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The Economic Origins of Vaccine Uptake: Evidence from Smallpox in Nineteenth-Century France

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Abstract

Why does a population become accustomed to vaccination? To explore this question, we gathered detailed data on the number of children vaccinated against smallpox annually in French departments from 1806 to 1888. By using wheat prices instrumented by rainfall and the phylloxera crisis as exogenous sources of income variation, we identify negative income shocks as a strong driver of vaccination. This outcome can be attributed to the higher smallpox mortality associated with negative shocks before the introduction of vaccination. Consequently, parents were more likely to vaccinate their children when their survival was potentially threatened by a higher (expected) prevalence and severity of the infectious disease. This behaviour explains the suboptimal diffusion of vaccination in France throughout the nineteenth century. These findings bear important implications for the diffusion of vaccination in the long run.

JEL codes : I12; I15; N33; N54

Keywords : economic shocks, vaccination, vaccine uptake, smallpox

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1 Introduction

Over centuries, humanity has battled against epidemics and pandemics, employing various strategies to mitigate their impact. Among the most effective tools in this arsenal are vaccines, which have revolutionised our ability to prevent and control the spread of infectious diseases. Vaccination is estimated to prevent about six million deaths each year worldwide, contributing to lower childhood mortality, higher life expectancy, and broader social and economic benefits such as improved education, productivity, and economic growth (Ehreth, 2003; Bloom et al., 2004, 2005). Yet universal immunisation remains elusive. In 2022, about 14 million children, mainly in low- and lower-middle-income countries, had never received a single vaccine (Kaur et al., 2023). Beyond social and economic barriers, vaccine hesitancy[1] has emerged as a major global health threat and is associated with a fall in vaccine uptake and a greater spread of vaccine-preventable diseases (Kennedy, 2020)[2]. Understanding the factors that drive vaccine uptake is therefore essential, but our knowledge of what enables populations to adopt vaccination widely remains limited, despite the increasing volume of scientific literature addressing vaccine uptake or hesitancy (see Figure A1). This is largely due to empirical challenges, as vaccines have seldom been both available and voluntary for a long time period.

Our paper contributes to fill this gap by investigating the impact of local income shocks on vaccine uptake. To do so, we collected data on vaccination against smallpox at the department level in France between 1806 and 1888[3]. The vaccination process was first introduced in France in 1800. Before its discovery and generalisation, smallpox was one of the major cause of death, accounting for around 10% of the overall mortality in Europe. Vaccination remained voluntary until 1888 in France, when it was made compulsory for the military, before becoming mandatory for all children in 1902. This setting therefore offers a unique opportunity to study the drivers of vaccine uptake for a deadly disease over nearly a century.

We employ two estimation strategies to identify the causal impact of economic shocks on vaccine uptake. Firstly, we rely on wheat prices as an indicator of the cost of cereals, which

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[1]This term encompasses various behaviours, including outright refusal of vaccines, postponing vaccination, accepting vaccines while being uncertain about their efficacy, or selectively choosing to receive certain vaccines while rejecting others. Vaccine-hesitant individuals are therefore in the middle of a continuum ranging from complete acceptors to complete refusers (MacDonald, 2015).

[2]A prominent example is the recent increase in measles cases in Europe and the US, coupled with a decline in MMR vaccination rates.

[3]Departments are administrative areas approximately similar in size to U.S. counties.

represented the largest part of people's diet in nineteenth-century France. We instrument the price of staple food by using monthly rainfall. We construct our rainfall measure using both historical information and data based on climate modelling. To reinforce the reliability of the IV estimations and take into account the potential issues linked to the use of rainfall instruments (Mellon, 2025), our second estimation strategy exploits the phylloxera crisis which caused a dramatic fall in wine production from the mid-1870s to the end of the century in France in an event-study setting. The contamination that followed the introduction of this insect is estimated to have cost France around 50% of one-year GDP. Its impact was mostly concentrated in wine growing departments.

Both estimation strategies provide consistent evidence that negative income shocks increased vaccination against smallpox. The first strategy indicates that a one standard deviation in prices was associated with an increase in the vaccination rate of around 15 percentage points. This is a considerable change, as the average vaccination rate over the century fluctuated around 60%. Similarly, the production crisis triggered by phylloxera shows a comparable effect. In departments affected by the insect, and where wine production dropped sharply, vaccination rates rose by 10–20 percentage points in the three years following full contamination, and by 25–35 percentage points in the subsequent years.

The results remain robust after controlling for various potential determinants of vaccination, including the concentration and fluctuations in the number of medical practitioners, the influence of other major epidemics, as well as levels of distrust toward the ruling elite and religion. Robustness checks using alternative measures of price levels, vaccination rates, and rainfall volumes likewise do not affect the significance of the findings. In particular, incorporating child and infant mortality in the construction of vaccination rates does not alter the results. Regarding the event-study approach specifically, robustness tests that use only never-treated or not-yet-treated departments as control groups, as well as those based on a balanced panel or alternative baseline periods, continue to yield significant results. Finally, both an instrumental variable approach and a standard difference-in-differences strategy confirm that negative income shocks associated with the phylloxera crisis had a positive impact on smallpox vaccination rates.

Next, we explore several transmission channels between negative shocks and a higher vac-

cination against smallpox. We argue the response reflects higher expected and effective prevalence and severity of smallpox during negative shocks, consistent with pre-vaccination evidence linking price spikes to smallpox mortality. Two factors explain this association: an increased prevalence of the disease due to a higher mobility and a stronger severity linked to malnutrition. Parents anticipated this potentially higher risk and chose to vaccinate their children more often when negative income shocks took place. This behaviour explains why herd immunity against smallpox was only attained in France when vaccination progressively became mandatory for the entire population.

To bolster this interpretation, we test alternative mechanisms suggested in the literature. First, we examine whether public authorities introduced greater incentives to vaccinate during times of negative economic shocks by collecting data on vaccination spending. We find no significant relationship between economic shocks and spending levels. Additionally, we provide suggestive evidence that agricultural workers did not have more free time during economic downturns, which could have reduced the opportunity cost of taking time to vaccinate their children.

From a public policy perspective, our findings carry significant implications for shaping vaccination policies. Our paper indeed shows that parents are significantly more likely to vaccinate their children when having their "back against the wall", notably in case of outbreaks and a higher (expected) prevalence and severity of infectious diseases. This time-inconsistent behaviour leads to a significant level of volatility in vaccine uptake over time. As of today, childhood vaccination remains only recommended in around 22% of the countries for which legal information on vaccination can be retrieved (Vanderslott and Marks, 2021) (see map in Figure A2), despite evidence that such mandates are effective in boosting vaccination coverage and lowering mortality across different settings and diseases (Abrevaya and Mulligan, 2011; Carpenter and Lawler, 2019; Acton et al., 2024; Brehm and Saavedra, 2024). Our findings support enforcing a legal vaccination mandate to maintain high immunisation levels in these countries, regardless of infectious disease prevalence or severity. Without such an obligation, we expect yearly vaccine uptake to be much more volatile, and the vaccination rate to fall short of herd immunity level in the long run, with potential dramatic consequences on health and economic outcomes.

Furthermore, our findings can help improve the effectiveness and timing of vaccination campaigns when mandatory vaccination is not feasible or enforceable. Our results indicate that individuals are more likely to accept vaccination during times of negative income shocks and of (expected) heightened prevalence or severity of infectious diseases. Consequently, efforts to boost vaccine uptake and disseminate information about vaccination should be intensified under such circumstances.

This paper contributes to the existing literature in three different ways. First, we contribute to the growing scientific production on the determinants of vaccine uptake. Complementing the studies cited above on legal mandates, this literature has shown that vaccination declines with deprivation, as a low income and socio-economic status is associated with a lower vaccine uptake. Education is generally found to have a positive effect on vaccination, even if there is a consistent negative effect of maternal high education on vaccination compliance (Feiring et al., 2015; Anello et al., 2017; Keats, 2018). The intensity of religious practice also lowers vaccine uptake (Pearce et al., 2008; Rondy et al., 2010), as well as living farther away from an immunisation site (Oster, 2009; Aggarwal, 2021). There is also strong evidence of a link between vaccine uptake and attitudes towards vaccination. Indeed, believing in vaccine efficacy and that vaccines do not lead to adverse effects are associated with higher vaccine uptake (Hak et al., 2005; Smith et al., 2017). Moreover, income and education generally impact vaccine hesitancy in the same way than they affect uptake, and this relationship also holds true in the COVID-19 context (Larson et al., 2014)[4]. Vaccine hesitancy therefore appears as being a strong driver of a lower vaccination coverage (Detoc et al., 2020). This literature nearly always considers correlation between opinion, socio-economic factors, and vaccine uptake relying on survey data in a static way. In this paper, we adopt a dynamic approach and, thanks to our historical data, we are able to investigate the determinants of vaccination in the long run, without having to focus on uptake in a given year within a subsample of the population. We are therefore able to study how and why a given country would get accustomed, or not, to vaccination. Our approach therefore also differs from and complements the existing literature focusing on incentives to improve uptake, and which has notably put forward the importance of social signalling, the communication of peer figures, as well as financial and consumption

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[4]At the society level, a relatively recent changing attitude towards scientific expertise and a profound distrust in elites and experts have also been identified as being strongly correlated with vaccine hesitancy (Kennedy, 2019).

incentives, to improve the diffusion of vaccination (Banerjee et al., 2010a; Ranganathan and Lagarde, 2012; Alsan and Eichmeyer, 2024; Karing, 2024; Banerjee et al., 2025).

Second, the findings of this paper also contribute to our understanding of diseases, epidemics and pandemics by investigating the determinants of vaccination, and thereby improving our knowledge of the means used to reduce their prevalence. To this date, much of the existing literature has primarily focused on the repercussions of epidemics or pandemics, or incorporated the shocks generated by these events into their analytical approach. The Black Death, Spanish flu, or more recently COVID-19 pandemics (among others) have notably been used to study the impact of pandemics on mass persecutions or violence (Jedwab et al., 2019; Cervellati et al., 2022), mortality (Clay et al., 2018; Barro et al., 2020) economic performance and labour market outcomes (Almond, 2006; Karlsson et al., 2014; Correia et al., 2022; Jedwab et al., 2022; Fenske et al., 2022; Guerrieri et al., 2022). The same is true for smallpox, as a large part of the existing literature focused on its demographic impact and the efficiency of vaccination in mitigating this effect (Mercer, 1985; Pitkänen et al., 1989; Sköld, 1997; Banthia and Dyson, 1999; Sköld, 2003; Ager et al., 2018; Schneider et al., 2023)[5]. To our knowledge, only two papers investigated the determinants of vaccination over time. They notably showed that, in the cases of Scania in Sweden and of the German states of Baden and Wurttemberg, vaccination spread was favoured by education, better information on vaccine, a higher level of trust in the authorities and the establishment of a public vaccination system which improved vaccine supply and the financial support of vaccinators (Dribe and Nystedt, 2003; Mühlhoff, 2022).

This paper also contributes to the literature on the effect of recessions on future health and economic outcomes. This literature has shown that early childhood exposure to adverse economic circumstances had negative effects on mortality later in life (van den Berg et al., 2006), adult health, educational attainment, employment and socioeconomic status (Case et al., 2005; Currie, 2009; Meng and Qian, 2009; Almond et al., 2018). Another strand of the literature has shown that, especially in industrialised countries with a developed welfare state (Suhrcke and Stuckler, 2012), recessions can be associated with a short-run improvement in health outcomes and a reduction in mortality. This is due to a decline in obesity, smoking, alcohol consumption

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[5]A debate on the link between smallpox and stunting appeared in *The Economic History Review* between 1996 and the early 2000s. It began with Voth and Leunig (1996), who found a negative effect of smallpox on height, a result challenged by Razzell (1998) and Heintel and Baten (1998). Oxley (2003) later argued that the apparent association reflected smallpox's prevalence in the poorest and most densely populated parts of London rather than a direct biological effect.

and the occurrence of motor vehicle accidents in periods of higher unemployment (Ruhm, 2000, 2003, 2005; Adda et al., 2009; Miller et al., 2009). Economic recessions might also contribute to decrease the transmission of viral diseases by reducing mobility between regions and inter-regional trade (Adda, 2016). We contribute to this body of literature by demonstrating that adverse income shocks can positively impact health outcomes in the short and long run through an increase in vaccination, if parents expect their children to be more severely impacted by diseases in times of negative shocks. Moreover, disease control thanks to vaccination, including against smallpox (Lazuka and Jensen, 2024), leads to better economic outcomes later in life (Bütikofer and Salvanes, 2020). Our results therefore show that the negative effect of negative shocks on both future economic and health outcomes can be partly compensated by their positive effect on vaccination.

The article proceeds as follows. Section 2 describes the historical background of smallpox and vaccination. Section 3 provides information on the data used and Section 4 presents the empirical strategies. The main empirical results are introduced and discussed in Section 5, while Section 6 presents the transmission channels. Section 7 concludes.

2   Historical Background

2.1   The Spread of Smallpox Until the Nineteenth Century

Smallpox is an infectious disease of viral origin, highly contagious and epidemic, caused by a poxviridae virus. The primary mode of transmission for the disease was through extended face-to-face contact with an infected individual, although it could also be transmitted, albeit rarely, through contact with contaminated objects. Initial symptoms typically included fever and vomiting, followed by the development of ulcers in the mouth and a skin rash characterised by the formation of fluid-filled blisters, which often result in scarring upon healing (see the course of smallpox in Figure A3).

After having emerged as a human disease in Africa around 10,000 BC and having spread to Asia during the first millennium BC (Saluzzo, 2004; Riedel, 2005), smallpox was most likely introduced in Europe by Arab armies during the 7th and 8th centuries[6]. From that time, it

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[6]Additional information on the spread of the smallpox virus is provided in subsection B.2 of the Appendix.

slowly spread all over the continent. By the mid-eighteenth century, smallpox had become a widespread endemic disease worldwide. In eighteenth-century Europe, around 80% of each cohort got infected, with a case fatality rate ranging from 10% to 30%. Smallpox was a leading cause of death, claiming an estimated 400,000 lives annually. One-third of all cases of blindness were also attributed to smallpox. In France alone, it is estimated to have caused between 50,000 and 80,000 deaths each year, contributing to approximately 10% of the total mortality during the eighteenth century (Darmon, 1986).

As it became endemic, smallpox also turned into a disease that mainly affected children (Davenport et al., 2011). During the eighteenth century, nearly all inhabitants of London were infected by age 7. But this was not restricted to big cities as the mean age at death was for example 4.5 years in the small English town of Penrith (Duncan et al., 1993). It is more generally estimated that this average age was of 2.6 years in Scotland (Razzell, 1977) and that 90% of smallpox deaths in England were under the age of 5 (Fenner et al., 1988).

2.2 Vaccination and the Slow Eradication of Smallpox

It seems to have been a common belief in eighteenth-century England that dairymaids infected by cowpox, one of the animal versions of the poxviridae family of viruses, became immune to smallpox. On 14 May 1796, the British physician Edward Jenner inoculated a child with pus taken from the hand of a farmer who had been infected with cowpox. Three months later, he inoculated the child from a fresh smallpox lesion. He didn't develop pustules, proving that he was immune to smallpox. In Latin, cow is represented by the word *vacca*, and cowpox is termed *vaccinia*. Jenner thus coined the word "vaccination" for this innovative procedure[7] (Fenner et al., 1988).

The vaccine could easily be transmitted from one person to another through arm-to-arm vaccination. This method consisted in extracting the pus from the few pustules which developed on the arm of a person inoculated with cowpox and to insert it under the skin of a sound individual. This method remained the most commonly used during the nineteenth century.

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[7]The method of protection against smallpox used before the introduction of vaccination was called variolation. This method consisted in immunising individuals using material obtained from someone infected with smallpox. By doing so, practitioners aimed at inducing a mild but protective version of the disease. More information on this first method is provided in subsection B.3 of the Appendix. There is a still a debate about who used cowpox first, as an English farmer, Benjamin Jesty, had already experimented this type of inoculation in 1774.

