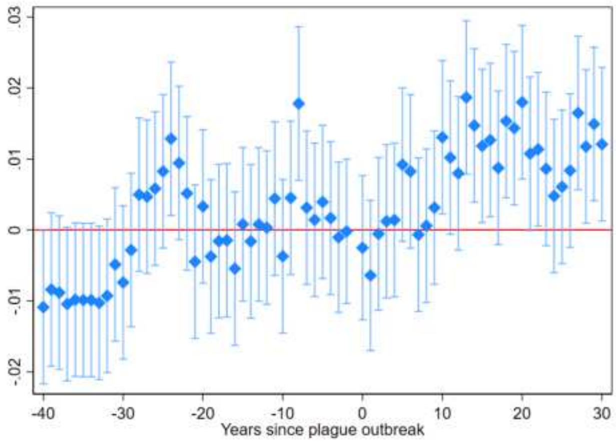
Notes: In Figures 17a and 17b: Estimation of equation 1 on T_{ijt} as the share of i's export to j in year t that is capital-intensive, by sector. In Figures 17c and 17d: Estimation of equation 1 on T_{ijt} as the volume of i's exports to j in year t, by factor intensity.

Figure 18: Exports of capital-intensive goods rose compared to labour-intensive goods

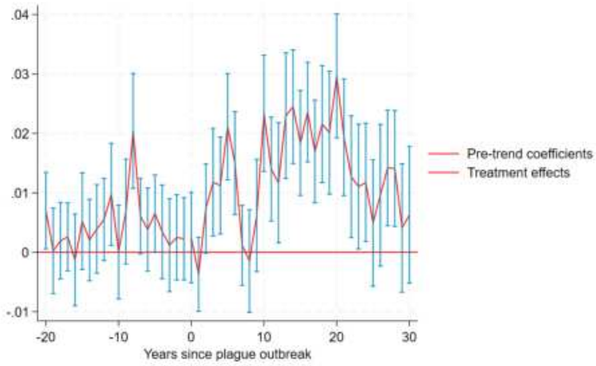


Notes: This regression avoids assumptions on 0s by regressing on capital-intensive exports while controlling for labour-intensive exports.

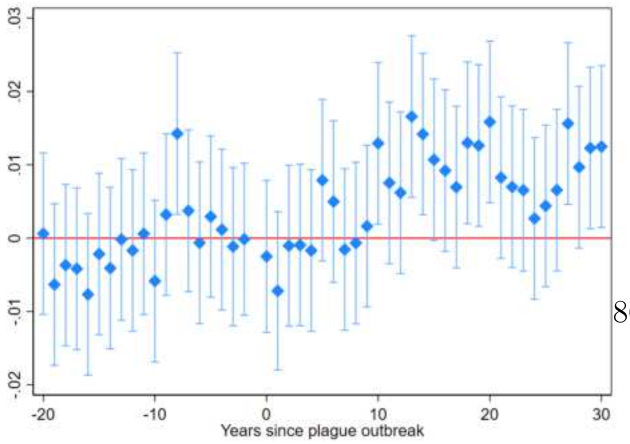
Figure 20: Robustness results for Fact #2: Forty pre periods, imputation estimator, underlying value, export volumes.



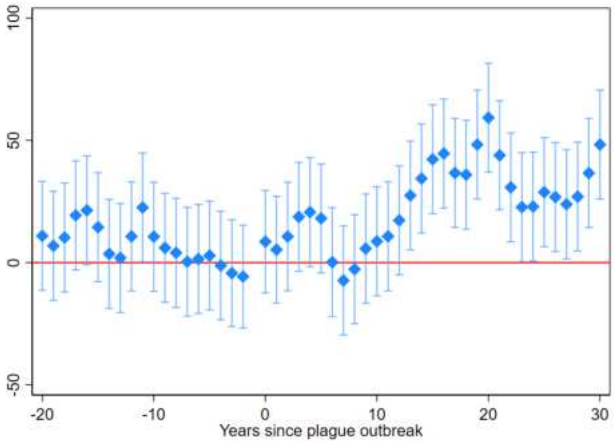
(a) Market shares with 40 pre periods.



(b) Imputation estimator.



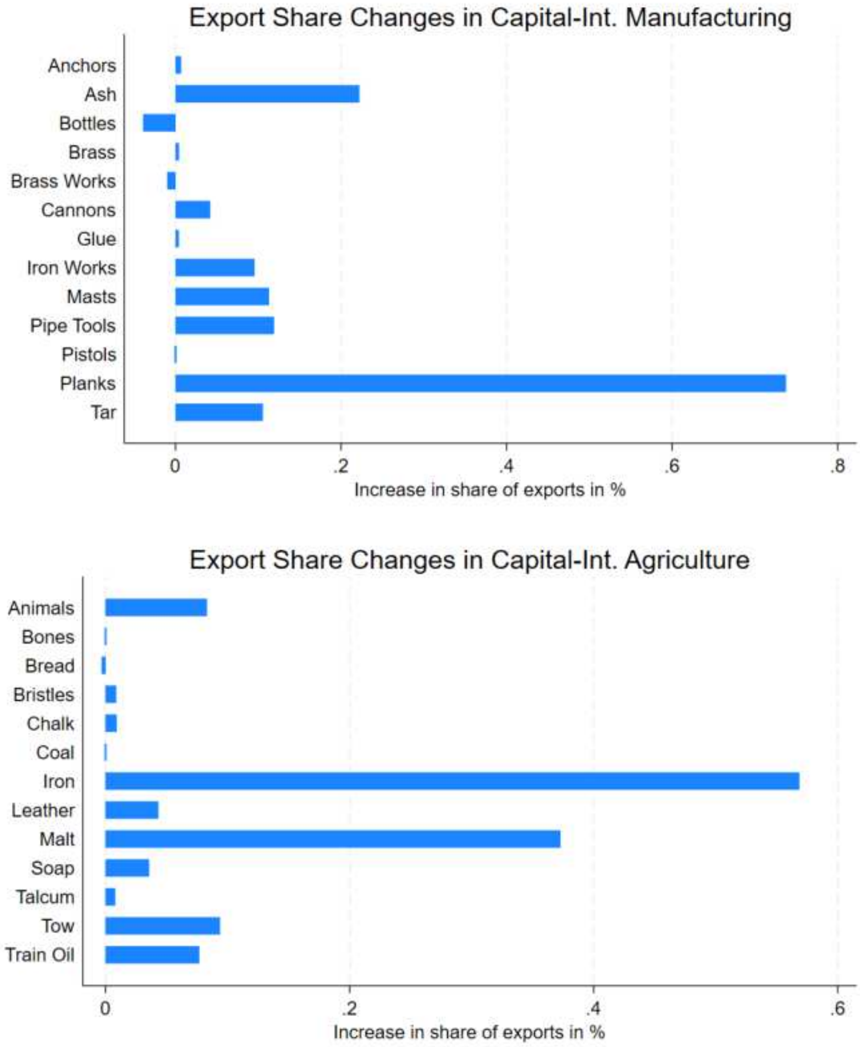
(c) Overall export shares, underlying value.



(d) Export volumes.

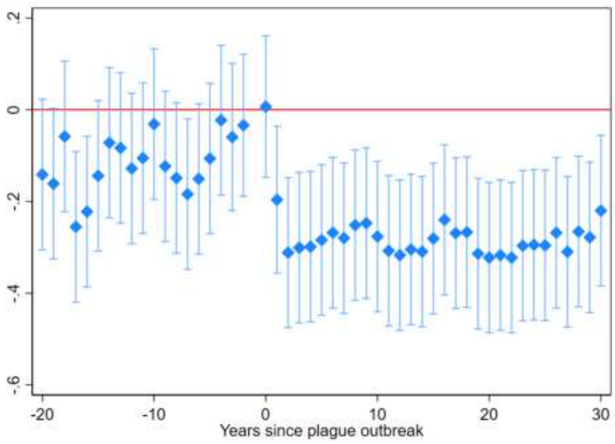
Notes: Figure 20a estimates equation 1 on shares, extending the pre-period to 40 years. Beyond that, no destination information are contained in the data. Figure 20b shows results from estimating equation 1 with 20 pre-trends and 30 post periods using the imputation estimator by Borusyak, Jaravel, and Spiess, 2021. Figure 20c shows regression results based on underlying value, as

Figure 19: Fact #1: Shift into capital-intensive exports by goods



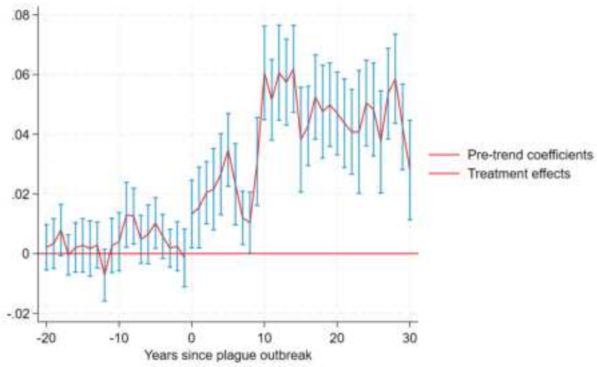
Notes: Results from regressing a post plague dummy on the share a good constitutes in ijt trade and annual data, controlling for area x year, origin x destination, and destination x year fixed effects. Shown are only point estimates that are significant at the 5% level.

Figure 21: Labour-intensive manufacturing exports decline: yarn.



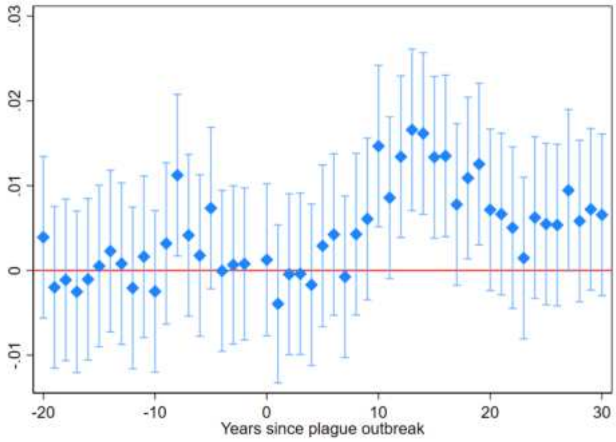
Notes: Estimating equation 1 on yarn exports. Plagued cities significantly reduce their exports of this labour-intensive manufacturing good.

Figure 22: Imputation estimator in Borusyak, Jaravel, and Spiess, 2021 produces stronger results for shift into capital-intensive exports.

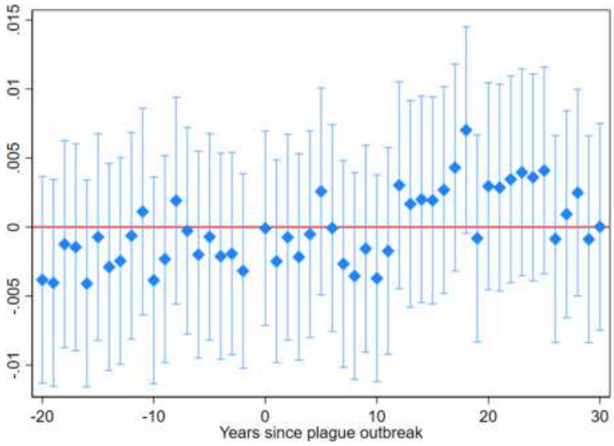


Notes: This Figure shows results from estimating equation 1 with 20 pre-trends and 30 post periods on the share of capital-intensive exports using the imputation estimator by Borusyak, Jaravel, and Spiess, 2021.

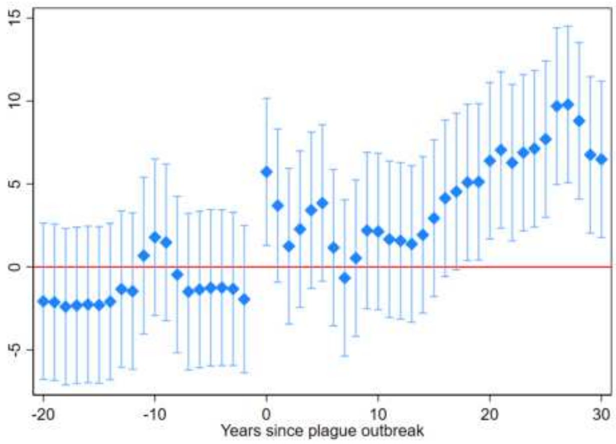
Figure 23: Intensive margin expansion, manufacturing.



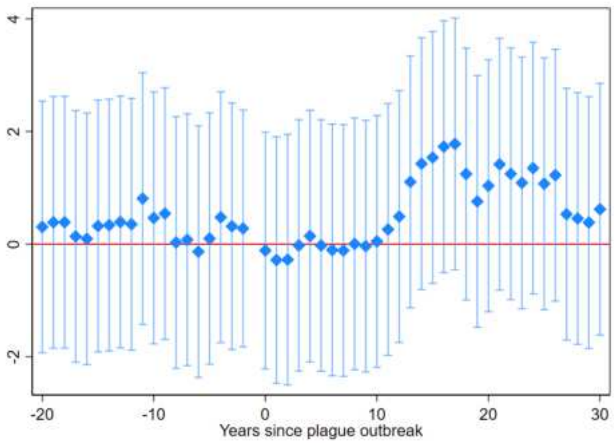
(a) Capital-int. man. export shares.



(b) Labour-int. man. export shares.



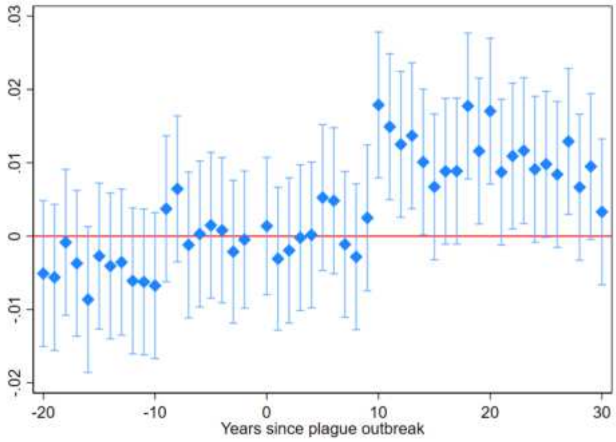
(c) Capital-int. man. export volumes.



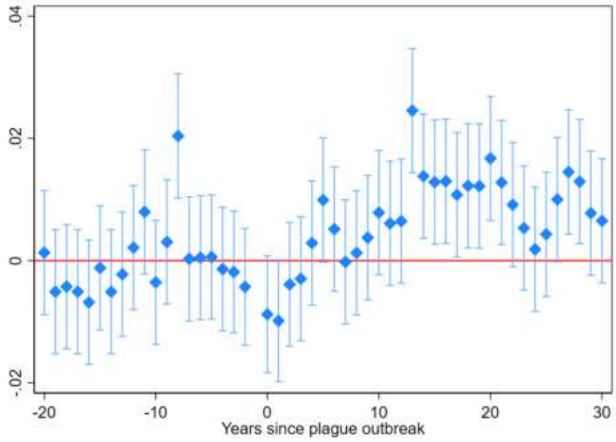
(d) Labour-int. man. export volumes.

Notes: Estimation of equation 1 on shares and volumes, respectively. Between 1668-1750, 55% of traded value was in labour-intensive agriculture, 27% in capital-intensive agriculture, 3% in labour-intensive manufacturing and 13 % in capital-intensive manufacturing.

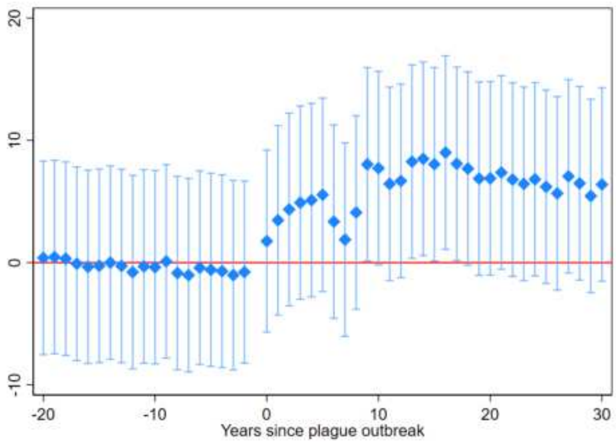
Figure 24: Intensive margin expansion, agriculture.



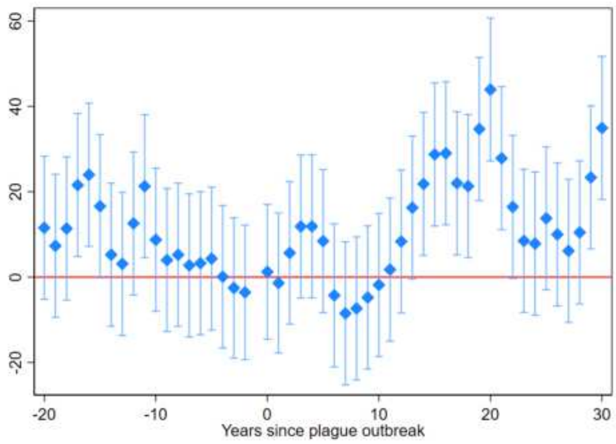
(a) Capital-int. ag. export shares.



(b) Labour-int. ag. export shares.



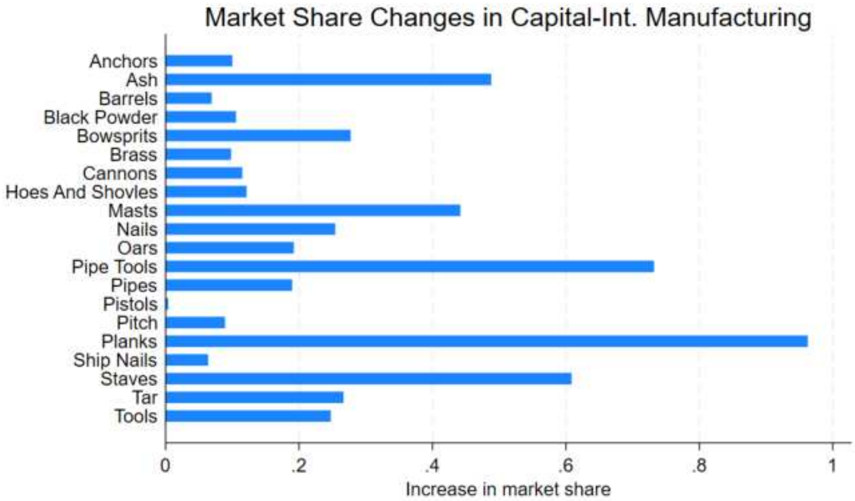
(c) Capital-int. ag. export volumes.

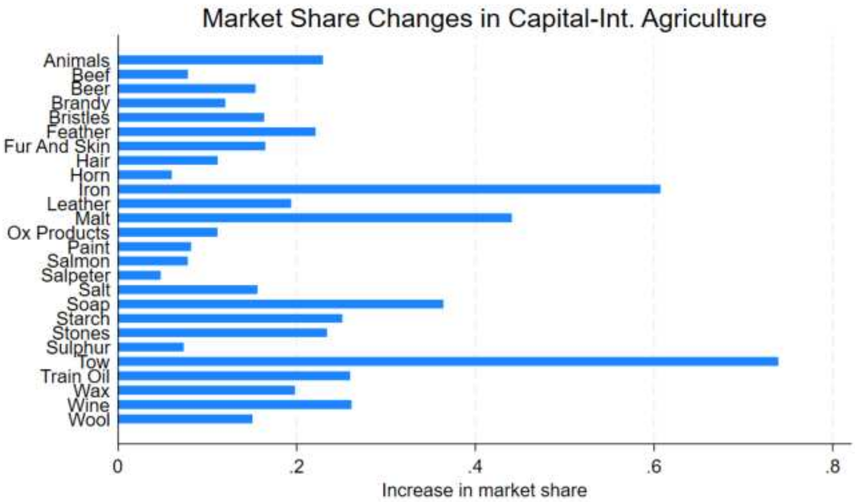


(d) Labour-int. ag. export volumes.

Notes: Estimation of equation 1 on shares and volumes, respectively. Between 1668-1750, 55% of traded value was in labour-intensive agriculture, 27% in capital-intensive agriculture, 3% in labour-intensive manufacturing and 13 % in capital-intensive manufacturing.

Figure 25: Fact #2: Market share gains by goods





Notes: Results from regressing a post plague dummy on i's market share in j in good g in annual data, controlling for area x year, origin x destination, and destination x year fixed effects. Shown are only point estimates that are significant at the 5% level.

Table 17: Gravity analysis of plague shock on bilateral trade.

	Total Trade		Agriculture		Manufacturing	
	(1)	(2)	(3)	(4)	(5)	(6)
Post Plague	0.677**	6.536***	0.667***	7.405*	0.454	11.635***
	(0.272)	(2.101)	(0.197)	(4.351)	(0.297)	(2.336)
Fixed Effects:						
– Origin x Year	✓	✓	✓	✓		✓
– Destination x Year	✓	✓	✓	✓	✓	✓
– Origin x Destination	✓	✓	✓	✓	✓	✓
Estimator	PPML	OLS	PPML	OLS	PPML	OLS
Observations	303,339	1,498,980	84,263	473,681	66,878	473,681

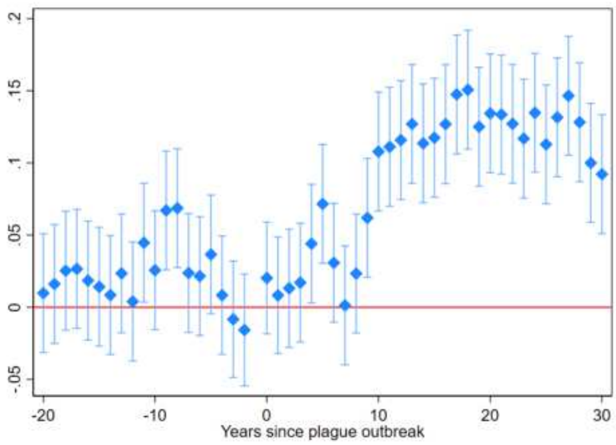
Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The independent variable is annual bilateral trade. The dependent variable is a bilateral plague dummy, equal to one after either the origin, the destination, or both cities suffered a plague outbreak.