The vaccine could therefore be spread within a given population relatively easily. It could also be stored in tubes and sent to another location where a new arm-to-arm vaccination process would start[8]. This process entailed sanitary risks as bacterial contamination and the transmission of syphilis. Even though this occurred in less than 0.1% of the cases, efforts were made to increase direct vaccination from calf lymph vaccine from the 1880s. This led to the progressive disappearance of arm-to-arm vaccination.

There is no precise estimation of the efficiency of the nineteenth-century vaccine, but modern estimates show that it was effective in preventing smallpox infection for 95% of the persons vaccinated. A high level of protection persisted for up to 5 years after vaccination, with partial immunity persisting for 10 years or more. The vaccine either stopped infection or lessened the seriousness of illness when administered shortly after exposure to smallpox (Belongia and Naleway, 2003).

Jennerian vaccination rapidly gained general acceptance and spread across Europe and the United States from 1800[9]. Vaccination caused an immediate decline in smallpox mortality, especially within countries with mandatory vaccination. In Sweden for example, where vaccination became compulsory in 1816, the average yearly smallpox mortality was of 2 deaths per 1,000 inhabitants between 1774 and 1800, 0.5 between 1800 and 1816 and 0.1 during the remaining part of the century (Sköld, 1997) (see Figure A4). As mandatory vaccination generalised, smallpox mortality progressively became a minor problem in Europe. The major vaccination campaigns that took place after WWII in the West led to the near-elimination of smallpox in this part of the world. The WHO intensified the global smallpox eradication effort in 1967, using ring vaccination within the African and Asian countries where smallpox remained endemic. The last naturally occurring case of indigenous smallpox was identified in Merca, Somalia, on October 26, 1977. Smallpox was officially declared eradicated by the WHO in 1980, making it the only human disease eradicated to this date (see Figure A5 for the decade of eradication by country) (Fenner et al., 1988). Several countries abandoned their compulsory vaccination policies during the 1970s, such as the United Kingdom in 1971 and France in 1979. The disease is estimated to have caused between 300 and 500 million deaths throughout the twentieth century.

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[8]Vaccine could be dried on ivory points for short-term storage or transport but an increasing use was made of glass capillary tubes for this purpose towards during the nineteenth century.

[9]More information on the diffusion of the smallpox vaccine is provided in subsection B.4 in the Appendix.

2.3   Vaccination in France During the Nineteenth Century

At the end of January 1800, the Duke of La Rochefoucauld-Liancourt, recently returned from emigration in England, founded the Central Vaccine Committee through public subscription. This committee established contact with physicians in London who sent the smallpox vaccine to France on June, 1800. A British physician, Woodville, was also invited to France to help with the first vaccinations of children. In February 1801, the Committee called on the mayors of the twelve districts of Paris to establish a free vaccination centre. Following these early efforts, vaccination committees and centres were quickly established in the main cities of the departments.

In April 1804, the Society for the Eradication of Smallpox was founded. Within this society, a central committee was charged with promoting this practice in all departments where local committees were also created. As early as 1804, ministerial circulars were sent to prefects, the administrative heads of departments, for the dissemination of the vaccine and recommended a completely free vaccination for the poor. A decree of March 16, 1809, mandated large cities to maintain stocks of vaccine to supply physicians as needed. Orphans were often used to maintain vaccine availability though arm-to-arm vaccination. To encourage vaccinations, Napoleon had his son, Napoleon II, King of Rome, vaccinated in 1811.

Contrary to what happened in the United Kingdom for example, vaccinations were carried out almost exclusively by medically trained professionals, with only very rare exceptions. They could be administered by surgeons, doctors, *officiers de santé*[10], pharmacists and midwives. These practitioners could vaccinate within the vaccination centres in the main towns, or during private medical consultations. Vaccinators were also touring the countryside to propagate the vaccine in remote locations.

Despite the enthusiasm about vaccination, no national budget in favour of its spread was ever established in France during the nineteenth century. Departments were responsible for maintaining vaccine stocks and opening vaccination centres in the main towns without any financial support from the central state[11]. They were also supposed to pay the vaccinators.

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[10]In France, from 1803, a person who practised the medical profession without the title of Doctor of Medicine was called an *officiers de santé*. To hold this title, it was required to spend three years at a medical school, or five years in a civil or military hospital, or six years with a doctor, and pass an examination before a departmental medical board.

[11]This latter only established an annual national competition from 1810, with a first prize of 3,000 francs, two of 2,000 and three of 1,000. There were also medals of honour distributed to vaccinators with a high number of

However, only a few of them, the departments of the Alsace region from 1810 for example, paid vaccinators a fixed salary. Within the other departments, vaccinators could be partially subsidised by the authorities, but this was not supervised by any national legislation and depended on the departments' financial health. Most of the times, departments relied heavily on the dedication of vaccinators to spread the vaccine at their own expense, insisting on their moral duty to vaccinate without charging families (Darmon, 1986)[12].

Departments' leeway in creating incentives to spread vaccination was also limited. Some prefects attempted, particularly at the beginning of the century, to enforce coercive measures. This included actions like doubling parental taxes if their children were not vaccinated (in departments such as Finistère in 1811 or Seine-Inférieure in 1813), or mandating parents of an infected child to cover the vaccination costs for the community (in Lozère in 1813). However, the state consistently nullified these measures, deeming them contradictory to the principle of citizen equality.

In this context, the number of vaccinations rapidly increased from the beginning of the century to the early 1830s and attained a number of 400,000 vaccinations per year. This number, which represents around 50% of the yearly number of births, stagnated until the 1850s, and then increased again progressively until the 1890s at a level between 500,000 and 600,000 vaccinations per year (Biraben, 1979).

France is therefore a perfect example to study the determinants of smallpox vaccination over time. Indeed, vaccination was either free of charge or accessible at a very low price. The supply of vaccine was good, as departments were legally forced to maintain its availability. There was also no legal obligation to vaccinate until the end of the century when several laws progressively made vaccination compulsory. Vaccination became mandatory for children enrolled in public schools in 1886 (Biraben, 1979) and for the military in 1888 (Berche, 2022). Finally, on 15 February 1902, a law on public health protection made smallpox vaccination compulsory in the first year of life, along with re-vaccinations at the ages of 10 and 21.

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vaccinations administered, alongside books or surgical instruments (Bercé, 1984).

[12]Vaccinators could charge the wealthiest families, typically around 2 francs to vaccinate a child. This was close to the daily wage of a male industrial or agricultural worker. This explains the fact that vaccination was never considered as profitable by medical practitioners during the nineteenth century (Léonard, 1977).

3 Data

3.1 Smallpox Vaccinations, Infections and Deaths

The data on smallpox come from a series of yearly reports entitled *Rapport sur les vacci-nations pratiquées en France.* These reports have been published from 1804, and they contain information at the department level on the number of births, smallpox infections and deaths, the level of spending in favour of vaccination and the name of the four main vaccinators from 1806 to 1888[13]. The information on the number of vaccinations was initially collected by vaccinators themselves. They were in charge of recording the exact number of persons they vaccinated and to specify in which municipality (they were also sometimes recording the names of these persons). Most of these initial reports are lost, and only the publications specifying the aggregate number of vaccinations were kept in the archives. However, those that passed through time testify of the high level of precision of these reports. In Figure A7, we reproduce an excerpt of the report for the Gers department in 1811, which details the name, profession and place of residence of vaccinators. For each of them, the number of vaccinations performed, in which municipality and district is also specified. This shows that the national reports are based on an extremely precise recording of the number of vaccinations performed and testifies of their high reliability[14].

The data on infections and deaths should be considered with more caution. They are less often provided in the reports and most likely underestimate the true impact of smallpox. This is especially true for the number of infections, as some people could contract smallpox and go unnoticed if they didn't die from it. Nonetheless, they should provide a good indication about the intensity of the disease over time.

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[13]These reports have been published by the Central Vaccine Committee until 1823, and then by the *Académie Nationale de Médecine* (National Academy of Medicine) They are freely accessible from https://gallica.bnf.fr/ark:/12148/cb32848237p/date&rk=21459;2 and https://gallica.bnf.fr/ark:/12148/cb42580552w/date&rk=42918;4. Figure A6 in the Appendix presents an abstract from one of these reports. The number of departments is of 86 during most of the period we analyse.

[14]To acquire lifelong immunity against smallpox, re-vaccinations were necessary. We only consider primary vaccinations here, as the re-vaccinations are not specified in the reports. However, since vaccination never covered the entire population that was susceptible to smallpox, re-vaccinations remained marginal in nineteenth-century France (Darmon, 1986). The reports therefore reliably reflect the intensity of vaccination within departments. Re-vaccination became mandatory for the first time in 1874 within the German Empire. Some countries imposed re-vaccination earlier in the century for military recruits when they enrolled, as Sweden did in 1853. However, even in this case, and within a country where vaccination was mandatory, civil re-vaccinations remained marginal outside of major-epidemic years, as the ones following the Franco-Prussian War. In the 1880s, it is estimated than re-vaccinations represented only 1% of the total vaccinations performed in Sweden (Sköld, 1996).

As explained before, vaccinations were mostly performed on very young children when they were between two months and five years old. Available estimations for Sweden show for example that the average age at vaccination was of 1 year and 2 months in the first part of the nineteenth century (Sköld, 1997). Unfortunately, information on the number of vaccinations by age group at the country level is not available in the French national reports. From the statistics transmitted by some vaccinators to the *préfets* and which were included in the reports, we can estimate that respectively 67%, 84% and 97% of the vaccinations were performed before one, two or five years of age in France during the nineteenth century (Table A2). This is coherent with the average age for other European countries.

Therefore, following what has already been done in the literature (Banthia and Dyson, 1999; Mühlhoff, 2022), we define our measure of the vaccination rate against smallpox as the number of vaccinations per 100 births during a given year t. This information is directly available each year from the *Statistique générale de la France*. We also compute the vaccination rate over the number of births in t and $t-1$ as a robustness check, which doesn't significantly affect our results. In Figure A8, we also show that past vaccinations are unrelated to birth counts at time t, which makes it unlikely for our vaccination rate to mechanically vary according to the number of past vaccinations.

Ideally, one would account for infant and child mortality- respectively defined as the number of children from 0 to 1 year of age or from 0 to 5 years of age who die during a given year-when constructing vaccination rates. Unfortunately, such data are unavailable at the department level for most of the century and could only be retrieved for the periods 1855–1868 and 1875–1884. Using this information, we show that neither our rainfall instrument nor wheat prices had a significant impact on infant or child mortality, and that the effect of negative economic shocks on vaccination remains robust when vaccination rates are adjusted for infant and child mortality.

3.2   Wheat Prices

We collected yearly wheat prices at the department level from Labrousse et al. (1970). From 1791, departments had to send these prices to the *Bureau des subsistances*, a public body belonging to the Ministry of the Interior. The price was computed per hectolitre of wheat, based on the prices used in all the market towns within the departments. The information on

prices was compiled by the Ministry of Agriculture and Trade in the *Tableaux des prix moyens et annuels de l'hectolitre de froment en France par département depuis le Ier Vendémiaire an IX (22 septembre 1800) jusqu'au 31 décembre 1870.* This volume reports the monthly price of wheat for each department between the beginning of the century and 1870. These data have then been gathered and extended to 1872 by Labrousse et al. (1970). As we collected the data from them, we are able to link yearly wheat prices to vaccinations against smallpox from 1806 to 1872. We also collected monthly prices to perform robustness checks on the yearly measure of price. Subsection C.2 provides more information on wheat prices.

3.3 Rainfall

We collect information on rainfall from two sources. Even if this information was not systematically centralised before 1878 and the creation of the *Bureau central météorologique de France* (French Central Meteorological Office), engineers and members of the local scientific societies often collected data on rainfall during the nineteenth century. Victor Raulin (1815-1905), a professor of geology at the Bordeaux Faculty of Science, spent a large amount of his life writing to administrative authorities of departments to be put in contact with these people. He managed from his hard work to collect data on rainfall for a significant percentage of departments and years along the nineteenth century, that he made available in a series of publication in the *Académie nationale des sciences, belles-lettres et arts de Bordeaux* from 1863 to 1881. This information was mainly provided by civil engineers trained in the *École nationale des ponts et chaussées.*

We also used the information on rainfall from the *Food and Agricultural Organization (FAO), FAOCLIM2: Worldwide Agroclimatic Database, Agrometeorology Group SDRN, Rome, 2001* which is introduced in Dooley (2005). This dataset is based on the same publications by Victor Raulin that we are using, and has for example been used in Mehlum et al. (2006). It provides a more restricted amount of information as it focuses only on departments where the rainfall series are available for a relatively large part of the century. When available, we therefore relied directly on these data.

Thanks to both sources, we were able to collect monthly data on rainfall for around 3,000 department-year observations, which roughly corresponds to half of the observations on vacci-

nation and wheat prices. Table A4 specifies if the rainfall data were collected from the FAO dataset or the publications from Victor Raulin and the corresponding dates[15]. Even if all departments appear in our dataset of collected rainfall, the quality of the information is not stable over time. As shown in Figure A10, the number of departments for which we could measure rainfall is lower or close to 20 over 86 from 1806 to 1835. It then steadily increases to 40 in 1845, 50 in 1855 and 80 or more from 1860 to 1870.

To tackle this problem and cover the entire nineteenth century, we will also make use of reconstructed rainfall data. To do so, we rely on Pauling et al. (2006) which provide reconstructed seasonal information on rainfall for the last 500 years at a grid resolution of 0.5°x0.5° longitude/latitude (around 2,000 square kilometres). These data are based on historical precipitation series, documentary evidence and several natural climate proxies as tree-ring chronologies, ice cores and corals. It has already been used in several economics papers as Sequeira et al. (2019) or Buggle and Durante (2021) for example. In Figure A11, similarly to what Chambru (2019) found for the 1650-1800 period, we show that the collected and reconstructed rainfall series are highly correlated, with only a slight overestimation of the rainfall level of 9% in the reconstructed data. Precipitation reconstructions for the nineteenth century therefore constitute reliable proxies for weather conditions in the past.

Throughout the article, rainfall is measured in millimetre (litre per square metre). One millimetre of rain corresponds to a height of water of one millimetre on a flat surface of one square metre, that is to say to a total volume of one litre of rainfall.

3.4 Phylloxera

All the variables related to the phylloxera crisis that are used in this article were collected from the work of Banerjee et al. (2010b) and Bignon et al. (2017), who mainly build on the work of Galet (1957). This book provides the year when phylloxera was first spotted in a given municipality within departments, and when it fully contaminated each of them (the insect is reported as present in every municipality). It also specifies the amount of wine production at the department level between 1850 and 1905, which we will use until 1888 when our vaccination

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[15]A comparison between places around Paris and the rainfall data collected by the Paris Observatory reassuringly shows that both series are coherent. In Figure A9, we show that the volume of rainfall for the departments of Oise and Seine-et-Oise neighbouring Paris are highly correlated with the series from the capital city. The rainfall data collected by Victor Raulin are therefore highly reliable.

rate measure stops. We present with more details the variables used in the Empirical Strategies section.

3.5   Economic and Demographic Variables

The main control variables we use in the estimations are the population of departments, population density, urban population, the literacy rate, and the amount of taxes per capita. As regards the three population variables and literacy, we use the *Statistique générale de la France* to gather information in 1806, 1821 and for the censuses taking place every five years from 1831 onwards. Literacy is defined as the share of spouses that could sign their marriage contract. The amount of taxes is defined as the sum of the land tax, the personal property tax on revenues coming from other sources than land and commercial activities, the *patente* tax on commercial resources and the tax on the number of doors and windows of habitations. All these taxes were established during the Revolution in France and this tax system remained remarkably stable all along the nineteenth century. These four taxes provide a very good approximation of the total resources available at the department level as they constituted the main part of the departments' total budget (Montalbo, 2022)[16]. The data on taxes are coming from the *Compte général de l'administration des finances* and the *Bulletin des contributions directes et du cadastre.* As information on these economic and demographic variables is not available every year, we use a linear interpolation to compute their value when missing. This enables us to include these variables as controls in the estimations. We also make use a spline interpolation as a robustness check, which does not modify our results[17].