Table 18: Impact of plague on probability to export.

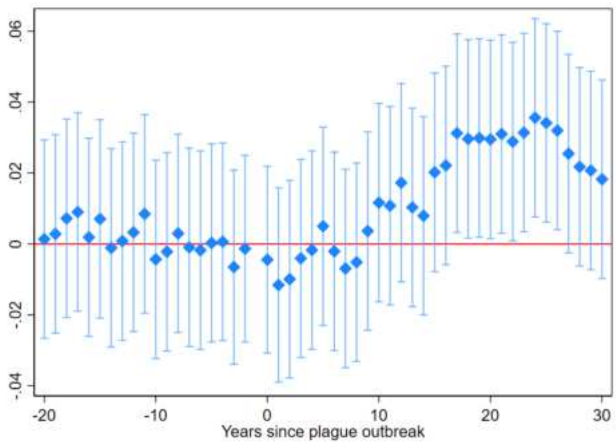
	Marginal Effect		Average Marginal Effect			
	(1)	(2)	(3)	(4)	(5)	(6)
Post Plague	0.033***	0.007***	0.030***	0.112***	0.053***	0.003***
	(0.001)	(0.002)	(0.001)	(0.026)	(0.002)	(0.001)
Fixed Effects:						
– Origin		✓		✓		✓
– Year		✓		✓		✓
Estimator	OLS	OLS	Logit	Logit	Tobit	Tobit
Observations	499,660	499,660	499,660	498,332	499,660	499,660

Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The independent variable is a dummy for whether a region exports in a given year. The dependent variable is a plague dummy, equal to one after the origin suffered a plague outbreak. For Tobit, I model the exporter dummy as left truncated at 0. For Logit and Tobit, average marginal effects are displayed. In the balanced trade panel, the share of active exporters in a given year averages 10.4%.

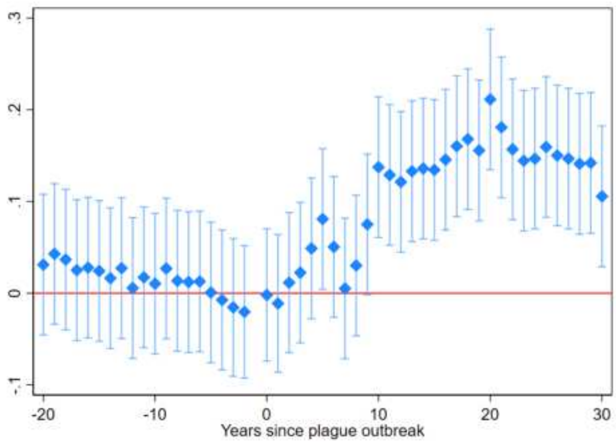
Figure 26: Extensive margin expansion, by sector.



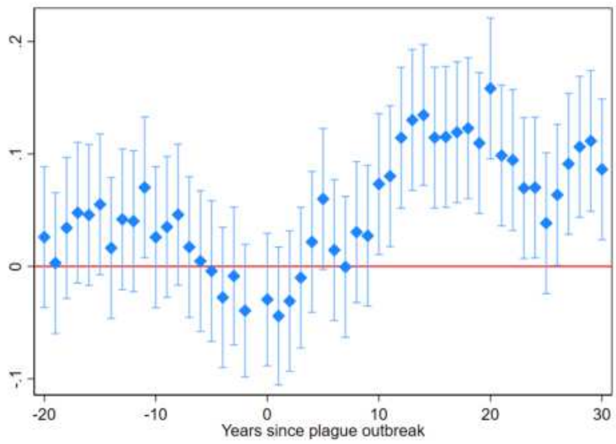
(a) # exported capital-int. man. goods.



(b) # exported labour-int. man. goods.



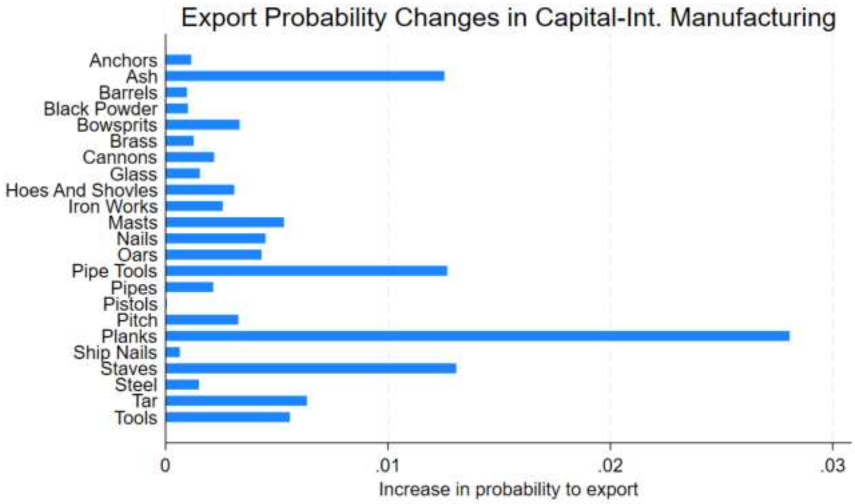
(c) # exported capital-int. ag. goods.

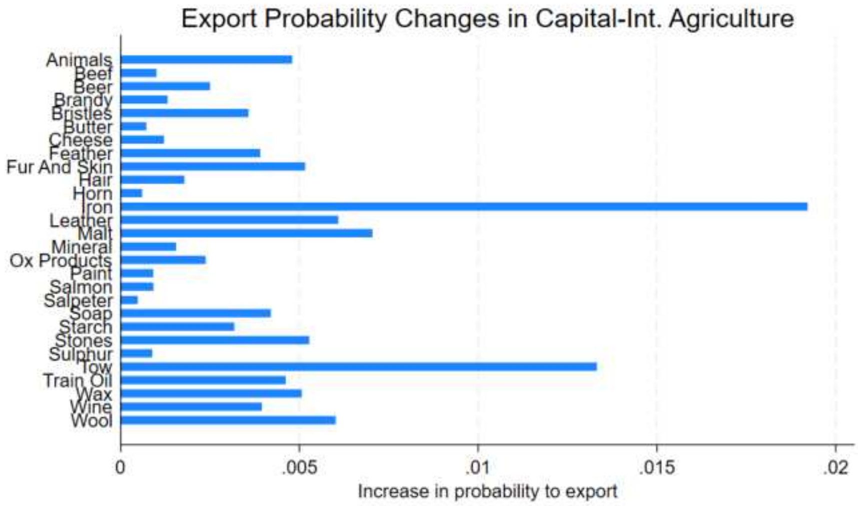


(d) # exported labour-int. ag. goods.

Notes: Estimation of equation 1 on the number of exported goods. Between 1668-1750, 55% of traded value was in labour-intensive agriculture, 27% in capital-intensive agriculture, 3% in labour-intensive manufacturing and 13 % in capital-intensive manufacturing.

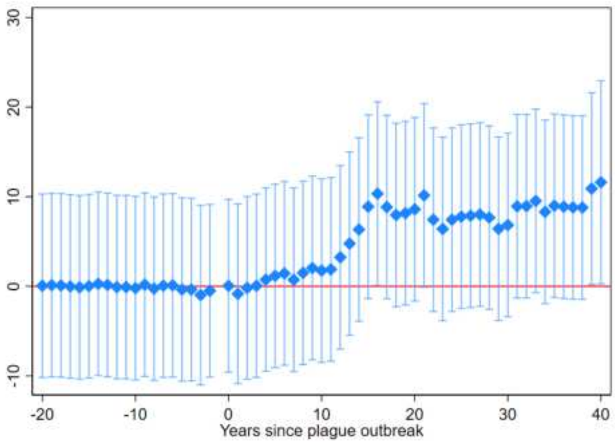
Figure 27: Fact #3: Extensive margin expansion by goods





Notes: Results from regressing a post plague dummy on a dummy for positive exports of good g from i to j in annual data, controlling for area x year, origin x destination, and destination x year fixed effects. Shown are only point estimates that are significant at the 5% level.

Figure 28: New exports at the intensive margin.



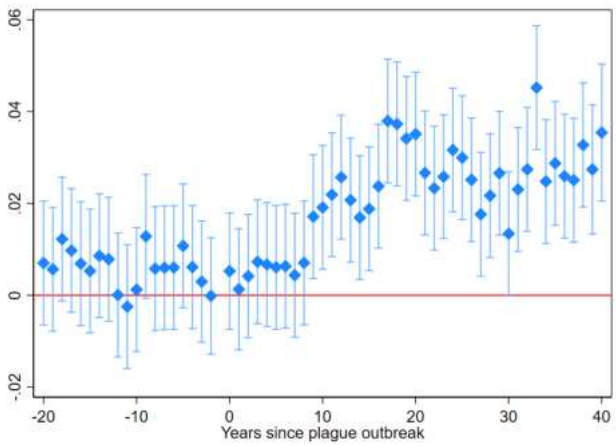
Notes: Estimation of equation 1 on trade volumes. A new export is defined as a good first exported by a city between 1689, 20 years before the onset of the plague in my study area, and 1732, 20 years after the last plague year in this region.

Table 19: Impact of plague on probability to export a good never exported before, by factor intensity.

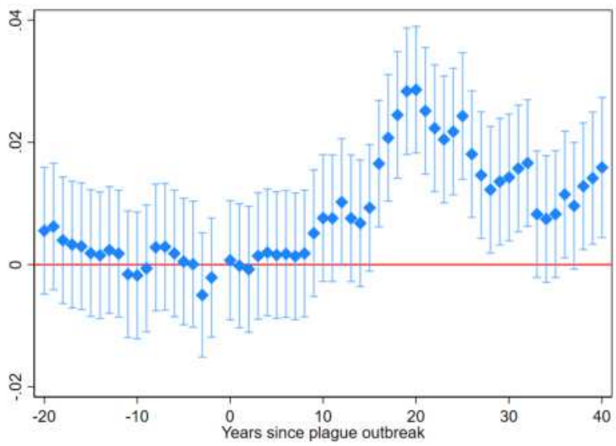
	Overall	Labour-intensive ag.	Capital-intensive ag.	Labour-intensive man.	Capital-intensive man.
	(1)	(2)	(3)	(4)	(5)
Post Plague	0.052***	0.011	0.021**	0.031***	0.012*
	(0.013)	(0.008)	(0.010)	(0.006)	(0.007)
Fixed Effects:					
– Area x Year	✓	✓	✓	✓	✓
– Origin	✓	✓	✓	✓	✓
– Controls	✓	✓	✓	✓	✓
Estimator	✓	✓	✓	✓	✓
Observations	37,296	37,296	37,296	37,296	37,296

Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The independent variable is a dummy for whether a region exports a good that it has never exported before. The dependent variable is a plague dummy, equal to one after the origin suffered a plague outbreak. The first 20 years of the data are dropped, as mechanically initially every good is new. Controls are annual growing season temperature, latitude x year, and longitude x year.

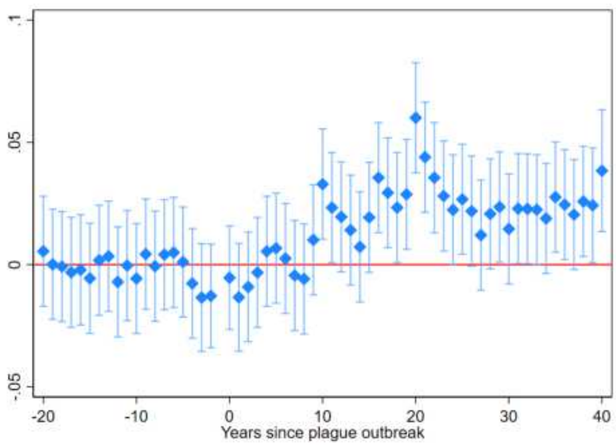
Figure 29: New exports at the extensive margin, by sector.



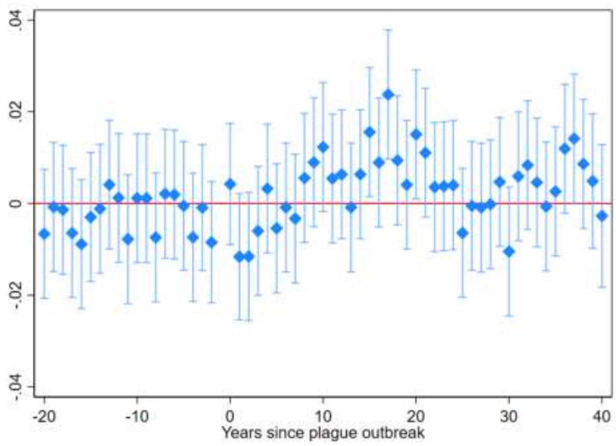
(a) # new exported capital-int. man. goods.



(b) # new exported labour-int. man. goods.



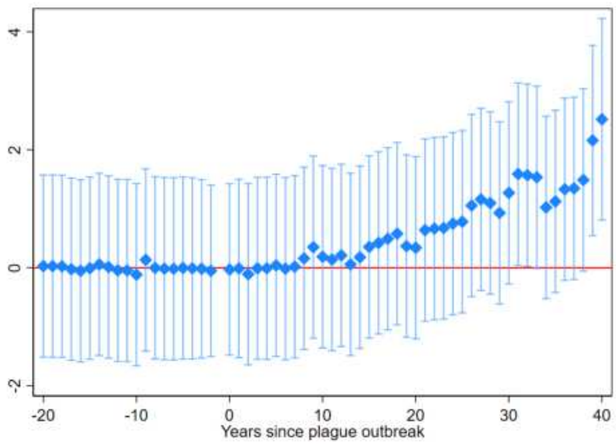
(c) # new exported capital-int. ag. goods.



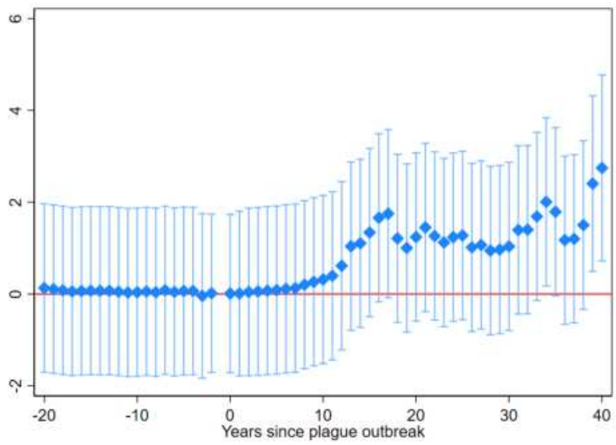
(d) # new exported labour-int. ag. goods.

Notes: Estimation of equation 1 on the number of exported goods, by sector. A new export is defined as a good first exported by a city between 1709, the onset of the plague in my study area, and 1732, 20 years after the last plague year in this region.

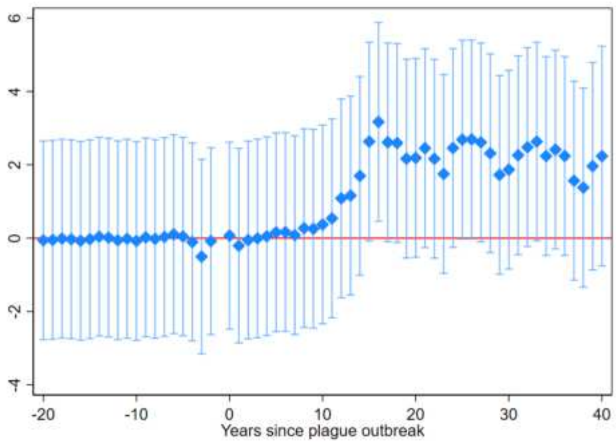
Figure 30: New exports at the intensive margin, by sector.



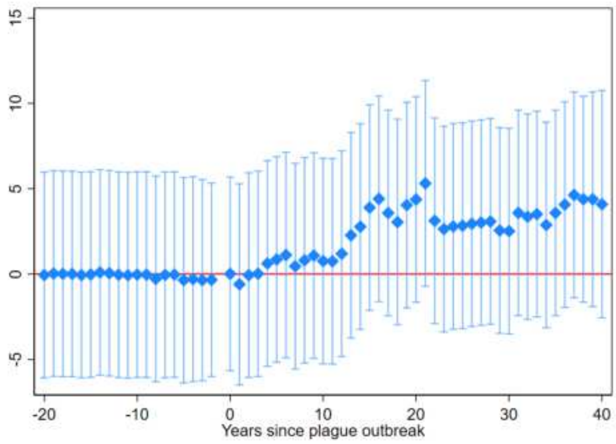
(a) Value of new export, capital-int. manuf.



(b) Value of new export, labour-int. manuf.



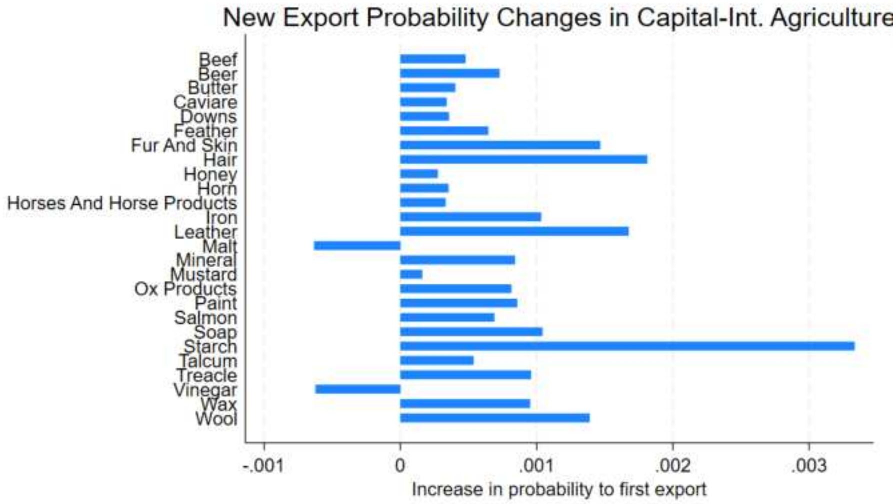
(c) Value of new export, capital-int. ag.

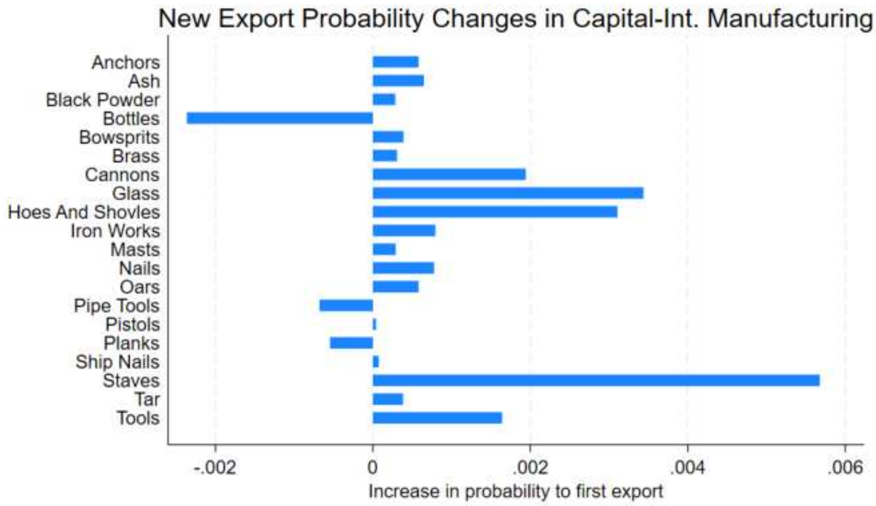


(d) Value of new export, labour-int. ag.

Notes: Estimation of equation 1 on export volumes, by sector. A new export is defined as a good first exported by a city between 1709, the onset of the plague in my study area, and 1732, 20 years after the last plague year in this region.

Figure 31: Fact #4: Increased probability of exporting a good for the first time





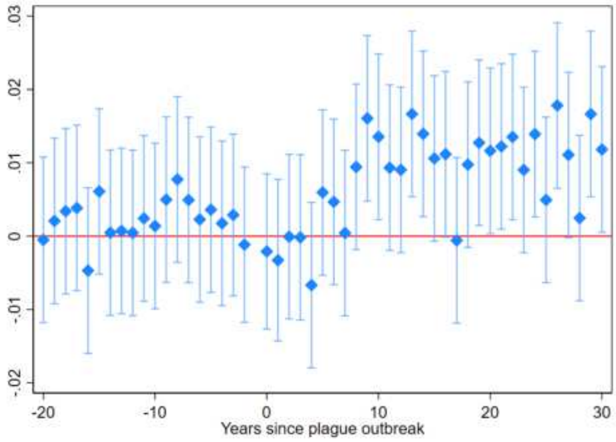
Notes: Results from regressing a post plague dummy on a dummy for a new export of good g from i to j in annual data, controlling for area x year, origin x destination, and destination x year fixed effects. A new export is a good not exported before the plague. Shown are only point estimates that are significant at the 5% level.

Table 20: Heterogeneity of trade findings by pre-plague export levels.