3.6   Descriptive Statistics

As described in the Historical Background section, the number of vaccinations in France increased quickly at the beginning of the nineteenth century, before reaching a plateau in the early 1830s. Figure 1 shows that the national vaccination rate followed the same path, pro-

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[16]More information on these taxes and on how their amounts were computed is also provided in Montalbo (2022).

[17]Figure A14 reports the actual data and the linear interpolation for the entire century. The evolution pattern of the population and literacy variable is quite clear all along the century. The amount of taxes per capita is moving in a more erratic way. Its level decreased in the first part of the century before stagnating from 1830 to 1870. Taxes then increased dramatically from 1870 to 1873 in connection with the Franco-Prussian War and the payment of the French indemnity (Silvant, 2014).

gressing quickly from around 20% in 1806 to 60% in 1835, and remaining at this level until 1875 when it started to increase again and reached 80% at the end of the 1880s. For the vast majority of the observations (93%, see Figure A15), the vaccination rate remained lower than 100%. However, when epidemics struck, the population usually reacted by vaccinating a large proportion of the children and of the unvaccinated adults, which could bring the vaccination rate above 100%. This is clearly visible in 1871, when the smallpox pandemic following the Franco-Prussian War of 1870-71 caused around 115,000 deaths in France and 500,000 all over Europe. This also shows that there was no major issue of vaccine supply during the nineteenth century. Vaccination could indeed massively increase when the demand was affected by smallpox outbreaks.

Vaccination against smallpox was never fully accepted in France until the legal obligation, at least not enough to reach herd immunity, which is in this case estimated to correspond to a vaccination rate between 71% and 83% by Mühlhoff (2022). The most striking feature of the vaccinating behaviour of departments is the very high volatility in the number of vaccinations year by year. Figure 1 presents this characteristic by depicting the absolute difference at the department level between the vaccination rate at time t and this rate at time $t-1$. It shows that, on average, the vaccination rate within departments was varying by 16.7 percentage points year by year over the century. This difference was also nearly always higher than 10 percentage points. Knowing that the average rate of vaccination was around 60% over the century, this represents a very high variation in the proportion of children that got vaccinated each year.

The geographical analysis of vaccination also reveals the same instability. There is indeed no clear and consistent geographical pattern of vaccination in the nineteenth century, and even the richer eastern departments which performed well at the beginning of the century saw their vaccination rates decrease from the 1870s (see Figure A16). This has led some researchers to believe that variations in the vaccination rate would always be resistant to interpretation (Darmon, 1986).

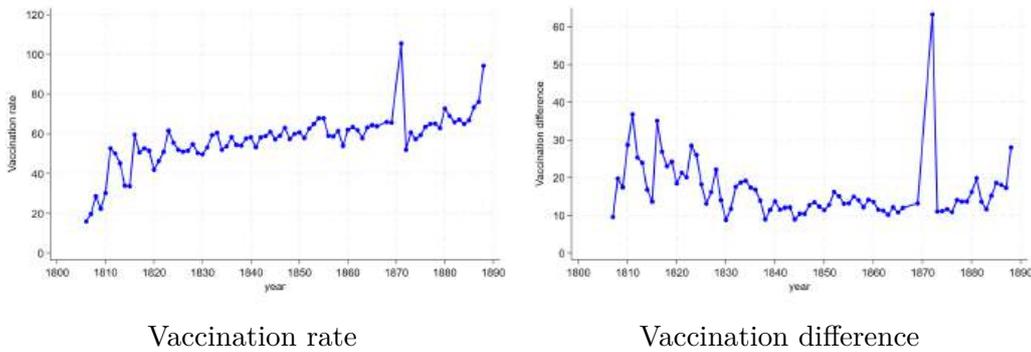Vaccination rate   Vaccination difference

Figure 1: Vaccination rate and vaccination difference, 1806-1888

Notes: The vaccination rate is defined as the number of vaccinations per 100 births. Vaccination difference is defined as the absolute value of the difference between the vaccination rate at time t and the vaccination rate at time $t-1$. This difference is computed at the department level.

An additional point worth mentioning here is that, in the absence of herd immunity, small-pox infections and deaths remained relatively high all along the nineteenth century, even if much lower than their eighteenth-century levels. The average annual number of deaths from smallpox was of around 3,300 at the country level, with an average number of infections of 20,800. These numbers remained quite constant during the century, after a decline from the introduction of vaccination to 1830. This initial drop in infections and deaths, from respectively 31,000 to 18,000 infections and from 4,200 to 3,000 deaths on average each year, might partly explain why the national vaccination rate stagnated around 60% during forty years. Families certainly perceived reduced private benefits from vaccination as disease prevalence declined (Mühlhoff, 2022) (see Figure A17 and Figure A18). All in all, between 1806 and 1888, approximately 39.6 million vaccinations were administered in France. During this time, there were at least 1.6 million smallpox infections and 260,000 deaths.

Figure A19 and Figure A20 in the Appendix report the distribution of wheat prices within departments and the variation in the average national price until 1872. The price of wheat varied mostly between 10 and 30 francs per hectolitre over the century, with an average value of 21 francs. Prices could increase dramatically following extreme weather conditions and bad harvest. It was for example the case in 1816 during the Year Without a Summer caused by the 1815 eruption of Mount Tambora, when the average price jumped to more than 35 francs.

Summary statistics for all the variables used are provided in Table A5.

4 Estimation Strategies

4.1 Wheat Prices Instrumented by the Volume of Rainfall

4.1.1 Wheat Prices and Negative Shocks on Income

The first empirical strategy we implement to evaluate the effect of income shocks on vaccination relies on variations of staple food prices to measure income shocks[18]. This strategy builds on the fact that the consumption of cereals represented the largest part of people's diet during the nineteenth century. The Agricultural Survey of 1852 shows for example that in the case of France, bread accounted for around 65% of the spending made on food by agricultural workers, and around 43% of their total spending (Demonet, 1990). Increases in cereals' price therefore represented strong negative real income shocks for the majority of the population.

In this article, we focus on the price of wheat to measure variations in cereal and staple food prices. The choice of wheat as the reference cereal is firstly motivated by its dominant position in France. Its cultivation covered seven millions of hectares in 1852, which represented 13% of the national territory, 20% of ploughed land and 34% of the land sown with cereals[19]. Wheat was therefore the most important cereal in France at that time, either in terms of cultivation or consumption, as a large part of the bread consumed was made from it (Heffer et al., 1986).

Moreover, because of this dominant position, the price of wheat was collected with much more regularity and diligence compared to the other cereals. Wheat is the only cereal whose price is consistently documented yearly and computed from several markets in every French department all along the nineteenth century (Labrousse et al., 1970; Drame et al., 1991).

Finally, even if the production and consumption of wheat varied between departments, the highest production levels being concentrated in the northern and central-western parts of France (see Figure A21), the price of wheat was very strongly correlated with the one of other cereals. By collecting data at the national level on the price of various cereals, flour and bread from the *Statistique agricole annuelle* for the 1866-1913 period, we show that the correlation between the price of wheat and the one of rye was of 0.94, 0.88 with the price of barley, 0.58 with the one of buckwheat and 0.68 with oats. This explains the very high correlations of

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[18]More specifications on why using cereal and wheat prices instead of other proxies as variations in taxes are provided at the beginning of subsection D.1 in the Appendix.

[19]Oats occupied 21% of the land sown with cereals, rye 14% and the remaining 30% were used to cultivate maize, buckwheat, barley and meslin.

0.98 between the price of wheat and the one of flour and bread (see Figure A22 and Table A6.) Therefore, the price of wheat constitutes a very good proxy for staple food prices and availability in nineteenth-century France, regardless of the agricultural structure and cereal specialisation of departments.

To be even more robust on this point, we use data from the *Compte Général de la Justice Criminelle* which details the number of violent and property crimes in France from 1826 at the department level (Bignon et al., 2017). Using fixed-effect OLS estimations, and similarly to what is found in Mehlum et al. (2006) using rye prices, we find no association between wheat prices and violent crimes, while an increase in price is significantly linked to a higher number of property crimes (see Figure A23 and Table A7). Variations in wheat prices at the department level are therefore a good proxy for local income shocks. The relative lack of market integration during a large part of the century certainly reinforced this phenomenon. When prices were higher in a given department, the negative income shock could not easily be compensated by importing cheaper cereals from another department (Drame et al., 1991)[20].

4.1.2 The Rainfall Instrument, Exclusion Restriction and Falsification Tests

To evaluate the causal impact of income shocks on vaccination, we use the volume of rainfall to instrument wheat prices. Even if reverse causality doesn't seem to be the most pregnant issue here[21], a third factor could influence both the vaccination rate and the price level. A general improvement in communications could for example increase agricultural productivity, enhance market integration and affect the price of cereals while making it easier for people to access vaccination centres. Using the Agricultural Survey of 1852 at the department level or data at the national level clearly shows that a higher production of wheat was linked to lower prices during the nineteenth century (see Figure A24). It is therefore the variation in prices

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[20]When using prices over an entire century to measure income shocks, it is also important to check if an increase of one unit in the price level means the same thing for people over time. Reassuringly, prices were on average very stable all along the nineteenth century in France as inflation was nearly absent (Plessis, 2005). Moreover, as nominal wages remained relatively constant during the same period (Ridolfi, 2019), one can safely assert that the economic meaning of price variations is consistent over time.

[21]Reverse causality would be a problem if the number of vaccinations could influence the price of wheat. To us, this could be the case if a higher (lower) number of vaccinations could contribute to increase (decrease) the number of agricultural workers and therefore the quality of harvests and eventually the price of wheat. However, as people dying from smallpox and who were getting vaccinated were mainly young children, this is hard to believe. Fewer vaccinations could however be linked to a higher number of deaths and a lower demand for cereals, which could then affect the price of wheat. This is a more plausible transmission channel for reverse causality in this case.

linked to the influence of rainfall on production that we will use in the estimations.

Subsection D.2 in the Appendix provides a detailed explanation of how we constructed our collected and reconstructed rainfall instruments. These instruments are based on the total volume of rainfall during the sprouting and before the sowing months of wheat. It is indeed during this period that higher precipitation contributed the most significantly to impede the optimal growth of wheat, and therefore to the increase in the price of the cereal.

Using rainfall to instrument wheat prices might violate the exclusion restriction if rainfall has a direct impact on the vaccination rate defined as the number of vaccinations per 100 births. This could notably be the case if: (i) rainfall influences the number of vaccinations through an impact on the prevalence of smallpox; (ii) rainfall affects child mortality and changes the pool of children who could be vaccinated, eventually leading to a modification of the number of vaccinations; (iii) fertility and the number of annual births are impacted by the level of precipitation.

First, we test for these channels by regressing annual smallpox cases and deaths on yearly rainfall (see Table A11). Neither outcome appears sensitive to climatic variation. Next, in Figure A26 and Figure A27, we examine whether rainfall correlates with infant and child mortality, and birth counts, using both our rainfall instrument and the annual precipitation. Infant and child mortality are calculated for 1855–1868 and 1875–1884, the only periods for which age-specific death statistics are available in the French national data before 1888. We observe no significant relationship between rainfall and mortality or between rainfall and births. Hence, we can be confident that our instrument does not influence vaccination uptake via alterations in smallpox prevalence, mortality, or birth rates.

Moreover, as explained in subsection D.2 of the Appendix, we don't include rainfall at year t in our instrument. Doing so would be problematic as rainfall could for example affect the quality of roads, which would make it harder for vaccinators to travel in the countryside of for people to access vaccination centres located in towns. By leaving aside rainfall in year t, we therefore ensure even more strongly that the exclusion restriction will not be violated because of a direct impact of rainfall on the number of vaccinations.

Finally, we also run a falsification test on rainfall to investigate whether future precipitation were significantly linked to the price of wheat. In Figure A28, we don't find such a potential

association.

4.1.3 The Estimation Model

Our estimation model is the following:

$$Price_{d,t} = \delta_1 Rain_{d,t-1} + \delta_2 X_{d,t} + \alpha_d + \gamma_t + \epsilon_{d,t} \tag{1}$$

$$Vacc_{d,t} = \beta_1 Price_{d,t} + \beta_2 X_{d,t} + \alpha_d + \gamma_t + \epsilon_{d,t} \tag{2}$$

where (1) corresponds to the first stage equation, (2) to the second stage and subscripts d and t to department and time. In the first stage, we use both our rainfall instruments on the price of wheat at time t. Department and time fixed effects α_d and γ_t are always included in the estimations. $X_{d,t}$ stands for the control variables and $\epsilon_{d,t}$ for the standard errors corrected for auto-correlation by clustering at the department level. In the main specification, the control variables are the ones defined in subsection 3.5, namely: the population of departments, population density, urban population, the literacy rate, and the amount of taxes per capita.

We control for urban population and population density as they are expected to have influenced the access to vaccination. If a higher proportion of a department's population was concentrated into towns, or if the distance between communities and villages was lower, this should have increased the access to vaccination centres and enable vaccinators to travel more easily through the countryside. It is also important to include taxes per capita to control for the level of departments' economic resources, as this influenced the support they could provide to vaccinators. These taxes were also strongly correlated with the wealth level of the population, which, even if vaccination was largely free of charge, could impact the number of vaccinations. The literacy level also partly accounts for wealth as it was highly correlated with resources. It also controls for the fact that more educated people may have been more receptive to medical innovation and therefore less reluctant to experiment new medical processes.

4.2 The Phylloxera Crisis: an Exogenous Shock on Wine Production

We only quickly summarise here the effect of phylloxera on wine production in France, as this has been extensively described in Banerjee et al. (2010b) and Bignon et al. (2017). We therefore encourage readers to refer to these articles for a more detailed description. Phylloxera is an insect that attacks the roots of vines. Indigenous to America, it was imported to France in the early 1860s and spotted for the fist time in 1863. It then spread slowly from the southern coast of France to the rest of the country. The insect had been spotted in 62 departments at the end of the 1880s (see Figure A29). Up until the grafting of European vines onto phylloxera-resistant American roots in the early 1890s, it is estimated that phylloxera destroyed around 40% of French vineyards. This contributed to a fall of the share of wine in GDP from 6% to 2% (see Figure A30). In an economy where agriculture still accounted for around 30% of GDP and wine production amounted to about one-sixth of the value of agricultural production, the introduction of phylloxera was bound to have dramatic economic consequences. The insect is estimated to have cost France twice as much as the war indemnity paid to the Germans in 1870, which amounted to 25% of one-year GDP.

We use the phylloxera crisis as an alternative estimation strategy in this paper for four reasons. Firstly, rainfall has been widely used as an instrument, a practice that inevitably increases the scope for potential violations of the exclusion restriction. Although studies that use rainfall to instrument income shocks tend to be less sensitive to violations that would render the estimates statistically insignificant, it remains impossible to test and address all the potential violations identified by Mellon, 2025. Excluding contemporaneous rainfall at year t from our instruments helps mitigate these concerns, but does not eliminate them entirely. The phylloxera crisis is therefore employed as a complementary source of identification, both to supplement the IV estimations and to strengthen their credibility. Secondly, if the impact we estimate with wheat prices is robust, we should find the same type of effect by using other negative income shocks. Thirdly, the information on wheat prices stops in 1872, which leaves us with sixteen unexploited years of vaccination, while a strong increase in the vaccination rate took place from 1875. Fourthly, even if we have shown that higher prices were linked to a lower production which affected the majority of the population, one could still argue that

higher prices could have benefited wheat producers and impact our results.

The fourth reason is certainly the most unlikely, or at least marginal enough not to bias our estimations. Indeed, landholdings were on average very small in nineteenth-century France as 55% of them were smaller than 5 hectares, with an average value of 12 hectares. It is therefore unlikely that the surplus drawn from selling wheat at a higher price would compensate the negative shock on real income caused by the higher price of staple food. Moreover, in 1851, 63.2% of all agricultural workers didn't own the land they were working on (Montalbo, 2023). This reduces even more the probability that higher wheat prices would be welfare-improving at the department level. In the heterogeneity analysis performed in Table A12, we also show that the effect of wheat prices was not affected by urbanisation, the level of wheat or cereal consumption, the level of wheat production and the share of landowners. Therefore, even in rural departments where the consumption of cereals was high and where more numerous landowners could have benefited from selling a high volume of wheat at a higher price, the effect of an increase in wheat prices on vaccination remained the same.

Very importantly, Banerjee et al. (2010b) and Bignon et al. (2017) show that the phylloxera crisis is an ideal natural experiment whose effect is not linked to confounding factors. Firstly, the spread of the epidemic was exogenous, as it was only caused by the movement of the insect. Secondly, there was no impact of phylloxera on demographic variables as it caused no significant changes in migration patterns, infant mortality, the composition of the population or urbanisation. This is an important point as these changes would have most likely affected vaccination. Finally, the crisis did not trigger a substantial shift towards other agricultural products and the area planted with vines did not decline during the second part of the nineteenth century. The income shock was therefore not compensated by a reorganisation of agricultural production and structural changes in the economic structure of departments.

To evaluate the impact of this strong negative income shock, we exploit the variation in the timing of the spread of phylloxera between departments, using an event-study strategy. The estimation model is the following:

$$Y_{d,t} = \sum_{\tau=T_0}^{T_1} \beta_\tau Phyllox_{\tau(d,t)} + \alpha_d + \gamma_t + \epsilon_{d,t} \tag{3}$$

with subscripts d and t corresponding to department and time. $Y_{d,t}$ corresponds to our variables of interest, which in the case of phylloxera will either be the level of wine production or the vaccination rate. $Phyllox_{\tau(d,t)}$ corresponds to a set of binary indicators of full contamination by phylloxera. As explained in Bignon et al. (2017), the insect took some time to spread fully within departments. On average, wine production therefore didn't decrease in the very first years after phylloxera was first spotted in one municipality of the departments. On the contrary, as soon as a department was fully contaminated by phylloxera, that is to say when all municipalities were infected, wine production started to decline. To correctly measure the negative income shock caused by phylloxera, we therefore only consider full contamination by the parasite, which characterised 40 departments at the end of the period studied. This variable keeps the value of 1 until the end of period in 1888, as it is only in the early 1890s that the solution to the disease was implemented on the French territory. *To* and *T1* represent the number of leads and lags considered. Department and time fixed effects α_d and γ_t are included in the estimations and the $\epsilon_{d,t}$ standard errors are clustered at department level. The reference period considered is $\tau = -1$, one year before full infestation.

Recent econometric studies highlight that, in the context of staggered treatment, identification and inference based on a classical TWFE model can be misleading. When treatment effects are constant across groups and over time, the TWFE estimator consistently recovers the average treatment effect on the treated (ATT). However, if the effects vary by cohort or period, the TWFE estimator will generally fail to produce a consistent ATT estimate (de Chaisemartin and D'Haultfœuille, 2020; Goodman-Bacon, 2021; Callaway and Sant'Anna, 2021). As departments started to be infested by phylloxera in different years, we therefore won't use the difference in differences strategy implemented in Banerjee et al. (2010b) and Bignon et al. (2017) as our main estimation technique. We will instead rely on heterogeneity-robust estimators for staggered treatment timing, alongside the standard TWFE model.

5 Estimations Results: a Positive Impact of Negative Income Shocks on Vaccination

5.1 The Effect of Wheat Prices on Vaccination

5.1.1 Baseline Outcomes

In this subsection, we present the effect of negative income shocks on vaccination against smallpox using the model specified in equations (1) and (2). Table 1 reports the OLS and IV estimations with and without controls, using both the collected and reconstructed data on rainfall. In the OLS estimations of columns (1) and (2), we restrict the sample to the observations available when using the collected data on rainfall. We also control for the effect of past vaccinations, which is defined as the cumulative sum of vaccinations (per 100 inhabitants) until $t-1$. Adding this variable is based on the idea that, if vaccinating against smallpox became a deeply-rooted habit in the population, parents would have often vaccinated their children regardless of the economic context. The positive correlation between the sum of past vaccinations and vaccinations at time t points towards this direction (Figure A31)[22]. For all IV estimations, the Sanderson-Windmeijer F-stat is always superior to ten, which tends to exclude the issue of weak instrument.

Both OLS and IV estimations show a positive impact of negative income shocks on vaccination against smallpox. A one-standard deviation of 5.5 francs per hectolitre of wheat is indeed associated with an increase in vaccination comprised between 4 and 20 vaccinations per 100 births. If we consider the IV based on reconstructed rainfall as the most reliable estimation, the effect is of 15 vaccinations. Knowing that the average vaccination rate was of around 60 over the century, this appears to be a very high magnitude. This effect is not due to changes in the number of births or infant and child mortality that might result from income shocks. Indeed, regressing these variables on the price of wheat, and using either OLS or IV estimations, does not produce any significant outcome (see Figure A32). This is coherent the fact that, contrary to what happened in pre-industrial Europe (Galloway, 1988), even the strongest increases in

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[22]The two-observation difference between columns (5) and (6) and (7) and (8) comes from the Alpes Maritimes department for which two measures of vaccination are available between 1806 and 1814, before it was returned to the Kingdom of Sardinia. No available information on literacy and urban population exists for this department at that time. As this department permanently joined France in 1860, an interpolation from 1860 to estimate these values would be too imprecise.

food prices during the nineteenth century didn't significantly impact the composition of the population in France (Xiaolan, 2014).

Negative shocks on real income therefore constituted a major driver of vaccination against smallpox in nineteenth-century France and are one of the main explanatory factors behind the strong year-to-year variations in vaccination (Figure 1). This effect is even more interesting considering the fact that no other variables included in the estimations, except the sum of past vaccinations, is significantly related to vaccination. The OLS estimates associated with wheat prices in columns (1) and (2) are also higher and more significant than the ones covering the entire century. This reveals that the impact of income shocks on vaccination was stronger in the second part of the century when the collected data on rainfall are more often available. A potential explanation for this finding is that the supply of vaccine improved over time and enabled parents to more strongly react to economic shocks later in the century. Another possibility is that parents were more reluctant to rely on a new medical discovery early in the century, and waited until vaccination proved to be harmless and efficient to get their children vaccinated. Both factors certainly played a significant role. The IV estimations based on reconstructed rainfall however show that the impact of shocks was valid all along the period considered, once the potential biases affecting OLS estimated are accounted for. The same pattern is also visible as regards the effect of past vaccinations and it can be explained following the same rationale. In a given department, as vaccination generalised along the century and a significant part of the newborns got vaccinated each year, the sum of past vaccinations ceased to be a good predictor of the vaccination rate. This being said, the strong significance of this variable in columns (6) and (8) when considering the entire century shows that it has to be included in the estimations to properly explain vaccination at time t.

The IV estimates are higher than the OLS ones by a factor of 3 or 4. This is often the case in articles using rainfall as an instrument, although this magnitude appears to be much lower than in other studies as Burke and Leigh (2010); Brückner and Ciccone (2011); Franck (2016). The difference between the two sets of estimates is most likely explained by a combination of three factors. First, even though wheat prices were consistently recorded all along the century, there might exist some noise in the data. Drame et al. (1991) notes for example that some mayors reported the same price during several months in a row, which can bias our annual

wheat price variable. Even though this effect is certainly limited as the department price was based on several markets, it could explain part of the difference between 2SLS and least square estimates. Second, our rainfall instruments stop in $t - 1$ and are therefore less efficient in predicting the variations in price taking place during the second part of year t following the harvest of July$_t$. As a consequence, we discard part of the end-of-the-year variations in price when using the IV estimations. Since most of the vaccinations were taking place between April and the end of the summer, we therefore exclude some of the months when income shocks were not likely to have a strong effect on vaccination. Finally, an attenuation bias might explain part of the difference. Indeed, if people anticipated that excessive rainfall would cause an increase in the price of food, they might have reacted by vaccinating their children on the spot and before any effective change in price. This would contribute to lower the effect of income shocks measure using the least square technique.

Table 1: Price of wheat and vaccination against smallpox

	Vaccination rate							
	OLS		IV: Rainfall$_{t-1}$		OLS		IV: Rainfall$_{t-1}$	
			Collected				Reconstructed	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Price of wheat	1.297***	1.154**	3.768**	3.863**	0.699*	0.693**	2.372*	2.815**
	(0.474)	(0.468)	(1.834)	(1.838)	(0.355)	(0.336)	(1.368)	(1.325)
Past vaccinations	–	0.022	–	-0.017	–	0.407***	–	0.412***
		(0.148)		(0.171)		(0.085)		(0.082)
Population	–	-0.407	–	-0.434	–	-0.214	–	-0.278
		(0.456)		(0.369)		(0.335)		(0.329)
Population density	–	0.027	–	0.027	–	0.019	–	0.022
		(0.021)		(0.017)		(0.015)		(0.015)
Urban population	–	0.690	–	0.793	–	-0.021	–	0.194
		(0.966)		(0.851)		(0.507)		(0.523)
Taxes p.c	–	-0.282	–	-0.082	–	-0.115	–	0.005
		(0.389)		(0.338)		(0.209)		(0.219)
Literacy	–	-0.489**	–	-0.380	–	-0.096	–	-0.080
		(0.225)		(0.246)		(0.105)		(0.111)
Department fixed effects	X	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X	X
Observations	2010	2010	2010	2010	4503	4501	4503	4501
R^2	0.575	0.581			0.344	0.357		
$F-stat$			29.209	27.651			20.682	19.111

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. The price of wheat is computed in francs per hectolitre. Past vaccinations are measured per 100 inhabitants and corresponds to the sum of vaccinations administered until $t-1$. Population is in ten thousands of inhabitants and population density is measured as the number of inhabitants per square kilometre. Urban population is in percentage and taxes are in francs per capita. Literacy is defined as the share of spouses that could sign their marriage contract. Standard errors are clustered at the department level. In columns (1) and (2), the number of observations used in the OLS estimations is restricted to the sample used in the IV estimations, and for which rainfall data are available. Collected rainfall is computed as the total rainfall over the months July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$. Reconstructed rainfall is measured as the total rainfall over the seasons Summer$_{t-2}$, Autumn$_{t-2}$, Spring$_{t-1}$, Summer$_{t-1}$ and Autumn$_{t-1}$.

In subsection E.1.1 of the Appendix, we also conduct an heterogeneity analysis to test if the impact of negative income shocks on vaccination against smallpox differed depending on various characteristics of the departments. We find that the effect of shocks on vaccination

was not affected by the urban population over the century, the consumption of wheat, cereals, the production of wheat, the share of landowners, the level of GDP or disposable income and the subscriptions to the *Encyclopédie*[23]. In a nutshell, this effect was not affected by an easier access to vaccinators, the consumption and production structure or wealth level of departments, the concentration of land ownership or the social proximity to science. We can therefore assert that the effect of shocks on vaccination was valid across all types of departments.

We also explore the possibility that the impact of negative income shocks was affected by (i) the intensity of child labour or (ii) the proportion of children in the population, which was correlated with a greater investment in children's human capital in nineteenth-century France. However, the results presented in the Appendix indicate that parents generally responded to shocks by increasing vaccination, regardless of the extent of child labour or their level of investment in children's human capital.

5.1.2 Accounting for Past and Contemporaneous Epidemics

When studying the drivers of vaccination, an important factor that should be taken into account and that is missing in the estimations presented in Table 1 is the prevalence of the associated disease. Indeed, it seems logical to expect that children got vaccinated more often when a strong epidemic hit a department (Oster, 2018). At the national level, it is for example clear that the pandemic of 1871 went hand in hand with a strong increase in the vaccination rate (see Figure A17 and Figure A18). Moreover, one can also think that the strongest epidemics would leave a deep mark in people's mind and potentially contribute to increase vaccination during several years.

In Figure 2, we explore this idea by looking at the correlation between smallpox infections and deaths from $t-10$ to t on the vaccination rate in t[24]. Both infections and deaths are positively related to vaccination at time t, and there is a significant negative correlation between vaccination at time t and these variables in $t-2$. The first correlation reveals the impact of epidemics on the propensity to vaccinate. This impact is restricted to year t, and we therefore find no positive impact of past epidemics on future vaccination.

To explain the second correlation, one has to keep in mind that a higher number of infections

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[23]We provide more detailed information on why these variables could have affected the influence of negative economic shocks in the Appendix.

[24]Smallpox infections and deaths are of course closely correlated, as shown in Figure A34.

or deaths may lower the number of vaccinations since fewer children need protection against smallpox in this case. Moreover, smallpox was mainly killing children above one year old, and children were rarely vaccinated during the first few months of their life. Therefore, a higher number of infections or deaths in $t-1$ would not strongly affect the cohort of children between 0 and 6 months old that will get vaccinated in t, and eventually not impact the vaccination rate. On the contrary, more infections and deaths in $t-2$ will reduce the number of children from 1 to 3 years old in t that could get vaccinated, and will negatively impact vaccination. Finally, infections and deaths in $t-3$ or before will not impact vaccination as the children impacted would have been at least three years old in t, while the percentage of vaccinations performed on children older than 3 years old was lower than 5% (Table A2)[25].

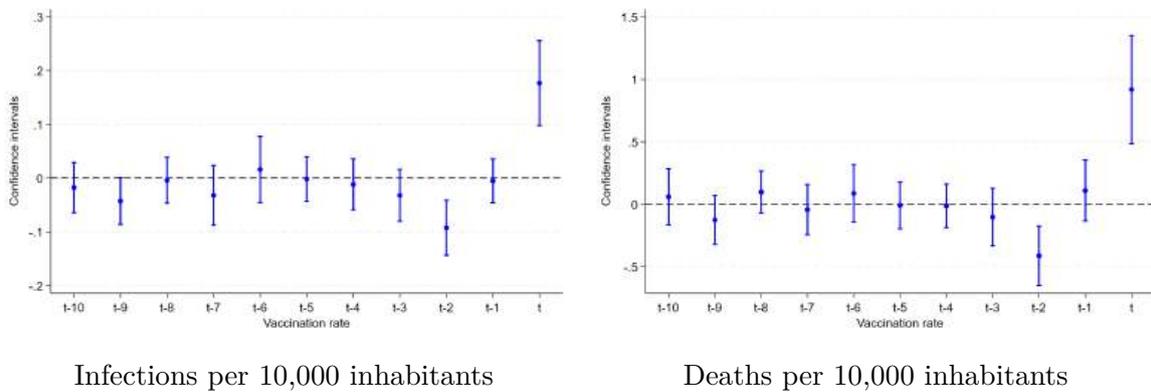Infections per 10,000 inhabitants   Deaths per 10,000 inhabitants

Figure 2: Infections, deaths from smallpox and vaccination rate

Notes: The figure depicts OLS estimation coefficients of the effect of smallpox infections and deaths from smallpox from $t-10$ to t on the vaccination rate in t. Infections and deaths are measured per 10,000 inhabitants. 95% confidence intervals are reported.

In Table 2, we control for the number of infections per 10,000 inhabitants in $t-2$ and t to take into account its effect on the pool of children that could get vaccinated[26]. Infections are less often specified in the national reports on vaccination, which reduces the number of observations. The effect of the infection variables is in compliance with the correlations found in Figure 2, and they appear to be significant drivers of vaccination. These results confirm the

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[25]One could have thought that, with a lot of children being infected by or dying from smallpox, parents would change their fertility behaviour, which could affect our vaccination rate measure. However, as shown in Figure A35, none of these two variables is significantly related to the number of births.