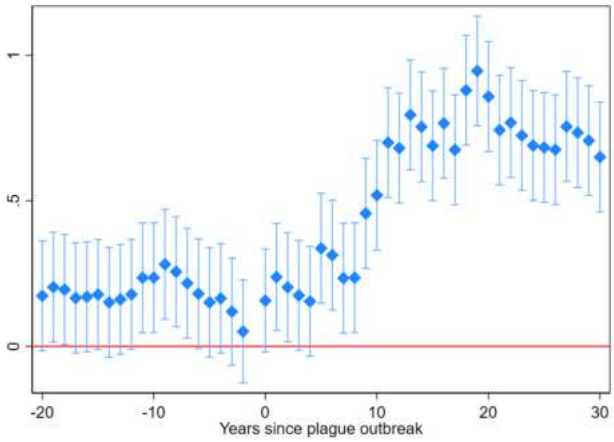
	Capital Share		Export Share		# Exported Goods		# New Exported Goods	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Post Plague	0.01391263***	0.00774167***	0.01030131***	0.00412286***	0.19896457***	0.12091257***	0.06557656***	0.02742579***
	(0.00050450)	(0.00058496)	(0.00095944)	(0.00111242)	(0.01605498)	(0.01975147)	(0.00416094)	(0.00511828)
Post Plague x Pre-Plague Exports		0.00000006***		0.00000006***		0.00004185***		0.00002045***
		(0.00000000)		(0.00000001)		(0.00000617)		(0.00000160)
Fixed Effects:								
– Area x Year	✓	✓	✓	✓	✓	✓	✓	✓
– Origin x Destination	✓	✓	✓	✓	✓	✓	✓	✓
– Destination x Year	✓	✓	✓	✓	✓	✓	✓	✓
Observations	488,538	488,538	488,538	488,538	488,538	488,538	488,538	488,538
Pre-Plague Average	0.0062	0.0062	0.0089	0.0089	0.3555	0.3555		

Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The dependent variable in columns 1-2 is the share of an origin's exports that are capital intensive. In columns 3-4, it is the market share origin i captures in j. In columns 5-6, it is the number of exported goods. In columns 7-8, it is the number of new exported goods. The independent variables for all four dependent variables are first a post plague dummy and then additionally its interaction with the level of exports (number of exported goods) for columns 1-4 (5-8).

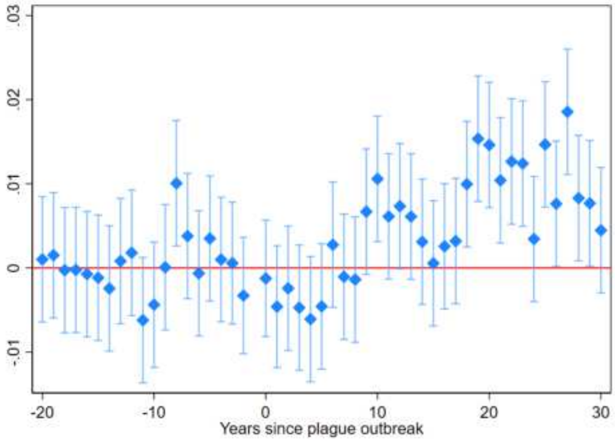
Figure 32: Export results not driven by negative demand shock in export hubs.



Import shares of plagued cities.



Number of imported goods of plagued cities.



Export shares, excl. top quintile of exporters.

Notes: If exports are concentrated in major hubs, a plague shock there would amount to a negative consumption shock. If production is less affected, then products brought to these market places would be pushed into exports. To the contrary, I find that plagued cities expand their imports at both margins, and that also smaller cities, unlikely to be export hubs, increase their exports after the plague.

D Model Appendix

This Appendix holds results supplementing the model. The first subsection describes how productivity growth is recovered from the model and the second subsection provides additional results on simulations and counterfactuals.

D.1 Recovering Sectoral Productivities

In this Section, I lay out my procedure for recovering sectoral productivities from the gravity equation. First, note that my setting compares to the approach chosen by Costinot, Donaldson, and Komunjer, 2011 in that I have an additional time dimension. Costinot, Donaldson, and Komunjer, 2011 show that the following relationship between trade flows, sectoral productivities, and trade costs is true in their model:

$$\frac{X_{ijk}X_{i'jk'}}{X_{ijk'}X_{i'jk}} = \left(\frac{A_{ik}A_{i'k'}}{A_{ik'}A_{i'k}}\right)^{\theta}\left(\frac{d_{ijk}d_{i'jk'}}{d_{ijk'}d_{i'jk}}\right)^{-\theta}. \tag{30}$$

This equation takes two ratios: one with respect to a reference sector k in i to eliminate wages in i, and another with respect to a reference region i' to eliminate the demand side for sector k. In my setting, I will additionally need to take time into account and form a third ratio. Thus, I will recover relative sectoral productivity growth. Time variation will be introduced into gravity equation 12 as follows:

$$X_{ijkt} = \frac{\chi_k A_{ikt}(w_{ikt})^{-\gamma_k\theta}d_{ijkt}^{-\theta}}{CMA_{jkt}}\alpha_k Y_{jt}. \tag{31}$$

The following result can be established from equation 31:

$$\frac{X_{ijkt}X_{ijk't'}X_{i'jkt'}X_{i'jk't}}{X_{i'jkt}X_{i'jk't'}X_{ijkt'}X_{ijk't}} = \frac{A_{ikt}A_{i'kt'}A_{ik't'}A_{i'k't}}{A_{ikt'}A_{i'kt}A_{ik't}A_{i'k't'}}\left(\frac{w_{ikt}w_{i'kt'}}{w_{i'kt}w_{ikt'}}\right)^{-\gamma_k\theta}\left(\frac{w_{ik't'}w_{i'k't}}{w_{i'k't'}w_{ik't}}\right)^{-\gamma_{k'}\theta}. \tag{32}$$

If one is willing to assume that $d_{ijkt} = d_{ijkt'} \forall (ij, kt)$ or at least that $\frac{d_{ijkt}}{d_{i'jkt}} = \frac{d_{ijkt'}}{d_{i'jkt'}}$, trade costs cancel out when forming this ratio. Therefore, an orthogonality assumption for trade costs is no longer required. As I am studying a relatively short period of time before the introduction of the steamship and it seems reasonable to further assume that trade costs were not changed by the plague, I am willing to make this assumption.

Three ratios are formed in equation 32. First, a ratio with respect to a reference sector k' in the same origin and time period. This allows to separate sectoral productivities from regional wages in period t, up to the wage equalisation condition induced by serfdom, which will be discussed below. Under appropriate assumption, the wage ratios will drop out. Second, a ratio with respect to a reference origin i' is formed, which leads to the demand side cancelling out in that equation 31 for both i and i' contains the same total expenditure and sectoral market access for destination j in period t. Third, a ratio with respect to a reference period t' is formed. This leads to the identification of growth relative to a reference period. Evidently, this three way differencing is precisely what a three-way fixed model delivers (Olden and Møen, 2022). I regress trade flows as follows:

$$X_{ijkt} = exp(\alpha + \delta_{ijt} + \delta_{jkt} + \delta_{ikt}) \times \epsilon_{ijkt}, \tag{33}$$

where i is the exporter, j the importer, k the sector, t the time, δ_{ijt} an importer-exporter-time fixed effect, δ_{ikt} an exporter-sector-time fixed effect and δ_{jkt} an importer-sector-time fixed effect. ϵ_{ijkt} is the error term. Note, first of all, that this specification nests all interaction terms of fixed effects and the model is therefore saturated (Angrist and Pischke, 2009). Second, note that the three-way fixed effect δ_{ikt} recovers differences-in-differences-in-differences (Olden and Møen, 2022):

$$\frac{\delta_{ikt}\delta_{i'kt'}\delta_{ik't'}\delta_{i'k't}}{\delta_{ikt'}\delta_{i'kt}\delta_{ik't}\delta_{i'k't'}} = \frac{\frac{\delta_{ikt}\delta_{i'k't}}{\delta_{ik't}\delta_{i'kt}}}{\frac{\delta_{ikt'}\delta_{i'k't'}}{\delta_{ik't'}\delta_{i'kt'}}}. \tag{34}$$

This is to say, δ_{ikt} recovers a time difference of what δ_{ik} recovered in Costinot, Donaldson, and Komunjer, 2011. Computing equation 32 confirms this finding, such that indeed δ_{ikt} captures the right hand side of equation 32:

$$\frac{A_{ikt}A_{i'kt'}A_{ik't'}A_{i'k't}}{A_{ikt'}A_{i'kt}A_{ik't}A_{i'k't'}}\left(\frac{w_{ikt}w_{i'kt'}}{w_{i'kt}w_{ikt'}}\right)^{-\gamma_k\theta}\left(\frac{w_{ik't'}w_{i'k't}}{w_{i'k't'}w_{ik't}}\right)^{-\gamma_{k'}\theta}. \tag{35}$$

Below, I will detail how equation 35 can be simplified in order to recover a productivity ratio from equation 33. Two assumptions are required:

1. All sectors have the same labour share, $\gamma_k = \gamma \forall k$.
2. **Either:** There is no time variation in the labour mobility friction, $\phi_{it} = \phi_{it'}$ and $\phi_{i't} = \phi_{i't'}$.
3. **Or:** The labour mobility friction does not vary within areas, such that $\phi_{ikt} = \phi_{jkt} \forall (k, t)$ and i,j within the same area.

To make progress in separating wages from productivities, I assume $\gamma_k = \gamma \forall k$. This permits to summarise both wage ratios. I then impose wage equalisation as assumed above. Allowing wages and the serfdom-induced labour mobility friction to vary over time, I assume:

$$w_{iMt} = \begin{cases} w_{iAt}, & \text{without serfdom,} \\ (1 + \phi_{it})w_{iAt}, & \text{with serfdom.} \end{cases} \tag{36}$$

Unclassified goods will be the reference sector k', which I assume to produce in the hinterland, paying wage w_{iAt}. Accordingly, for k=LA,CA, I can set $w_{ikt} = w_{ik't} \forall (i,t)$, such that the wage ratio drops out. Thus, δ_{ikt} identifies sectoral productivity growth compared to a reference region and sector, here unclassified goods, for both agricultural sectors.

For manufacturing, k=LM,CM, I plug in wage equalisation assumption 36 to obtain:

$$\delta_{ikt} = \frac{A_{ikt} A_{i'kt'} A_{ik't'} A_{i'k't}}{A_{ikt'} A_{i'kt} A_{ik't} A_{i'k't'}} \left(\frac{(1+\phi_{it})(1+\phi_{i't'})}{(1+\phi_{i't})(1+\phi_{it'})} \right)^{-\gamma\theta}. \tag{37}$$

The ratio of ϕ parameters simplifies to 1 under one of two conditions. First, if $\phi_{it} = \phi_{i't}$ and $\phi_{i't'} = \phi_{it'}$. At all points in time, the labour mobility friction would thus have to be of the same level, which I refuse to assume. Instead, I opt for the second condition: if $\phi_{it} = \phi_{it'}$ and $\phi_{i't} = \phi_{i't'}$, the ϕ ratio equals 1 and δ_{ikt} in equation 33 recovers a productivity ratio. This assumption implies the absence of time variation in the labour mobility friction. While Raster, 2023 argues for increased serfdom after the plague in Northern Estonia, this finding is compatible with the assumption as long as the degree to which this limits labour mobility is unchanged. I consider this a realistic assumption as serfdom restricted moving to urban areas before and after the plague. Further, the fundamental hurdle of moving to a German-speaking city while not having been allowed to learn a trade remained in place.

Alternatively, one can permit time variation in the serfdom-induced labour mobility friction, as long as the ϕ parameters do not vary within areas. In that case, area-sector-time fixed effects in equation 13 will absorb this area-sector-time specific variation. In this case, the plague may well have worsened serfdom and its effects on labour mobility. As long as these changes are symmetric within an area, the ϕ ratio will be absorbed by fixed effects.

A special case is presented by Denmark (including Norway and large parts of modern-day Schleswig Holstein), which is the only country in this area that re-introduced serfdom in 1733 (Gary et al., 2022). The ϕ ratio simplifies to $(1+\phi_{it})^{-\gamma\theta}$ when plugging in that region i in Denmark did not use to have serfdom ($\phi_{it'} = 0$) and that reference region i' had serfdom at no point in time ($\phi_{i't} = \phi_{i't'} = 0$). Therefore, for a value of ϕ_{it} in Denmark and parameter values γ, θ, the fixed effect δ_{ikt} can be cleaned for the change in serfdom. For both manufacturing productivities in areas that reintroduced serfdom, this adjustment is necessary when including Denmark and Norway and making the first assumption on serfdom, not the second. Figure 15 shows the value of ϕ_{it} for Copenhagen and her hinterland, based on wage data by Gary et al., 2022. The wage wedge takes a few years to materialise after 1733. The mean of ϕ_{it} after 1740 is 0.8, which means that urban wages were 80% higher than rural wages in the region of Copenhagen.

Regarding choosing a reference region i', I show that the choice of the reference region is irrelevant with the appropriate specification. The reference region matters for regressions on productivity growth without any fixed effects. Appendix Table 21 regresses a plague dummy on log productivity growth for agriculture and manufacturing for different choices of reference regions: London, Amsterdam, Rouen, Edinburgh, and Oslo, none of which were plagued[43]. Appendix Table 22 shows that the choice of reference region cancels out when introducing region and time fixed effects. Regarding the reference time t', I transform the recovered growth ratios such that they are at 1 in the first year of my data, 1668. Thus, all values are defined relative to 1668.

Table 21: Impact of plague on sectoral productivity growth, by reference region.

	Capital-int. Agriculture					Capital-int. Manufacturing				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Plague Dummy	1.657***	3.260***	2.016***	1.939***	0.484	0.589**	1.113***	0.987***	1.571***	2.474***
	(0.196)	(0.243)	(0.239)	(0.214)	(0.323)	(0.260)	(0.182)	(0.195)	(0.160)	(0.225)
Reference Region	London	Amsterdam	Rouen	Edinburgh	Oslo	London	Amsterdam	Rouen	Edinburgh	Oslo
Fixed Effects:										
– Region										
– Area x Year										
Observations	35,096	35,096	35,096	35,096	35,096	35,096	35,096	35,096	35,096	35,096

Notes: Bootstrapped standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The dependent variable is sectoral productivity growth by reference region. The independent variable is first a plague dummy that equals 1 for plagued cities after the plague hit. The second independent variable is the mortality rate, which for half of cities is imputed as the predicted value from regression results presented in Appendix Table 11.

Table 22: Impact of plague on sectoral productivity growth, by reference region.

	Capital-int. Agriculture					Capital-int. Manufacturing				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Plague Dummy	1.000***	1.000***	1.000***	1.000***	1.000***	0.400*	0.400*	0.400*	0.400*	0.400*
	(0.268)	(0.268)	(0.268)	(0.268)	(0.268)	(0.218)	(0.218)	(0.218)	(0.218)	(0.218)
Reference Region	London	Amsterdam	Rouen	Edinburgh	Oslo	London	Amsterdam	Rouen	Edinburgh	Oslo
Fixed Effects:										
– Region	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
– Area x Year	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Observations	34,932	34,932	34,932	34,932	34,932	34,932	34,932	34,932	34,932	34,932

Notes: Bootstrapped standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The dependent variable is sectoral productivity growth by reference region. The independent variable is first a plague dummy that equals 1 for plagued cities after the plague hit. The second independent variable is the mortality rate, which for half of cities is imputed as the predicted value from regression results presented in Appendix Table 11.

[43] One would expect that the assumption of no productivity growth is hardest to maintain for London as a reference region, which clearly saw manufacturing productivity growth at the onset of the Industrial Revolution. This is mirrored in the results of Appendix Table 21 in that the point estimates are slowest for the choice of London as the reference region. Compared to manufacturing productivity growth even in London, plagued regions still saw significantly faster productivity growth. As the comparison with London is the hardest one to survive, I choose London as the reference region i'.

Section 2 outlined how the end of the Little Ice Age saw temperatures rise across Northern Europe. Non-plagued regions will therefore have seen agricultural productivity growth as outlined by Waldinger, 2022. To account for exogenous and spatially varying temperature change at the end of the Little Ice Age, I permit agricultural productivity growth also in non-plagued regions as a function of temperature change. In plagued regions, I additionally allow for plague-induced productivity changes. I assume that for a non-plagued region i':

$$\frac{A_{i',At}}{A_{i',At'}} = \left(\frac{temp_{i',t}}{temp_{i',t'}}\right)^{\epsilon_A}. \tag{38}$$

I assume a value of $\epsilon_A = 1$ and correct the recovered agricultural productivity ratios for both labour- and capital-intensive agriculture for this term.

Finally, instead of estimating with OLS as in Costinot, Donaldson, and Komunjer, 2011 I use PPML on a balanced panel, which is required for the equivalence between their equations (17) and (18). There are a number of reasons for preferring PPML. First of all, the model generates a gravity equation for trade, so all arguments for PPML in Santos-Silva and Tenreyro, 2006 apply. The issue of zeros is much more prevalent in my data than in the data by Costinot, Donaldson, and Komunjer, 2011, whose trade data cover 21 countries and 13 industries. Mine cover 676 cities and 99% of observations in the balanced panel are zeros, highlighting the need for an appropriate estimation strategy. A share of zeros above 90% is common in granular historical trade studies (Jacks, O'Rourke, and Taylor, 2020).

To check if the recovered agricultural productivity growth values make sense, I analyse agricultural productivity growth by exploiting exogenous temperature variation[44]. In Table 23, I regress recovered agricultural productivity growth on (log) temperature growth compared to the 1660s and several time-invariant geographic controls. I find that agricultural productivity growth is significantly lower in areas further North and in more rugged areas and significantly higher in areas with higher long-run temperature averages. Appendix Map 33 shows how these agricultural productivities are distributed spatially. Clusters of high agricultural productivity growth are found in the Southern Baltic, the Low Countries, and on the French Atlantic Coast.

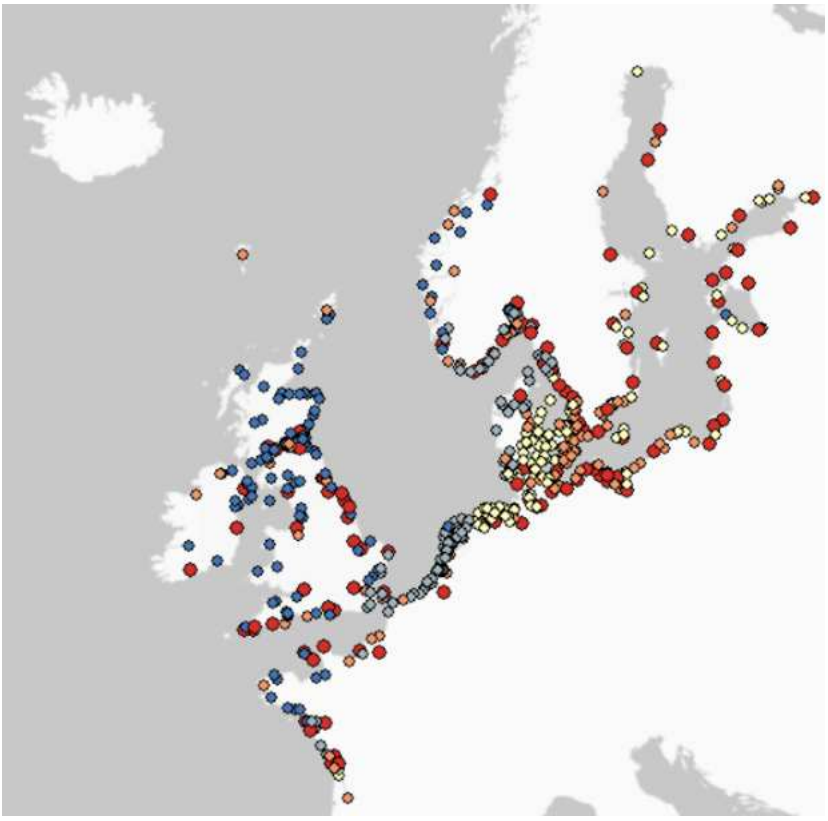
[44] I sum labour-intensive and capital-intensive agriculture as one sector for this exercise.

Table 23: Agricultural productivity growth and geography.

	Log Agricultural Productivity Growth					
	(1)	(2)	(3)	(4)	(5)	(6)
log Temperature Change	7.876***					
	(0.501)					
Temperature Change		7.999***				
		(0.500)				
Latitude			-0.0294***			
			(0.00819)			
Longitude				0.00956***		
				(0.00348)		
Long-run Temperature					0.0852***	
					(0.0162)	
Ruggedness						-0.00000307***
						(0.000000403)
Observations	47,714	47,714	47,714	47,714	47,714	47,714

Notes: Bootstrapped standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The dependent variable is agricultural productivity growth, relative to the 1660s, a reference region whose agricultural productivity growth is assumed to only be determined by exogenous temperature changes, and relative to productivity growth in non-tradables which I assume to be 0. The independent variables are temperatures during the growing season, latitude, longitude, the long-run temperature in a location (defined as the average growing season temperature during the 1950s, i.e. before the onset of man-made climate change but after the end of the Little Ice Age), and ruggedness.

Figure 33: Agricultural productivity growth between 1660 and 1800 by region.



Notes: Regions by quantiles of log agricultural productivity growth between 1660 and 1800. Warmer colours denote regions with higher agricultural productivity growth. Using assumption 38, I have adjusted recovered productivity growth for temperature changes during the end of the Little Ice Age.

D.2 Simulations

Figures 34 and 35 show simulation results comparing a simulated manufacturing productivity growth increase in the hypothetical full sample to the observed sample. I find that neither for trade nor for the recovered productivities the geographical particularity of my data, in that only ships passing through the Sound are registered, drives the results. For these simulations, I choose reference levels for wages, market access, χ_k, α_k, and Y_j and compute trade costs as $d_{ij}^{-\theta}$, where d_{ij} is distance over sea. I simulate two time periods, where in the first all regions, abstracting from simulated noise, have the same manufacturing productivity levels. Plagued regions then experience manufacturing productivity growth and have higher levels in the second period, whereas non-plagued regions keep their period 1 manufacturing productivity level. As all other variables and parameters are the same across regions, this implies that plagued regions' manufacturing productivity growth was twice as high as that of non-plagued regions. Thus, the simulated effect is $ln2 = 0.693$.