[26]We take the number of infections instead of the number of deaths as this information is more often available in the reports on vaccination. The number of infections at time t can be influenced by the number of vaccinations, which would create a problem of bad control in this specification (Angrist and Pischke, 2008). However, its strong and positive correlation with the number of vaccinations makes it a factor that we need to account for.

idea that parents strongly reacted to smallpox outbreaks and that vaccine uptake significantly increased in times of sanitary crisis.

The effect of negative income shocks on vaccination against smallpox remains significant when controlling for the number of infections. The magnitude of the 2SLS estimates is increased by the inclusion of these additional controls. These results indicate that the positive effect of income shocks on vaccination is robust to the negative effect of past epidemics on the pool of children that could get vaccinated and to the positive effect of contemporaneous smallpox prevalence on vaccination. In the Transmission Channels section, we will specify more why finding an effect robust to the inclusion of contemporaneous outbreaks is important to understand the impact of negative income shocks on vaccine uptake.

Table 2: Price of wheat and vaccination against smallpox

				Vaccination rate				
	OLS		IV: Rainfall$_{t-1}$		OLS		IV: Rainfall$_{t-1}$	
			Collected				Reconstructed	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Price of wheat	0.925**	0.830*	4.716**	4.855**	0.768**	0.801**	3.358*	4.089**
	(0.450)	(0.472)	(2.126)	(2.208)	(0.348)	(0.342)	(2.014)	(1.974)
Smallpox infections	0.133*	0.123*	0.122*	0.106	0.199***	0.184***	0.207***	0.193***
	(0.068)	(0.069)	(0.065)	(0.067)	(0.049)	(0.048)	(0.048)	(0.048)
Smallpox infections$_{t-2}$	-0.153**	-0.155**	-0.120*	-0.131**	-0.169***	-0.161***	-0.150***	-0.139***
	(0.061)	(0.059)	(0.063)	(0.058)	(0.033)	(0.034)	(0.032)	(0.032)
Controls		X		X		X		X
Department fixed effects	X	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X	X
Observations	1252	1252	1252	1252	2546	2546	2546	2546
R^2	0.606	0.611			0.426	0.440		
$F-stat$			19.164	23.559			7.255	7.030

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. The price of wheat is computed in francs per hectolitre. The number of infections is measured per 10,000 inhabitants. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level. In columns (1) and (2), the number of observations used in the OLS estimations is restricted to the sample used in the IV estimations, and for which rainfall data are available. Collected rainfall is computed as the total rainfall over the months July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$. Reconstructed rainfall is measured as the total rainfall over the seasons Summer$_{t-2}$, Autumn$_{t-2}$, Spring$_{t-1}$, Summer$_{t-1}$ and Autumn$_{t-1}$.

5.1.3 Other Potential Determinants of Vaccination and Robustness Checks

The estimation outcomes of Table 1 could be subject to an omitted-variable bias if they fail to control for significant determinants of vaccination. Within subsection E.1.3 of the Appendix, we explore the potential effect of several of them: (i) the concentration and variations in the number of medical practitioners, (ii) the effect of other major epidemics by focusing on cholera, (iii) distrust towards the ruling elite and (iv) religion. We find that the effect of income shocks is robust to controlling for the concentration of medical practitioners, and that parents didn't react differently to economic shocks when the number of potential vaccinators available was higher. The effect of other epidemics on vaccination against smallpox is also expected to be marginal, as controlling for the number of cholera deaths doesn't affect the significance of the effect of income shocks. Moreover, the political colour of departments, their turnout level taken as a proxy for civic-mindedness, and the intensity of their religious practice are found to be uncorrelated to the variations in vaccination.

The results of Table 1 also remain statistically significant across a battery of robustness checks, detailed in Appendix E.1.4. First, we vary key variable definitions by (i) measuring the wheat price since the last harvest in $t-1$ and (ii) computing vaccination rates using births over $t-1$ and t rather than only t. Second, we modify the rainfall instrument by (i) including all months, and therefore not only those with the strongest effect on harvests, and (ii) entering monthly rainfall separately instead of using their sum. The results remain significant across all these specifications. Finally, placebo tests that relate economic shocks to past vaccinations show no significant effects.

5.2 Phylloxera and the End-of-the-century Increase in Vaccination

The phylloxera crisis that struck France during the second part of the nineteenth century had a very strong negative impact of wine production. We therefore expect it to have positively influenced vaccination against smallpox. Descriptively speaking, there is a negative correlation (of -0.32) at the country level between wine production and vaccination from 1850. Figure 3 shows that when wine production increased from 20 million hectolitres in the mid-1850s to around 80 million in 1875, the vaccination rate stagnated around 60%. It is at this date that departments began to get fully contaminated by phylloxera and that wine production drastically

decreased to go back to its 1855 level. Vaccination against smallpox increased strongly during the same years, from 60% to 90% at the very end of the period. This is a first indication that the negative shock on wine production caused by phylloxera impacted vaccination positively.
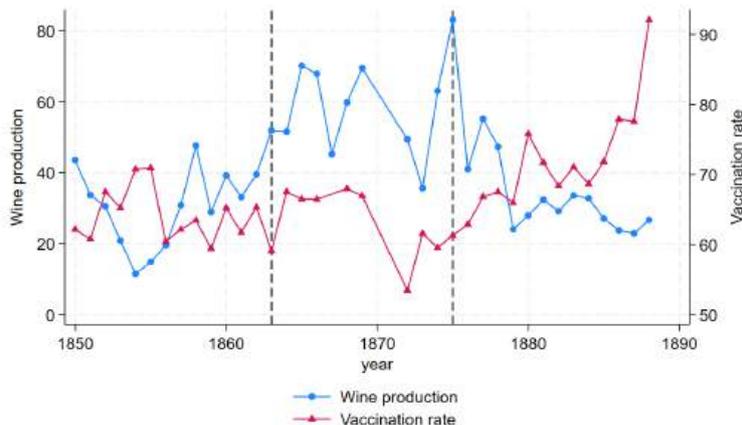

Figure 3: Wine production and vaccination rate

Notes: Wine production is measure in millions of hectolitres. The years 1870 and 1871 are excluded from the graphs as wine production is not available for these two years. Dotted vertical lines for the years 1863 and 1875 represent respectively the year in which phylloxera was first spotted in France, and the year in which a department was fully contaminated for the first time.

5.2.1 The Dynamic Effect of Phylloxera on Vaccination

Figure 4 presents the event-study outcomes based on Equation (3). To estimate the effect of phylloxera, we use, alongside the standard TWFE estimator, the heterogeneity-robust estimators for staggered treatment timing introduced in Sun and Abraham (2021); Callaway and Sant'Anna (2021); Borusyak et al. (2024); de Chaisemartin and D'Haultfœuille (2024)[27]. We gather both the effect on the log of wine production (graph a) and on the vaccination rate (graph b) in this figure. The event-study analysis focuses on wine-intensive departments, which, following Banerjee et al. (2010b) and Bignon et al. (2017), we define as the ones in which wine production represented at least 15% of agricultural production in 1862. This corresponds to a level above the median threshold during the last year before phylloxera was first spotted. Indeed, no negative income shock is found for the departments whose agricultural output was not dependent on wine production[28]. The figure indicates first that the estimates align with

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[27]A description of these estimators is provided in de Chaisemartin and D'Haultfœuille (2022) and in Roth et al. (2023).

[28]The outcomes are presented in Figure A43 in the Appendix, which reproduces the results of Figure 4 within non-wine-intensive departments. As regards wine production, four estimators out of five consistently report no

the parallel trends assumption: regardless of the estimator applied, most of the coefficients for the years preceding full contamination by phylloxera are close to zero and display no clear pre-trends[29]. This finding is in compliance with the results from Bignon et al. (2017) which show that partial contamination by phylloxera didn't impact wine production significantly.

The figure highlights a striking symmetry between the impact of phylloxera on wine production and its effect on smallpox vaccination rates. Full contamination immediately reduced production, with losses deepening between the second and seventh year of infestation. The decline was severe, ranging from about 30% three years after full contamination, to 60% after six years, and nearly 90% after seven years. Wine-intensive departments thus experienced dramatic negative economic shocks following phylloxera's spread. A parallel pattern appears for vaccination rates against smallpox: the increase in vaccinations closely mirrored the decline in wine production. Infected departments saw vaccination rates rise by 10–20 percentage points in the three years following full contamination, and by 25–35 percentage points thereafter—roughly equivalent to a one-standard-deviation increase. This substantial effect likely stems from the fact that, beyond reducing wine output, phylloxera disrupted the entire wine industry, adversely affecting related sectors such as barrel and cork production, thereby amplifying the economic shock. Overall, these findings suggest that, from the early 1870s to 1888, changes in vaccination rates in wine-intensive departments were closely linked to the timing and intensity of the economic downturn caused by phylloxera.

significant effect. There is also clear signs of a pre-trend when relying on the Borusyak et al. (2024) estimator. The effect on vaccination is in compliance with this absence of a significant effect on wine production and therefore of a negative income shock. No pre-trends are visible and there is no significant impact following full contamination by phylloxera. Between 1875 and 1887, phylloxera completely infested 40 departments. Apart from Vaucluse, which was fully contaminated in 1875, all other departments reached full infestation starting in 1878 (see Figure A44 in the Appendix). When estimating the dynamic impact of phylloxera, we keep eight treatment periods to avoid having to deal with imprecise estimates. Figure A45, which reports the event-study estimations using a standard TWFE model, clearly shows that the coefficients are less precisely estimated after eight periods, even though their magnitude is not different.

[29]Running the test for parallel trends with the *did_imputation* command from Borusyak et al. (2024) shows that pre-event coefficients are jointly non-significant (F-stat= 1.48; p-value= 0.2).
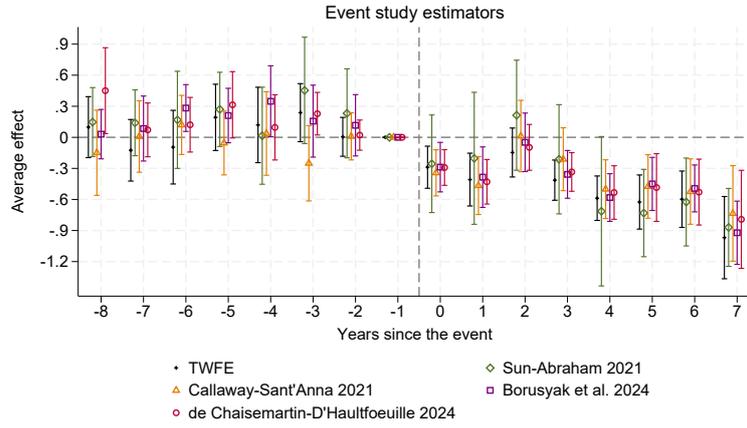
(a) Log of wine production
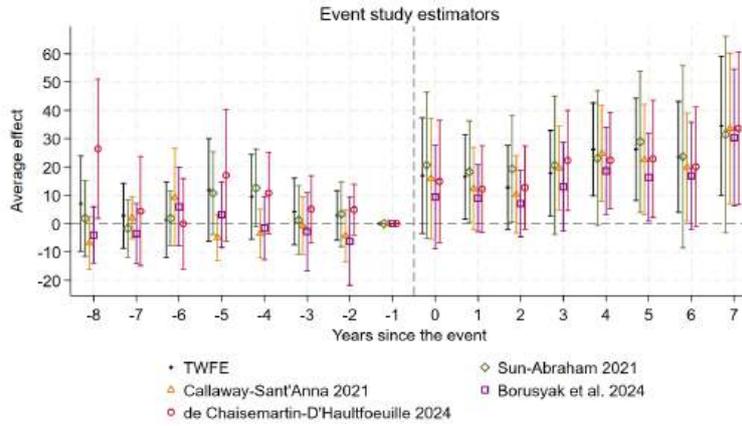
(b) Vaccination rate

Figure 4: Event-study plot: effect of phylloxera on wine production and vaccination rate within wine-intensive departments

Notes: The event-study plot is built using five different estimators: a dynamic TWFE model (black cross markers), Sun and Abraham (2021) (green diamond markers), Callaway and Sant'Anna (2021) (orange triangle markers), Borusyak, Jaravel, and Spiess (2024) (purple square markers) and de Chaisemartin and D'Haultfoeuille (2024) (pinkish-red circle markers). The treatment variable is full contamination by phylloxera. The time span of the data covers eight years before full infestation, and seven afterwards. The reference period considered is $\tau = -1$, one year before full contamination. The outcome variables are respectively the log of wine production (graph a) and the vaccination rate (graph b). Wine production is measured in hectolitres and the vaccination rate is defined as the number of vaccinations per 100 births. Wine-intensive departments are defined as the departments in which wine production represented at least 15% of agricultural production in 1862. 95% confidence intervals are reported. Standard errors are clustered at the department level.

5.2.2 Robustness Checks

The baseline event-study results remain statistically significant across several robustness checks, detailed in Appendix E.2.2. The checks we run consist in (i) considering vaccination rates adjusted for infant and child morality, (ii) using only the never treated or the not-yet treated as a control group, (iii) relying on a balanced panel of departments that can be observed at every period, and (iv) using other baseline periods. The event-study outcomes remain largely unmodified across all these specifications.

In addition to these checks, we reproduce the difference in differences strategy based on a

standard TWFE model implemented in Banerjee et al. (2010b) and Bignon et al. (2017). In compliance with the event-study outcomes, this approach also shows that the crisis primarily disrupted output in regions heavily dependent on wine production. In these areas, moving from no or partial phylloxera infestation to full contamination led to roughly a 48% drop in wine output. Conversely, in regions where viticulture comprised a small share of agricultural activity, phylloxera had no significant effect on wine production. Consistent with these findings, full phylloxera contamination in wine-intensive departments is associated with a 17.5 percentage-point rise in vaccination rates. Analyses using the entire sample, and using scaling factors based on the level of wine production rather than restricting to wine-heavy regions, yield similar results, underscoring that the adverse shock caused by phylloxera was a major driver of vaccination uptake. We also find a similar effect of phylloxera by considering a vaccination rates that accounts for the level of infant or child mortality.

We further assess the impact of phylloxera by applying the IV specification employed by Bignon et al. (2017) as an alternative estimation approach, using phylloxera indicators as instruments for wine production. The results consistently reveal a negative relationship between higher wine production and smallpox vaccination rates, aligning with our findings that negative income shocks tend to increase vaccination uptake. Finally, it is also important to mention that, as explained in subsection E.2.2, the baseline results are already robust to controlling for the potential effect of the Franco-Prussian War of 1870-71, and of the smallpox pandemic triggered by the conflict, on vaccination.

6 Transmission Channels

6.1 Epidemiology of Smallpox

6.1.1 Smallpox Mortality and Economic Shocks Before the Introduction of Vaccination

Several studies have explored the link between economic shocks and smallpox mortality prior to the advent of vaccination. Establishing this relationship is challenging because most records of smallpox infections and deaths began to be systematically collected only after vaccination was introduced. To address this issue, researchers have first focused on London, where the

Bills of Mortality documented five infectious diseases; tuberculosis, smallpox, measles, French pox, and plague; as potential causes of death starting in 1632 (Rusnock, 2002). Leveraging long-term data on bread prices, these studies have demonstrated a positive correlation between negative income shocks, high food prices, and the number of smallpox deaths (Galloway, 1985; Landers, 1986, 1987). Drawing on parish records that accurately recorded causes of death, researchers have also demonstrated that smallpox mortality in Sweden during the seventeenth and eighteenth centuries was also positively correlated to negative economic shocks (Bengtsson, 1999; Bengtsson and Quaranta, 2017; Larsson, 2020).

In order to identify the transmission channels between income shocks and vaccination, we explore the link between smallpox mortality and income shocks using the few cities for which the price of staple food and the number of smallpox deaths are both available prior to the introduction of vaccination (and for a sufficiently high number of years). To the best of our knowledge, these cities are: London, Edinburgh, Copenhagen and Berlin. We could obtain information on smallpox deaths for London from 1664 to 1800, for Edinburgh for the period 1739-1776, for Copenhagen in 1751-1798, and for Berlin for the years 1758-1774 and 1784-1794[30]. From the sources used, we are able to measure smallpox mortality, which we define as the number of deaths due to smallpox per 100 deaths[31].