I construct simulated trade volumes following equation 12. In particular, I simulate trade volumes for the entire sample of theoretically observable trade connections. While in the observed sample only trade passing the Sound is registered, such that trade on only one side of the Sound is not observed, in the theoretical, full sample I simulate trade volumes also on these routes, for example from Amsterdam to London or Stockholm to Riga. Below, I show results for a log-normal specification of noise, where I take the log of simulated trade values, add standard normally distributed noise, and then take the exponential of these noise-amended trade flows. Results with multiplicative and uniformly distributed noise display the same pattern. I then recover sectoral productivities as described in Section D.1, in particular choosing non-tradables as the reference sector, London as the reference region, and the 1660s as the reference decade. I then regress a plague dummy on the recovered manufacturing productivity growth. These results are displayed in Figure 34. The simulated effect lies at 0.693, which is within 36 out of 100 confidence intervals for the regressions on the full sample without fixed effects and within 90 out of 100 CIs when including region and time fixed effects. For the observed sample, 86 out of 100 confidence intervals contain the simulated effect in the specification without fixed effects. The same is true for 96 out of 100 CIs when including region and time fixed effects. Overall, point estimates in all cases are centred around the simulated effect. The variance in the full sample is larger and across samples the specification with region and time fixed effects contains the simulated effect considerably more often.

I find similar results when regressing simulated trade volumes in both samples on a plague dummy, including origin-destination and destination-time fixed effects. These results, presented in Figure 35, show that a significant export increase is picked up in both samples. I run 100 simulations and show that the point estimates are very similar when comparing the full to the observed sample. In both samples, the point estimates are centred around the simulated effect, suggesting no bias is introduced by restricting to the observed sample. An important role here is played by the origin-destination fixed effects that control for time-invariant route selection.

I conclude that, most importantly, the sample restriction of only observing ships passing through the toll station is not introducing a bias in my productivity growth and trade estimates. I further conclude that the productivity growth specification with fixed effects produces more reliable results.

E Mechanisms Appendix

Table 24 shows that following a plague outbreak, cities significantly increased the number of ships they owned, which I interpret as a proxy for the capital stock.

Table 24: Impact of plague on proxied capital stock.

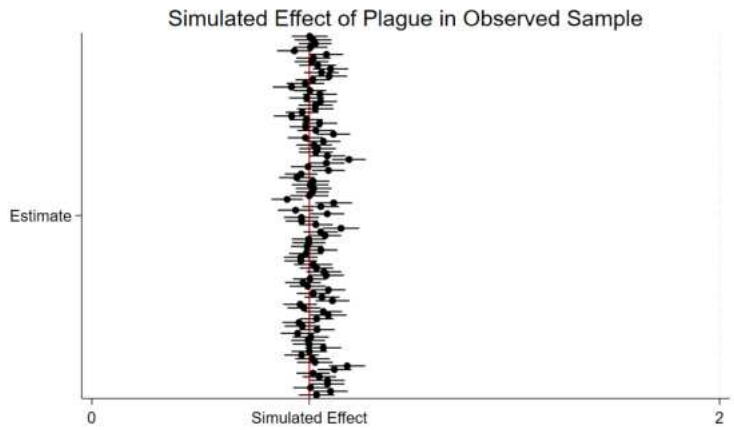
	# Ships							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Plague Dummy	195.331***	128.640***	190.905***	109.144***				
	(15.984)	(14.974)	(15.896)	(14.892)				
Mortality Rate					422.279***	284.977***	410.467***	234.493***
					(37.998)	(36.155)	(37.677)	(35.550)
Fixed Effects:								
– Region		✓		✓		✓		✓
– Decade			✓	✓			✓	✓
Observations	20,340	20,340	20,340	20,340	20,340	20,340	20,340	20,340

Notes: Bootstrapped standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The independent variable is the number of ships registered in a city. It is assumed that ships do not sit idle and therefore that every owned ship appears once a decade. Further I assume that ships from the same city with the same captain in the same year are duplicates and drop these. The dependent variable is first a plague dummy that equals 1 for plagued cities after the plague hit. The second dependent variable is the mortality rate, which for half of cities is imputed as the median over the available data.

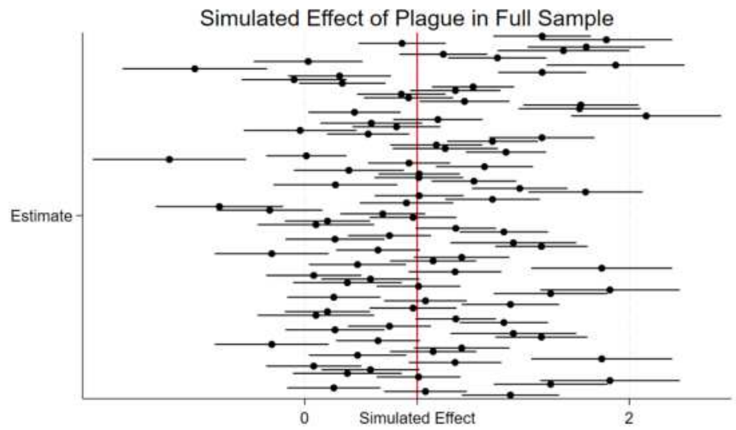
This Appendix shows results supporting the mechanism proposed in this paper. Table 25 adjusts manufacturing productivities in Denmark and Norway for the introduction of serfdom based on wage wedges identified in data by Gary et al., 2022. For full details, see Appendix D.1. I adjust manufacturing productivities in serfdom-switching areas after 1740, as the 1733 reintroduction did not immediately show an increased wage wedge between city and hinterland (see Figure 15).

Table 26 shows that farms shifted more strongly out of labour-intensive and into capital-intensive agriculture the closer they were to plagued cities. Figure 36 shows output per farm in Scania, adjusting for farm size, and documents only a small and brief dip in output after the plague. Figure 37 decomposes the wharves producing ships for the Swedish East India Company. Those that were built in wharves founded after the plague in plagued regions account for the majority on all accounts.

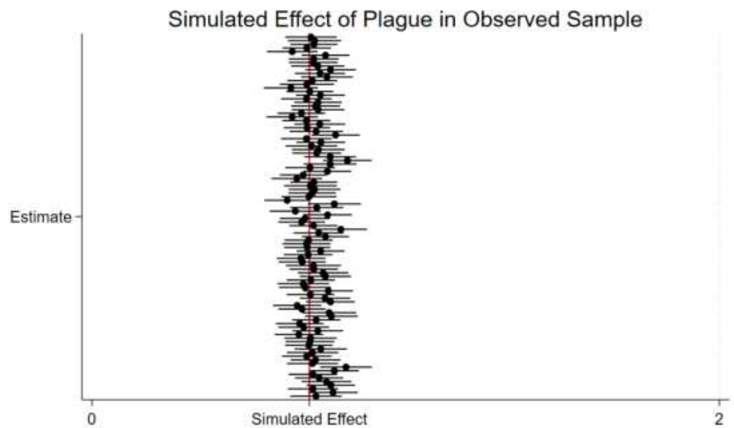
Figure 34: Simulated productivity growth increase in observed vs. full sample.



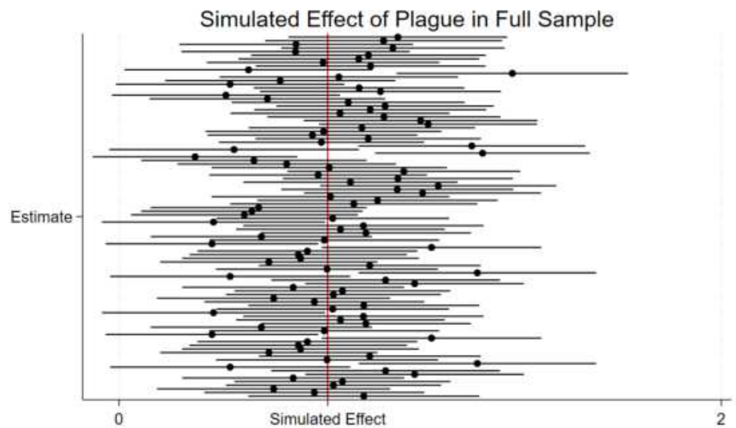
(a) Observed sample; no fixed effects.



(b) Full sample; no fixed effects.

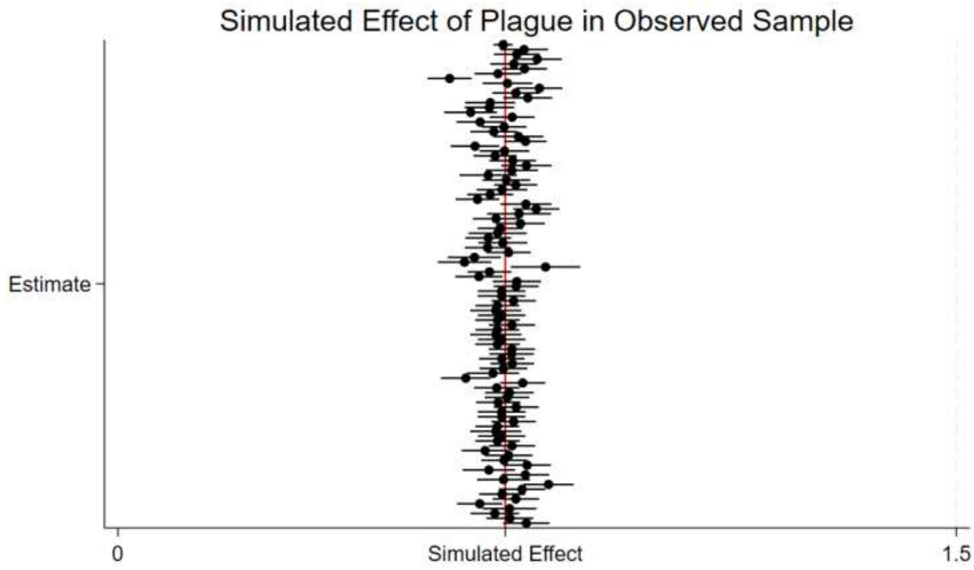


(c) Observed sample; region and time fixed effects.

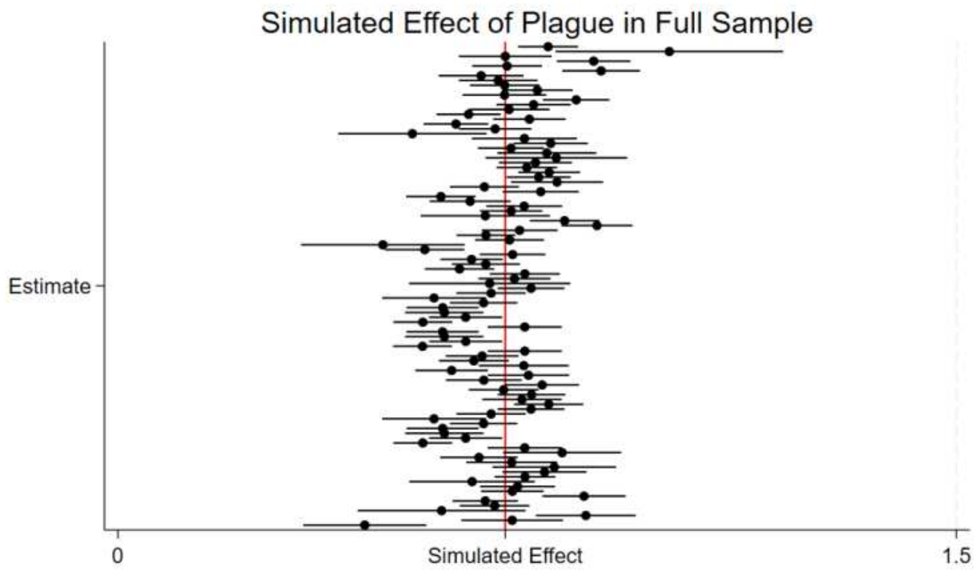


(d) Full sample; region and time fixed effects.

Figure 35: Simulated trade in observed vs. full sample.



(a) Observed sample; origin-destination and destination-time fixed effects.



(b) Full sample; origin-destination and destination-time fixed effects.

Table 25: Impact of plague on sectoral productivity growth, by sector and factor intensity. Manufacturing productivity adjustment for Denmark reintroducing serfdom.

	Agriculture				Manufacturing			
	Labour-intensive		Capital-intensive		Labour-intensive		Capital-intensive	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Plague Dummy	0.282		0.778***		-1.086***		0.174	
	(0.181)		(0.212)		(0.169)		(0.173)	
Mortality Rate		0.534		2.003***		-2.789***		0.700
		(0.471)		(0.553)		(0.440)		(0.451)
Fixed Effects:								
– Region	✓	✓	✓	✓	✓	✓	✓	✓
– Area x Year	✓	✓	✓	✓	✓	✓	✓	✓
Observations	47,550	47,550	47,560	47,560	47,560	47,560	47,560	47,560

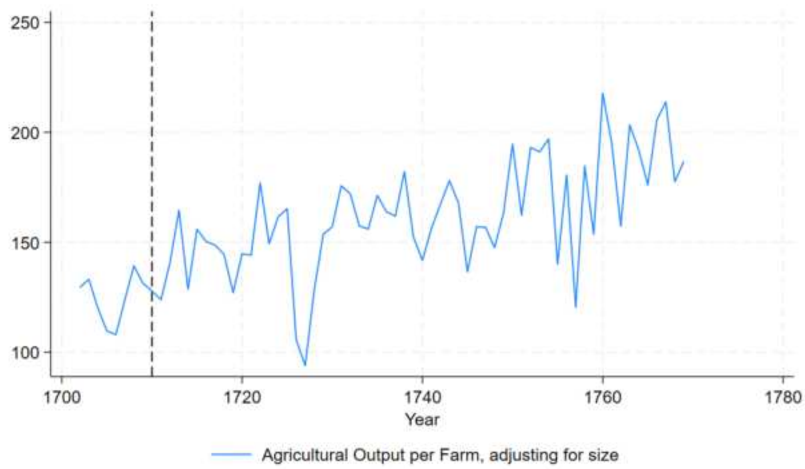
Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The dependent variable is log sectoral productivity growth. This has been adjusted for the introduction of serfdom in Denmark and Norway. The independent variable is first a plague dummy that equals 1 for plagued regions after the plague hit. The second independent variable is the mortality rate, which for half of regions is imputed as the predicted value from regression results presented in Appendix Table 11.

Table 26: Farm production and distance to plagued cities.

	Calves	Rye	Barley
	(1)	(2)	(3)
Plague Distance x Post Plague	-0.00656***	0.0182***	0.0355***
	(0.000717)	(0.000529)	(0.000636)
Fixed Effects:			
– Year	✓	✓	✓
– Farm	✓	✓	✓
Observations	5,683	5,304	5,304

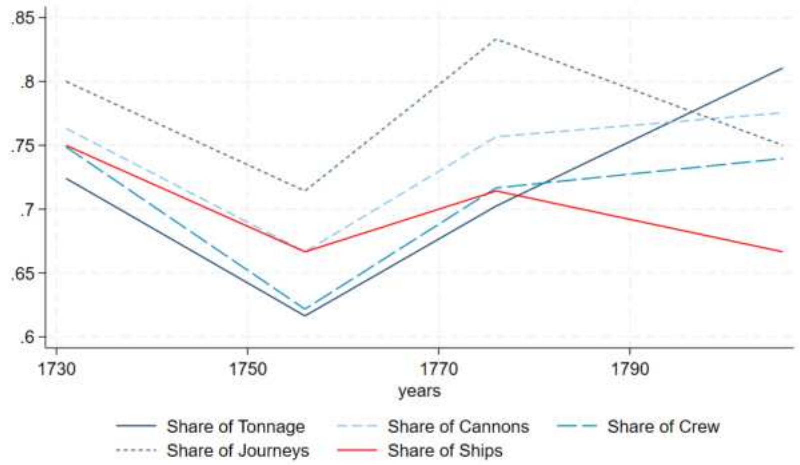
Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The independent variables are farm's production of calves, rye, and barley. The dependent variable is the sum of distances multiplied by a plague dummy over the four closest cities in Scania province. Both Ystad and Malmö suffered a plague outbreak in 1712 with a mortality rate of 38% and 35%, respectively, whereas Landskrona and Helsingborg did not suffer plague outbreaks.

Figure 36: Total value of agricultural production per farm, controlling for farm size.



Notes: Figure 36 covers all farms in Scania and their total output.

Figure 37: Share of Swedish Wharf Output by Plague Status.



Notes: Based on data on the production location of all ships (n=30) operated by the Swedish East India Company. Wharves founded in plagued regions after 1714 are classified as located in plagued regions. The y axis denotes the share of tonnage, journeys, cannons, crew and ships for four points in time produced in wharves founded after the plague in plagued regions.

Tables 27 and 28 differentiate post-plague productivity growth by serfdom.

Table 27: Impact of plague on sectoral productivity growth, by second serfdom.

	Agriculture		Manufacturing	
	Labour-intensive	Capital-intensive	Labour-intensive	Capital-intensive
	(1)	(2)	(3)	(4)
Plague	0.083	1.287***	-0.890***	0.464
	(0.300)	(0.351)	(0.279)	(0.286)
Plague & Serfdom	0.187	-0.634	-0.919**	-0.141
	(0.427)	(0.501)	(0.398)	(0.407)
Fixed Effects:				
– Region	✓	✓	✓	✓
– Area x Year	✓	✓	✓	✓
Observations	34,922	34,932	34,932	34,932

Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The dependent variable is log sectoral productivity growth. The independent variable is a plague dummy that equals 1 for plagued regions after the plague hit interacted with a dummy for second serfdom. Denmark and Norway have been dropped from the sample as they reintroduced serfdom in 1733.

Table 28: Impact of plague on sectoral productivity growth, by second serfdom. Manufacturing productivity adjustment for Denmark reintroducing serfdom.

	Agriculture		Manufacturing	
	Labour-intensive	Capital-intensive	Labour-intensive	Capital-intensive
	(1)	(2)	(3)	(4)
Plague	0.093	1.272***	-0.853***	0.441*
	(0.270)	(0.317)	(0.252)	(0.259)
Plague & Serfdom	0.326	-0.849**	-0.402	-0.459
	(0.346)	(0.406)	(0.323)	(0.331)
Fixed Effects:				
– Region	✓	✓	✓	✓
– Area x Year	✓	✓	✓	✓
Observations	47,550	47,560	47,560	47,560

Notes: Standard errors in parentheses. * p <0.10, ** p <0.05, *** p <0.01. The dependent variable is log sectoral productivity growth. This has been adjusted for the introduction of serfdom in Denmark and Norway. The independent variable is a plague dummy that equals 1 for plagued regions after the plague hit interacted with a dummy for second serfdom. Denmark and Norway have been dropped from the sample as they reintroduced serfdom in 1733.

F Counterfactuals

This appendix provides details on the counterfactuals provided in Section 6.

Shutting Down The Productivity Channel

Constructing export shares, the outcome of equation 1, according to gravity equation 12, I find that shares can be expressed as:

$$s_{ijk} = \frac{X_{ijk}}{\Sigma_i X_{ijk}} = \frac{A_{ik}(w_{ik})^{-\gamma_k\theta} d_{ijk}^{-\theta}}{\Sigma_i A_{ik}(w_{ik})^{-\gamma_k\theta} d_{ijk}^{-\theta}}. \tag{39}$$

When plugging in equation 14 for wages and equations 10 for firm and consumer market access, I arrive at an equation defining market shares as a function of productivities, sectoral employment, trade costs, wages, and total income:

$$s_{ijk} = \frac{A_{ik}^{\frac{1}{1+\gamma_k\theta}} L_{ik}^{\frac{\gamma_k\theta}{1+\gamma_k\theta}} \left(\Sigma_j d_{ijk}^{-\theta} Y_j \left(\Sigma_i A_{ik}(w_{ik})^{-\gamma_k\theta} d_{ijk}^{-\theta} \right)^{-1} \right)^{\frac{-\gamma_k\theta}{1+\gamma_k\theta}} d_{ijk}^{-\theta}}{\Sigma_i A_{ik}^{\frac{1}{1+\gamma_k\theta}} L_{ik}^{\frac{\gamma_k\theta}{1+\gamma_k\theta}} \left(\Sigma_j d_{ijk}^{-\theta} Y_j \left(\Sigma_i A_{ik}(w_{ik})^{-\gamma_k\theta} d_{ijk}^{-\theta} \right)^{-1} \right)^{\frac{-\gamma_k\theta}{1+\gamma_k\theta}} d_{ijk}^{-\theta}}.$$

To shut down the productivity channel, I assume A_{ik} to be fixed. I also assume fixed trade costs d_{ijk} and destination income Y_j. Only trade between the Baltic and North Seas is observed, and the plague struck almost exclusively on the Baltic Sea, rendering this a reasonable assumption. I also make an assumption on the sum $\Sigma_i A_{ik}(w_{ik})^{-\gamma_k\theta} d_{ijk}^{-\theta}$ to keep changes tractable. Essentially, I assume that wage changes in plagued regions leave the entire sum almost unchanged.

Let PRE denote pre-plague, POST immediately after the plague, and t the number of years since the plague. Assume $\Sigma_i A_{ikPOST} w_{ikPOST}^{-\gamma_k\theta} d_{ijkPOST}^{-\theta} \approx \Sigma_i A_{ikPOST} w_{ikPOST}^{-\gamma_k\theta} d_{ijkPOST}^{-\theta}$. While individual regions' wages changed and I assume productivities and trade costs to be fixed, I essentially assume that wage increases in a few plagued regions do not move the entire sum over all regions by much.

In the estimation equation, destination-sector-time fixed effects absorb changes in these sums regardless. When counterfactually shutting down the productivity channel, one can then write $s_{ijkt}^c = \frac{L_{ikt}}{L_{ikPRE}}^{\frac{\gamma_k\theta}{1+\gamma_k\theta}} s_{ijkPRE}$.

I model the population recovery from L_{iPOST} to L_{it} to happen exponentially over 90 years. This is the upper bound, as by 1800 plagued cities had recovered their populations. I assume that after 90 years, regional and not just urban populations had recovered. This yields:

$$s^c_{ijkt} = (1 - m_i)^{\frac{\gamma_k \theta}{1+\gamma_k \theta}} \left(\frac{1}{1 - m_i} \right)^{\frac{\frac{\gamma_k \theta t}{1+\gamma_k \theta}}{90}} s_{ijkPRE}.$$