We also collected data on the main cereals consumed for each city. For London, we could obtain a series of bread and wheat prices, to which we added one of wheat prices for the city of Eton, located 37 kms as the crow flies from Tower Bridge. Wheat is also used for Edinburgh, while the Copenhagen and Berlin series allow us to use more cereals. Subsection F.1 of the Appendix provides more detailed information on the sources used to collect information on smallpox deaths and prices.

The outcomes are reported in Table 3. We only explore the correlation between prices and smallpox, as the restricted number of years available prevent us from using other tools

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[30]The *Tabellverket* provides information on smallpox deaths for each Swedish parish from 1749. However, until 1773, this number is not separated from measles deaths (Sköld, 1996), which reduces the number of years for which we can measure both prices and smallpox deaths precisely. This explain why studies linking smallpox mortality and economic shocks have focused on specific parishes which precisely reported the number of smallpox deaths. It is also unfortunately impossible to replicate these outcomes for France, as there was nearly no record of the cause of death before the nineteenth century in this country (Rusnock, 2002).

[31]We do so to take into account the fact that the population of the cities we consider often drastically changed during the second part of the eighteenth century. Copenhagen went for example from 60,000 to 90,000 inhabitants, which could mechanically increased the number of smallpox deaths. We however couldn't obtain the exact yearly number of inhabitants for each city, which is why we only measure smallpox mortality over the total number of deaths.

than OLS. We use the log of the price as very different price units are reported in the data[32], which prevents any direct comparison between the cities. The results show that, for all four cities, there existed a positive correlation between food prices and smallpox mortality before the introduction of vaccination. For example, a one-percent increase in the price of (a 1.8kg) bread in London was associated with a 2.9 percentage-point increase in smallpox mortality.

For Copenhagen and Berlin, the magnitude of the correlation is also coherent with the volume of cereal production. For example, according to the Danish *Statens Statistiske Bureau* (National Bureau of Statistics), over around 1,000,000 hectares sown with cereals in 1861, 360,000 were sown with oats, 300,00 with barley and 210,000 with rye. An increase in the price of oats or barley therefore represented a stronger negative income shocks for the Danes, which should have been linked to a higher effect on smallpox mortality compared to an increase in the price of rye. This is indeed what is found in the outcomes[33]. The results therefore confirm the positive association found in the literature between staple food price and smallpox mortality prior to the introduction of vaccination.

Table 3: Price of cereals and smallpox mortality

	Smallpox mortality										
	London			Edinburgh	Copenhagen			Berlin			
	Bread	Wheat (Eton)	Wheat	Wheat	Oats	Barley	Rye	Rye	Oats	Wheat	Barley
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Log of price	2.857**	1.719*	2.312*	7.766*	4.495***	3.803***	2.599*	13.331***	11.708**	14.967**	8.961
	(1.401)	(0.894)	(1.315)	(3.927)	(1.570)	(1.375)	(1.300)	(3.937)	(5.231)	(5.798)	(5.397)
Observations	137	137	71	35	45	45	45	21	21	21	21
R^2	0.033	0.025	0.039	0.103	0.105	0.089	0.047	0.159	0.114	0.121	0.072

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Smallpox mortality is defined as the number of deaths due to smallpox per 100 deaths. The prices for Berlin are reported in mark per 1000 kg, in Danish skilling per litre for Copenhagen in pence per litre per Edinburgh. In the case of London, the bread price is in pence per 4 pounds (1.8 kgs), while the wheat prices are given in shillings per Winchester quarter. A Winchester quarter represented a volume of approximately 2.273 litres. Robust standard errors are used.

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[32]The prices for Berlin are reported in marks per 1000kg, in Danish skilling per litre for Copenhagen and in pence per litre for Edinburgh. In the case of London, the bread price is in pence per 4 pounds (1.8kg), while the wheat prices are given in shillings per Winchester quarter. A Winchester quarter represented a volume of approximately 2.273 litres.

[33]In the case of Berlin, the *Statistisches Jahrbuch für das Deutsche Reich* (Statistical Yearbook for the German Reich) of 1880 specifies that, within the boundaries of Prussia, 4,500,000 hectares were sown with rye, 2,500,000 with oats, 1,000,000 with wheat and 875,000 with barley. The results are globally coherent with this structure of production.

6.1.2 Prevalence and Case Fatality Risk of Smallpox

Two factors can be put forwards in order to explain the relationship found in Table 3: (i) a higher prevalence of smallpox linked to a heightened mobility, (ii) a higher case fatality rate of the disease resulting from malnutrition.

Indeed, the existing scientific literature has shown that negative economic shocks have historically constituted one of the main push factors causing migrations (see for example Moch (2003) for an analysis of European migrations since the mid-seventeenth century) and that human mobility is associated with the spread of infectious diseases through an increase in the number of interactions between people (Lessani et al., 2023). The prevalence of smallpox was therefore also affected by mobility, especially by increased migrations in times of high prices and famine (Bercé, 1984; Mielke et al., 1984; Sköld, 1996), which eventually contributed to increase the number of smallpox deaths.

As regards the second factor, a vast medical literature shows that the malnutrition problem created by income shocks contributes to dramatically increase the case fatality rate of infectious diseases (Rice et al., 2000; Olofin et al., 2013). This is caused by immunodeficiency and the lower production of antibodies associated with malnutrition (Scrimshaw and SanGiovanni, 1997; Rytter et al., 2014). Another explanation put forward is therefore that the increase in smallpox deaths was due to an increased case fatality rate as a result of malnourishment, which contributed to weaken children and to lower their resistance to smallpox. According to Duncan et al. (1993), the impact of negative income shocks in London mostly worked through malnutrition, while migration probably was of secondary importance. A similar argument has also been put forward in the case of early modern Sweden (Larsson, 2020). This idea has also received some empirical support from epidemiologists involved in the eradication efforts in India and who observed that cases of smallpox seemed to be more severe and fatalities more common among undernourished villagers and refugees compared to those who were better nourished (Fenner et al., 1988)[34].

The effect of shocks on mortality is therefore very likely to have worked through migrations

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[34]Related to this point, it is reassuring that the efficiency of the smallpox vaccine was unrelated to age, sex, and the nutritional status of children after WWII (Ifekwunigwe et al., 1980). It is therefore highly unlikely that economic shocks reduced the proportion of successful vaccinations in nineteenth-century France. We can therefore exclude the possibility that the effect of shocks on vaccination against smallpox worked through the multiple vaccination of the same children to ensure an efficient protection.

and malnutrition. While mobility impacted smallpox deaths through a higher prevalence of the disease, nutrition rather influenced the mortality rate of individuals infected with smallpox (Dawson, 1979)[35].

6.1.3 Parents' Expectations Regarding the Impact of Negative Income Shocks

The strong correlation found in Table 3 provides extremely valuable insights. It shows that, before the introduction of vaccination, families lived in a reality where negative income shocks were closely linked to intensified smallpox prevalence and mortality. Given that approximately 80% of each cohort in eighteenth-century Europe contracted the disease and that smallpox outbreaks were recurrent, it is highly likely that this association became common knowledge among families. But is there any evidence that parents anticipated the effects of economic shocks on smallpox outcomes?

Historical evidence from the eighteenth century reveals that, long before the rise of modern epidemiology, ordinary people and local authorities recognised the connection between population mobility and the spread of infectious diseases, including smallpox[36]. Although medical opinion remained divided on the subject of smallpox transmission, most practitioners nonetheless recommended avoiding contact with the infected (Mead, 1720; Hillary, 1740; Haygarth, 1785). Recommendations on isolation were explicitly included in William Buchan's *Domestic Medicine*, one of the most widely read medical works in Europe, which sold over 80,000 copies across nineteen editions during his lifetime (Buchan, 1774). Diaries and newspaper advertisements from Britain also reveal that many adults avoided visiting towns known to have cases of smallpox. Outbreaks often led to the closure or relocation of markets and disrupted county court sessions (Razzell, 1977). From the mid-seventeenth century, local authorities across Britain and Europe also organised pest houses for smallpox patients. These local containment practices had measurable epidemiological effects, reducing transmission and mortality in communities that systematically isolated cases (Davenport et al., 2018; Davenport, 2020)[37].

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[35]Unfortunately, we can't add new insights on these mechanisms and distinguish between them, as it would require to have information on the individual nutritional and health status of people, as well as yearly mobility patterns between and within departments, which are not available for the nineteenth century.

[36]The idea that smallpox contagiousness could be prevented by restricting mobility and isolating the patients is ancient, as it was already mentioned in the work of Avicenna (980-1037) and Ibn al-Khatib (1313-1374) (Berche, 2022).

[37]Debates concerning the risks associated with variation and the necessity of isolating newly inoculated individuals, particularly in urban settings and within market towns where epidemics could spread more readily, also reveal an awareness of the connection between mobility, frequent interpersonal contact, and the prevalence

Moreover, a wide range of historical evidence indicates that ordinary people possessed a shared understanding of how mobility influenced smallpox transmission, and recognised isolation as an effective measure to curb its spread. Through a detailed examination of eighteenth-century family diaries and correspondence from the counties of Oxfordshire and Norfolk, Leadbeater (2015) offers numerous examples supporting this view. This leads her to conclude that: "the personal testimonies consistently reveal that smallpox was believed by all parties to be transmitted through contagion. Indeed, cases explored for this thesis confirm that eighteenth-century families had a clear appreciation of the significance of person-to-person transmission, albeit without the knowledge of the concept of virus theory" (Leadbeater, 2015, pages 168-170).

Together, these sources illustrate that the relationship between human mobility, frequent interpersonal contact and smallpox mortality was part of a shared, practical epidemiology. People may not have understood the mechanisms of viral transmission, but they grasped the correlation between the circulation of people and the circulation of the disease. This awareness was sharpened during times of economic crisis. The poor, compelled to move in search of work or sustenance (Moch, 2003), became the inadvertent carriers of contagion. Communities, recognising this risk, reacted by erecting social and spatial barriers, closing parish boundaries, forbidding travellers, or imposing quarantine. These actions were all predicated on the expectation that crisis-driven mobility would worsen epidemic outcomes. In this sense, the association between negative income shocks, migration and smallpox mortality was indeed part of the "common knowledge" of the time.

Regarding the effect of income shocks on smallpox case fatality rates through their influence on nutrition, the historical evidence is largely anecdotal. Some eighteenth-century physicians observed that malnutrition appeared to increase the risk of death from smallpox. A notable example comes again from Buchan (1774) (chapter XXIII), who wrote: "Children are most liable to this disease; and those whose food is unwholesome, who want proper exercise, and abound with gross humours, run the greatest hazard from it.". Nevertheless, based on the available evidence, it is not possible to determine whether parents at the time understood that adverse economic conditions could lower their children's chances of survival once infected with smallpox.

Historical evidence thus suggests that smallpox was seen as a greater threat to child survival

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of smallpox. For additional detail about variation, see subsection B.3 of the Appendix.

during times of economic hardship, linked to the impact of negative shocks on migration and the resulting rise in smallpox prevalence. Before vaccination, parents had limited means to reduce mortality; variolation was not widely accessible in France, and most people could not easily isolate themselves from their communities. However, once vaccination became available, families were able to protect their children more effectively from smallpox, and they did so.

High prices were also correlated with an increase in mortality from fevers, typhus or dysentery prior to the nineteenth century (Galloway, 1985; Landers, 1986, 1987; Larsson, 2020). Thus, it is conceivable that part of the impact of shocks actually reflects a broader parental impulse to use every available method, including smallpox vaccination, to enhance their children's protection in times of negative income shocks. The mechanism would be the same in this case, with parents increasing protection only when the survival of children became more uncertain.

Based on the available data, it is challenging to determine precisely whether parents responded to negative shocks immediately, even before any actual increase in prevalence, or if they waited until the number of infections rose. We can gain insights into whether parents reacted to expected or actual prevalence by controlling for the number of smallpox infections at time t, which is done in Table 2. While this method is not perfect, it provides some information on whether parents increased vaccination rates when prices rose, given a specific prevalence level. The OLS and IV estimations remain significant within this specification, which indicates that parents indeed reacted to a higher expected prevalence, and not only to a higher actual one. This pattern aligns with research indicating a correlation between childhood vaccination and the perceived prevalence or severity of diseases (Smith et al., 2017; Oster, 2018).

These findings indicate that the significant fluctuations in vaccine uptake throughout the nineteenth century were driven by parents' perception of varying levels of threat to their children's survival based on the economic context. This behaviour explains why vaccine uptake consistently fell short of the level needed for optimal public health, preventing herd immunity against smallpox from being achieved until vaccination became mandatory.

6.2 Alternative Transmission Channels

We explore several alternative transmission channels in subsection F of the Appendix. Firstly, we investigate the potential stronger intervention of departments in favour of vaccination in times of negative income shocks. There is indeed historical evidence about payments made by authorities to indigents to increase the vaccination rate (Darmon, 1986). One might expect that, during periods of negative income shocks, families were more likely to turn to vaccination as an additional source of income in departments where financial incentives were offered. Local authorities may also have taken advantage of such shocks to introduce these incentives and boost vaccination rates. If this was the case, we should observe an increase in departmental funds allocated to vaccination following negative shocks. We however find no significant relationship between spending and vaccination, or between negative shocks and spending during the nineteenth century.

We also check for the possibility that negative income shocks impacted vaccination through a change in the number of hours worked by parents. Negative shocks might indeed have induced a reduction in agricultural production and the number of hours worked. This would have left more time for parents to vaccinate their children and to look after them, as they could develop fever and muscle aches during several days after getting vaccinated (Belongia and Naleway, 2003). We provide evidence that this transmission channel is unlikely to account for the strong effect of shocks on vaccination.

7   Conclusion

In this paper, we study the determinants of vaccine uptake and investigate why, in the absence of legal obligation, a population can get accustomed to vaccination. Leveraging data on smallpox vaccination in nineteenth-century France, we demonstrate a robust positive association between negative income shocks and vaccination rates throughout the century. This finding holds strong significance across both of our estimation approaches, whether we employ wheat prices or the phylloxera crisis as a measure of negative shocks. We posit that this phenomenon is attributable to a higher (expected) prevalence and severity of smallpox during periods of negative income shocks. Prior to the implementation of vaccination in the early

nineteenth century, these shocks were correlated with an increased smallpox mortality. Parents foresaw this elevated risk and consequently intensified efforts to safeguard their children's health when facing such adverse circumstances. This dynamic prevented the French population from achieving herd immunity throughout the nineteenth century.

From a public policy standpoint, this paper offers valuable insights for shaping vaccination policies. It indeed demonstrates that the lack of legal vaccination mandate likely results in more volatile vaccination rates, with parents more inclined to vaccinate only under pressure, such as during disease outbreaks or in times of higher expected prevalence and severity of the disease. This poses a threat on the diffusion of vaccination over time, and is likely to lead to a vaccination rate falling short of herd immunity level in the long run. We believe that our findings can also partly help explaining the recent increase in vaccine hesitancy, even within countries with mandatory vaccination policies. Indeed, in the absence of external shocks and when the prevalence of diseases decline, the benefits of vaccination are likely to be under-valued. This is expected to result in increased reluctance to vaccinate, ultimately leading to diminished vaccination coverage over time.

Our paper suggest new research avenues. Our findings indeed also offer valuable insights into the dissemination of new vaccines. Without a legal mandate for vaccination, our study predicts that vaccine uptake within a given population may remain suboptimal decades after the introduction of the new vaccine. In the case of France, even 80 years were not enough to achieve herd immunity. Moreover, our results reveal that suboptimal vaccine diffusion occurs even when the risk of death from the infectious disease is as high as 10%, which was the case in Europe prior to the introduction of vaccination against smallpox. As climate change is expected to aggravate existing infectious diseases (Mora et al., 2022), widen or at least change their geographical distribution (Lafferty, 2009), several existing or new vaccines are likely to be introduced in populations previously unexposed to them in the future. Our findings therefore bear important implications for the diffusion of these vaccines in the long run. However, further studies are necessary to enhance our understanding of this crucial aspect.

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Online Appendix

A   Introduction
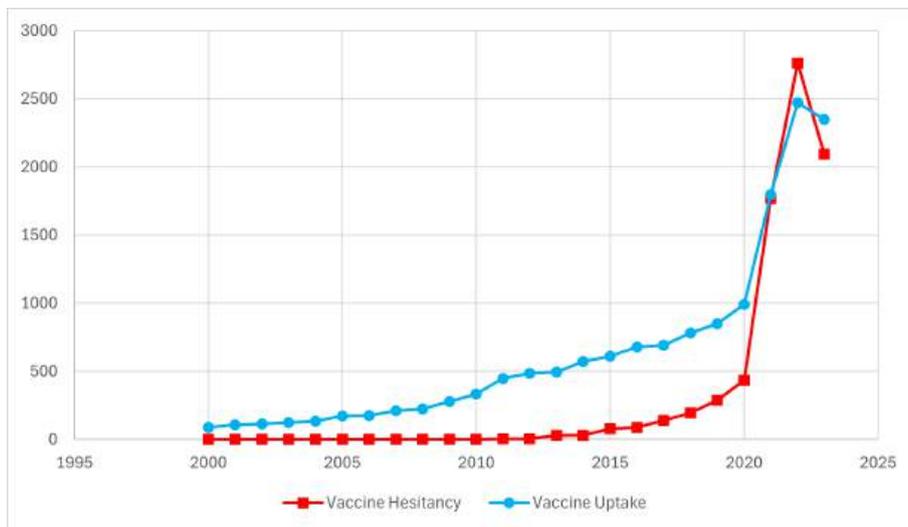
Figure A1: References to "vaccine hesitancy" and "vaccine uptake" in PubMed, 2000–2023

Note: The number of references is measured as the number of articles that mention the terms "vaccine hesitancy" or "vaccine uptake".
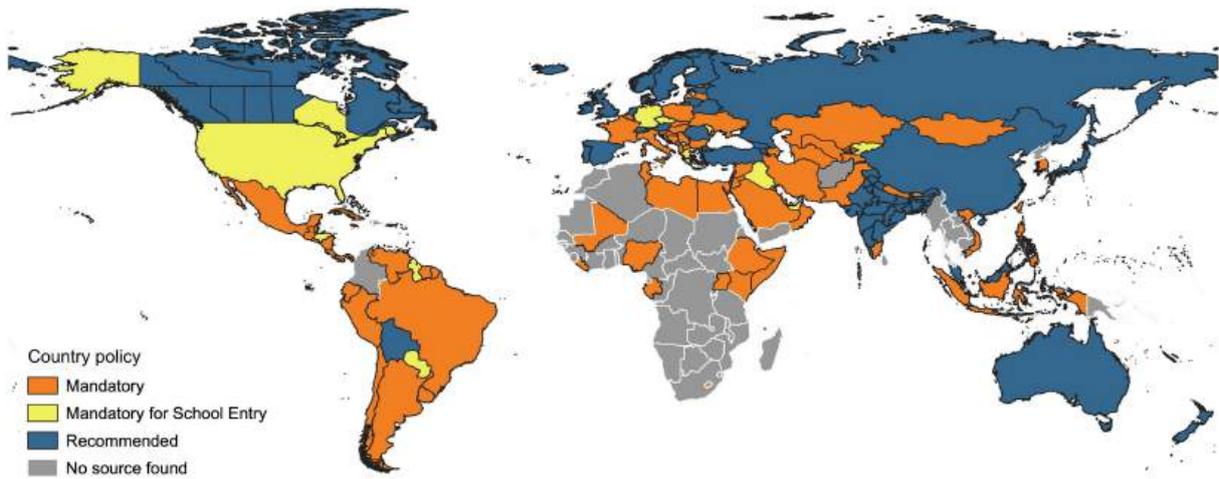
Figure A2: Map of mandatory childhood vaccination worldwide

Source: (Vanderslott and Marks, 2021).

B Historical Background

B.1 Smallpox Clinical Types and the Course of Smallpox Infection
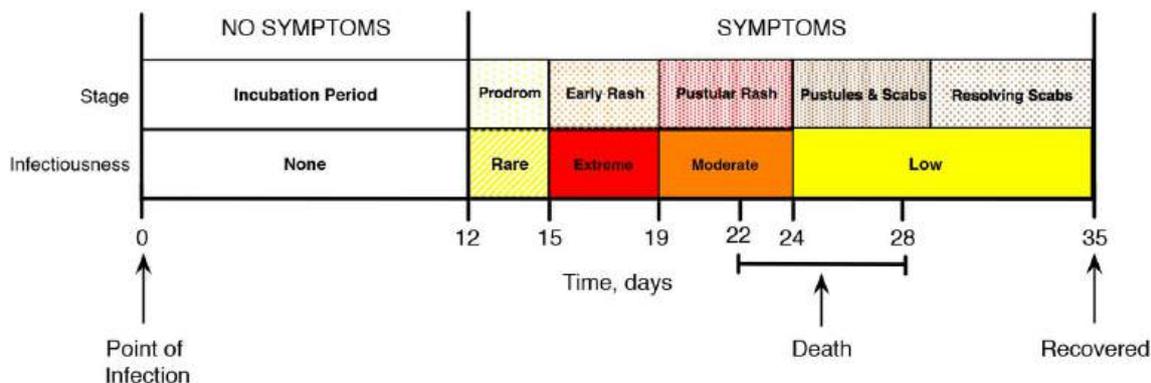
Figure A3: Course of smallpox infection

Source: (Krylova and Earn, 2020).

Note: The stage of the disease and its infectiousness are represented depending on the number of days from the point of infection.

The extent of the rash, which started around 15 days after the infection, was variable but proportionate to the severity of the disease. From the eighth day of the rash, the pustules dry out. It is typically from this point, and during a period of approximately one week, that death could occur. When the infected person survived, this phase was accompanied by a definitive drop in fever, ending between the fifteenth and thirtieth day of the rash. The infectiousness was the highest between two and three weeks after the initial infection, and then progressively decreased.

The most common sequelae were facial scars, present in 65% to 80% of the survivors, followed by blindness due to eye damage (1% of the survivors), and limb deformities due to joint or skin damage (2% of surviving children) (Fenner et al., 1988).

Smallpox existed in two main forms, variola major and variola minor, each of them being associated with a different severity. Variola major was associated with a case fatality rate of around 30%, while the minor was far less lethal with a rate of 1%. Variola major could lead to seven subtypes of smallpox, each of them having a different frequency and case fatality rate (see Table A1). Infection with variola minor virus conferred immunity against the more dangerous variola major virus, and vice-versa.

Table A1: Classification of clinical types of Variola major

Type of smallpox	Description	Case fatality rate (%)		Frequency (%)	
		Unvaccinated	Vaccinated	Unvaccinated	Vaccinated
Ordinary discrete	Areas of normal skin between pustules, even on face	9.3	0.7	42.1	58.4
Ordinary confluent	Confluent rash on face and forearms	62	26.3	22.8	4.6
Ordinary semi-confluent	Confluent rash on face, discrete elsewhere	37	8.4	23.9	7
Modified	Like ordinary type but with an accelerated course	0	0	2.1	25.3
Malignant aka Flat	Pustules remained flat; usually confluent or semi-confluent	96.5	66.7	6.7	1.3
Early haemorrhagic	Widespread haemorrhages in skin and mucous membranes, with purpuric rash	100	100	0.7	1.4
Late haemorrhagic	Haemorrhages into base of pustules	96.8	89.8	1.7	2.0

Source: (Rao, 1972; Fenner et al., 1988).

Notes: The case fatality rate and frequency of smallpox types for unvaccinated and vaccinated individuals are measured from around 7,000 hospitalised patients in Madras. The case fatality rate is defined as the percentage of people infected that died from the disease. The frequency is defined as the percentage od individuals infected by a given type of smallpox among all infected individuals.

B.2 Initial Spread of the Smallpox Virus

Smallpox is believed to have emerged as a human disease around 10,000 BC, coinciding with the establishment of the first agricultural settlements in northeastern Africa. The most plausible hypothesis is that smallpox evolved from a terrestrial African rodent virus between 68,000 and 16,000 years ago (Li et al., 2007). The earliest evidence of skin lesions resembling those caused by smallpox was discovered on the face of the mummy of Pharaoh Ramses V, who died at the age of 40 in 1157 BC. Speculation suggests that Egyptian traders may have introduced smallpox to India during the first millennium BC (Saluzzo, 2004; Riedel, 2005). Smallpox likely entered China in the first century AD from the south-west, and by the 6th century, it had spread from China to Japan, causing a devastating epidemic from 735 to 737, which claimed the lives of up to a third of the population.

The exact timing of smallpox's arrival in Europe and southwestern Asia remains uncertain. Arab armies may have introduced smallpox to southwestern Europe during the 7th and 8th centuries. There also speculations about the fact that the Antonine Plague of AD 165-180 was due to smallpox. In the 9th century, the Persian physician Rhazes provided one of the earliest detailed descriptions of smallpox, distinguishing it from measles and chickenpox. Smallpox became established on the continent thanks to population growth and mobility. By the sixteenth century, smallpox was widespread in Europe, where it had a mortality rate as high as 30% (Sköld, 1996).

The introduction of smallpox in a population with no immunity had devastating consequences. The epidemic that struck Iceland in 1241 led to the loss of a third of the island's population. The disease was introduced in the New World by Spanish and Portuguese conquistadors, killing a large part of local populations and contributing to the downfall of the Aztec and the Inca Empires. The establishment of English settlements along the east coast of North America was also accompanied by devastating smallpox outbreaks among Native American populations, leading to high case fatality rates of up to 90% (Berche, 2022). Smallpox was also linked to one of the earliest instances of biological warfare. During the French-Indian War (1754–1763), Sir Jeffrey Amherst, commander of British forces in North America, suggested deliberately using smallpox to reduce the population of American Indians hostile to the British (Riedel, 2005).

In French, the disease is called *variole* or *petite vérole*. The word *variole* was coined from the Latin *variola* (small pustule), which itself derives from the words *varius* (speckled) and *varus* (pustule). The term *variole* was first used by Marius of Avenches to describe an epidemic in France and Italy in 570.

The term "smallpox" emerged in England during the sixteenth century to differentiate the disease from syphilis, which was referred to as the "great pox" at the time. Throughout history, smallpox has also been known by various other names such as pox, speckled monster, and red plague (Saluzzo, 2004).

B.3 The First Protection Against Smallpox: Variolation

The first method of protection against smallpox that was developed historically is inoculation, also called variolation. This process consisted in immunising individuals using material obtained from someone infected with smallpox, or from a recently variolated person. The procedure was most commonly carried out by inserting powdered smallpox scabs or fluid from pustules into superficial scratches made in the skin of a sound individual, or by blowing it into the nostril of the person. By doing so, practitioners aimed at inducing a mild but protective version of the disease. The main danger was of course to transmit a strong version of smallpox and potentially to create an epidemic. It is estimated that around 2% of the inoculated individuals died from the disease, which is significantly lower than than the case fatality rate of natural smallpox (Razzell, 1977). This practice seems to have started in China around the 1500s and to have already been established in India and Africa before its introduction in Europe during the first half of the eighteenth century. It was the action of the aristocrat Lady Mary Wortley Montagu, the wife of a British diplomat to the Ottoman Empire, that promoted the procedure and contributed to the introduction of variolation in England[38]. After a successful trial on Newgate prisoners and orphaned children in 1721, and the inoculation of two daughters of the Princess of Wales in 1722, the method progressively gained acceptance[39]. The London Smallpox Hospital in charge of relieving poor people infected by smallpox and of inoculation opened in 1746. The method was also introduced to the New World after the smallpox outbreak which struck Boston in 1721. Japan adopted variolation later, from the middle of the century. France was the one of the final European nations to adopt variolation from the 1750s, notably following the advocacy of the physician Théodore Tronchin.

The diffusion of variolation was however slow and unequal across regions. There was for example less than 1,000 inoculations in Great Britain and the American colonies between 1721 and 1728. The diffusion generally remained low because of the need to isolate people after the inoculation and of the price which could be prohibitive. People living in market towns also remained reluctant to accept variolation, which could cause a smallpox epidemic and ruin economic activity. In England, this partly changed with the a new variolation technique introduced by the Sutton family which contributed to decrease the price of inoculation and to increase the spread of the method from 1767[40]. Variolation was also favoured by the fact that some parishes preferred to inoculate indigents freely rather than paying the very heavy alternative cost of having to nurse and bury smallpox cases. However, debates regarding the

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[38]Her brother die from smallpox in 1713 and she was herself left with facial scarring after being infected in 1715. The first mention of variolation in Europe was made in 1714, when the physician Emmanuel Timoni wrote a letter to the Royal Society of London describing the technique, which he had witnessed in Istanbul.

[39]A heated debate on the efficiency of smallpox inoculation took place in the 1720s in England. This debate mostly focused on comparing the number of deaths caused by natural smallpox to those linked to inoculation (Rusnock, 2002). More generally, the inoculation of prominent leaders during the eighteenth century, as King Louis XVI of France and his children in 1778 or Catherine II of Russia and her son in 1769, contributed to increase acceptance (Riedel, 2005).

[40]The effectiveness of their approach stemmed from a superficial scratch, meticulous selection of donors with only mild symptoms, and the absence of bleeding or excessive purging. They managed to lower the price of variolation from 10 guineas per inoculation to 2 (Razzell, 1977).

appropriateness of inoculating urban population, given the high risk of spreading smallpox, hindered the widespread adoption of inoculation in the second part of the eighteenth century (Rusnock, 2002). It is estimated that around 200,000 persons were inoculated between 1766 and 1800 in England (Berche, 2022). However, it is clear that smallpox mortality didn't significantly decline before the introduction of vaccination (Davenport et al., 2016; Krylova and Earn, 2020)[41].

In France, variolation triggered a large medical dispute and aroused the hostility of many doctors because of the risk of causing an epidemic[42]. Inoculation was blamed for spreading the disease after the Paris epidemic of 1762, and, on June 8, 1763, the Paris Parliament issued a temporary ban on urban inoculations. Inoculation had to be carried out in the countryside, and people put in isolation for 40 days. It wasn't until four years later, on January 15, 1768, that the Paris Faculty of Medicine finally declared the practice of inoculation to be "acceptable". In this context, the spread of variolation remained very limited, as only 60,000 to 70,000 people were inoculated in France during the eighteenth century (Berche, 2022). This represents only 5% of the total number of vaccinations that took place in France between 1806 and 1810. Variolation therefore never spread significantly in French society[43].

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[41]Davenport et al. (2018) shows that, in eighteenth-century southern England, inoculation contributed to reduce the spread of smallpox, but it was then coupled with a more systematic isolation of infected persons in both pest houses and private residences, and with the suspension of markets and other communal gatherings.

[42]This debate saw the opposition between arithmeticians and philosophers, as Voltaire or La Condamine, who were in favour of inoculation, and the physicians who globally rejected it. In 1760, in a presentation to the Royal Academy of Sciences in Paris, Daniel Bernoulli demonstrated that, despite the risks, if variolation became widespread, life expectancy at birth could be increased by about two years. Bernoulli's work, which laid the foundations for epidemiological modelling, probably had no immediate practical consequences on inoculation (Rusnock, 2002).

[43]The spread of variolation was even more restricted considering the fact that more than half of the total number of variolations over the century were administered by the physician Jean-François-Xavier Girod within the limits of the Franche-Comté region. In other countries like Sweden, variolation also remained limited (Sköld, 1996).

B.4 The Spread of Smallpox Vaccine

The spread of smallpox vaccination around the world from 1800 was extremely fast. As early as 1803, the Spanish Crown orchestrated the Balmis expedition, aiming to carry the vaccine to the Spanish colonies in the Americas and the Philippines. Vaccination was also introduced in India in 1802. It rapidly replace variolation, which was even sometimes banned as it was the case after 1842 in the United Kingdom. The spread of the vaccine within countries was also fast in Western Europe. In France, for example, around 1.5 million vaccinations were administered between 1806 and 1810, in a country of around 30 million inhabitants. Vaccination against smallpox also rapidly became mandatory in several countries: in 1807 in the Kingdom of Bavaria, in 1810 in Denmark, 1816 in Sweden, 1835 in Greece, 1874 in the entire German Empire but only in 1902 in France (Bercé, 1984).

Part of the population sometimes resisted these mandatory vaccination policies. Several small organisations were for example formed in England to oppose vaccination, before merging into the National Anti-Vaccination League at the end of the century. Its American equivalents were the Anti-Vaccination Society of America, formed in 1879, and the Anti-Vaccination League of America. In the USA, this opposition led to the *Jacobson v. Massachusetts* (1905) and *Zucht v. King* (1922) decisions of the Supreme Court which respectively affirmed the power of states to implement compulsory vaccination laws and ruled that public schools had the constitutional authority to exclude unvaccinated students from attending, regardless of the absence of an active outbreak. Another example if the Vaccine Revolt which took place in the city of Rio de Janeiro in 1904. On the English case, and the recognition of conscientious objection in 1907, see for example Williamson (2007).
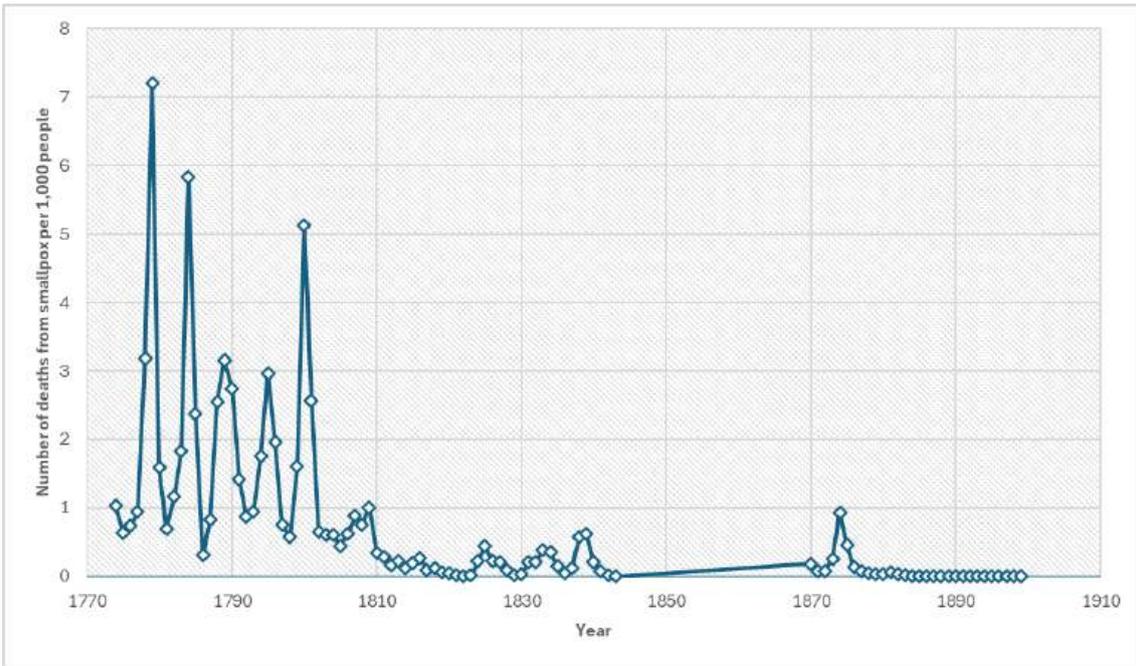
Figure A4: Number of deaths from smallpox in Sweden - 1774-1900

Source: (Edwardes, 1902).

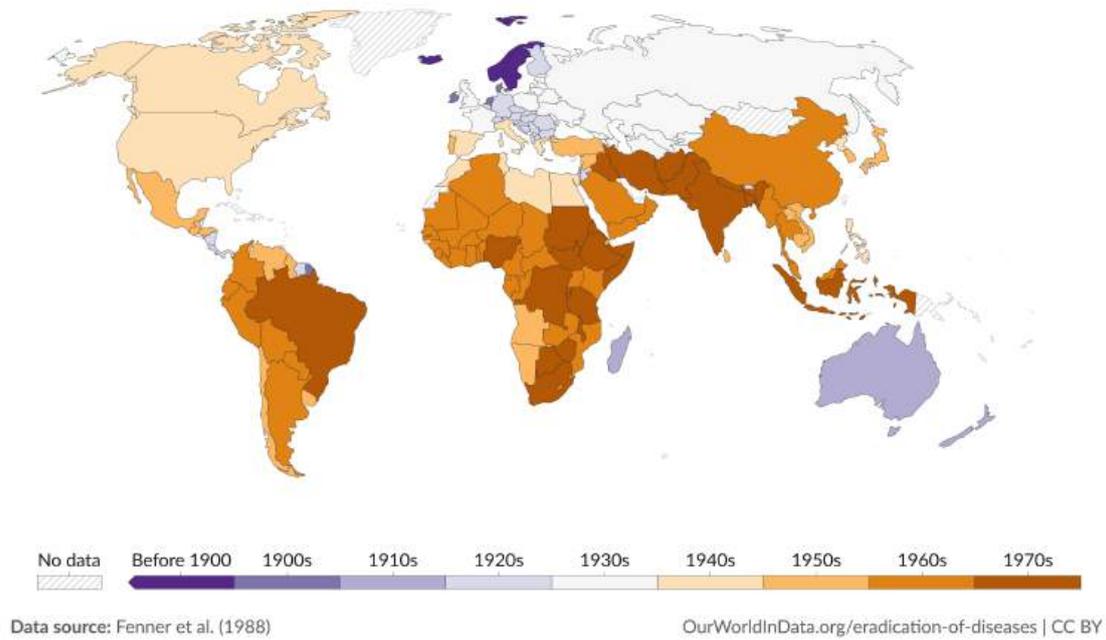*Note*: The number of deaths is represented per 1,000 people.

Figure A5: Decade when smallpox was eliminated in each country

Source: (Fenner et al., 1988) and Our World in Data.

C   Data and Descriptive Statistics

C.1   Smallpox Vaccination

Figure A6: *Rapport sur les vaccinations pratiquées en France - 1825*

Note: The picture reports an extract of the 1825 report on vaccinations against smallpox in France.

The following document is an excerpt of the annual report on vaccinations against smallpox for the Gers department in 1811. It was obtained from the F/8/110 box in the French National Archives in Pierrefitte-sur-Seine. It specifies the name, profession and place of residence of vaccinators (column 4). For each of them, the number of vaccinations performed (column 3), in which municipality (column 2) and district (column 1) is also specified. Some observations made by the vaccinators themselves (column 5) are also included in the report.

Figure A7

Source: Box F/8/110 in the French National Archives.

Table A2: Number and percentage of vaccinations per age group

Age group	Number of vaccinations	Percentage of vaccinations	Cumulative percentage
0-1	20,091	66.5	66.5
1-2	5,238	17.4	83.9
2-3	2,088	6.9	90.8
3-4	1,257	4.2	95
4-5	524	1.7	96.7
> 5	990	3.3	100
Total	30,188	100%	

Note: These figures have been computed using all the available information from the *Rapports sur les vaccinations pratiquées en France.*

Table A3: Number and percentage of vaccinations per month

Month	Number of vaccinations	Percentage of vaccinations	Cumulative percentage
January	1,428	2.8	2.8
February	1,946	3.7	6.5
March	2,395	4.6	11.1
April	3,449	6.6	17.7
May	11,838	22.7	40.4
June	9,671	18.6	59
July	7,070	13.6	72.6
August	2,654	5.1	77.7
September	3,367	6.5	84.2
October	3,407	6.5	90.7
November	2,555	4.9	95.6
December	2,299	4.4	100
Total	52,079	100%	

Note: These figures have been computed using all the available information from the *Rapports sur les vaccinations pratiquées en France.*
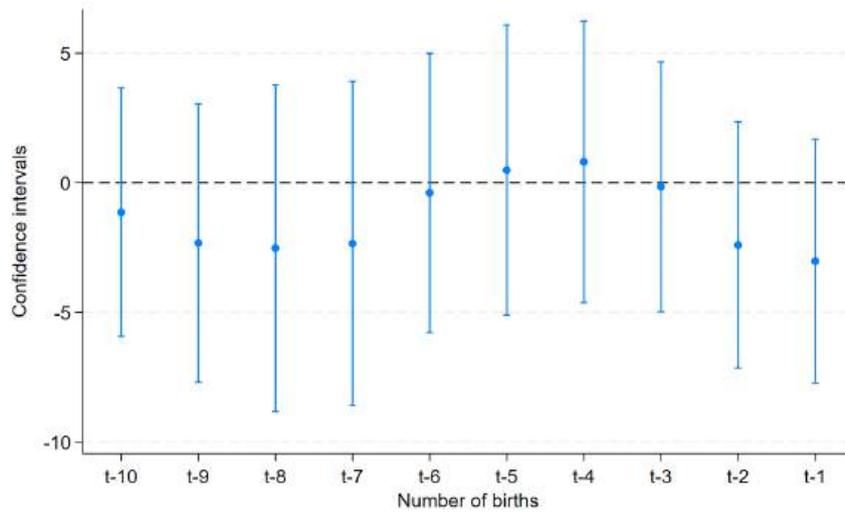
Figure A8: Past vaccination rates and the number of births

Note: The figure depicts OLS estimation coefficients of the effect of past vaccinations from $t - 10$ to $t - 1$ on the number of births at time t. Vaccination rate is defined as the percentage of vaccination over the number of births. 95% confidence intervals are reported.

C.2 Wheat prices

Collecting wheat prices, which would serve for the establishment of tax collection, stewardship of armies, changes in land rents, determination of bread prices, publication of export authorisations or bans, was mandatory since the Ordinance of Villers-Cotterêts in 1539 for more than 500 markets throughout the Kingdom of France. However, prices and documentation prior to the revolutionary period are mostly lost (Drame et al., 1991). During the nineteenth century this information was received by various ministries: the Ministry of the Interior, the various economic ministries created in the nineteenth century, the Ministry of the General Police during the First Empire, and the Ministry of War.

Wheat prices were first collected by the mayors of the towns, and then transmitted to the prefects. Several amendments to the system were made in 1812 and 1817. Prior to 1812, the records for each town were sent to Paris by the prefect every ten days. From 1812 onwards the reports became fortnightly, consisting only in a summary statement for the department. From 1817, the price within a department was not computed any-more as simple average of prices between market towns, but as a weighted average based on volumes sold.

The number of markets providing prices varied from one department to another, following closely the total volume of wheat production. The department of Calvados exhibited for example the highest number of markets in 1870 with 34 markets, while there were "only" 10 markets in Pas-de-Calais, or 9 in Corsica. However, the number of markets does not affect the quality and reliability of the data collected as it depended only on the intensity of wheat trade within departments and not on the diligence of prefects in recording and reporting prices.

One might also fear that some minor markets with excessively low or high prices would bias the average price at the department level. However, as this price was computed as a weighted average based on volumes sold from 1817 onwards, this should not bias our measure for most of the time period considered. Labrousse et al. (1970) also note that there was a high degree of consistency in prices within the same department, which is confirmed by the analysis of Drame et al. (1991).

Moreover, the variations in prices are very consistent with the ones exhibited by the data in Italy, Belgium, Switzerland, the Netherlands and Germany, which reinforces the credibility of the documents held in the Paris archives (Labrousse et al., 1970).

C.3 Rainfall

The data on rainfall were collected from the publications by Victor Raulin. The complete references for these publications are: (Raulin, 1863, 1864, 1866, 1867, 1871, 1878, 1881). When these data were already collected and gathered in the FAO dataset (FAO, 2001), we relied on this source of information.

The following table specifies if the rainfall data were collected from the FAO dataset or the publications from Victor Raulin. It also indicates the towns where the volume of rainfall was measured and the corresponding dates. When this town was not the administrative centre of departments, the as-the-crow-flies distance from this centre is also specified. The vast majority of the data is measured from the administrative centres, and when it is not, the average distance is of around 31 kilometres. Dates specified with an hyphen mean that data on rainfall are available for the entire period. For the Calvados department for example, information on rainfall is available from 1861 to 1888.

Table A4: Availability of the rainfall data by department

		Data on Rainfalls	
Départements number	*Départements* name	FAO Data	Raulin Data
1	AIN		1838-1843 (Saint-Rambert-en-Bugey, 31 kms) ; 1845-1870 ; 1871-1872 (Nantua, 29 kms)
2	AISNE		1859-1860 (Berry-au-Bac, 25 kms) ; 1861-1870
3	ALLIER	1859-1888 (Vichy, 49 kms)	1841-1857 (Villeneuve-sur-Allier, 10 kms) ; 1858
4	BASSES-ALPES		1858-1867 ; 1870 (Barcelonnette, 47 kms)
5	HAUTES-ALPES		1846-1848 ; 1859-1850 (Briançon, 58 kms) ; 1858-1870
6	ALPES-MARITIMES		1865-1874

7	ARDECHE		1806-1830 (Viviers 27 kms) ; 1836-1859 (Davézieux, 59 kms) ; 1860-1864 (Lamastre, 28 kms) ; 1865-1870 ; 1871-1873 (Vals-les-Bains, 22 kms)
8	ARDENNES		1865-1870 (Sedan, 17kms)
9	ARIEGE		1851-1870
10	AUBE		1859-1865 (Barberey-Saint-Sulpice, 5 kms) ; 1866-1870
11	AUDE		1813-1815 and 1818 and 1820 and 1823 and 1825-1828 and 1836-1840 (Sallèles-d'Aude, 45 kms) ; 1821-1822 and 1824 (Saissac, 23 kms) ; 1829-1835 and 1841-1848 (Castelnaudary, 34 kms) ; 1849-1870
12	AVEYRON		1845-1852 ; 1854-1870 ; 1871-1873 (Laguiole, 45 kms)
13	BOUCHES-DU-RHONE	1806-1888	
14	CALVADOS	1861-1888	
15	CANTAL		1858-1870 (Saint-Flour, 51 kms) ; 1871-1874
16	CHARENTE		1860-1870 (Confolens, 53 kms)

17	CHARENTE-INFERIEURE	1810-1888	
18	CHER		1855-1858 (La Chapelle-d'Angillon, 32 kms) ; 1859-1870
19	CORREZE		1861-1872 (Argentat-sur-Dordogne, 21 kms)
20	CORSE	1855-1888	
21	COTE-D'OR	1821-1888	
22	COTES-DU-NORD		1863-1865 (Glomel, 54 kms) ; 1866-1870 (Lamballe-Armor, 14 kms)
23	CREUSE		1835-1837 and 1850-1859 (Ahun, 16 kms) ; 1860-1870 (Dun-le-Palestel, 22 kms) ; 1872
24	DORDOGNE		1857-1861 (Coulounieix-Chamiers, 4 kms) ; 1862 and 1864-1867 (Bour-deilles, 16 kms) ; 1868-1870
25	DOUBS	1845-1888	
26	DROME		1846-1870
27	EURE		1856-1865 (Fatouville-Grestain, 71 kms) ; 1866-1870
28	EURE-ET-LOIR		1854-1857 (Mar-boué, 36 kms) ; 1862-1870
29	FINISTERE	1861-1888	1810-1840 and 1855-1860 (Brest, 52 kms)

30	GARD		1806-1815 and 1817-1825 and 1827-1832 (Alès, 39 kms) ; 1837-1870 (Saint-Hippolyte-de-Caton, 29 kms)
31	HAUTE-GARONNE	1809-1888	
32	GERS		1861-1870
33	GIRONDE	1842-1888	
34	HERAULT	1851-1888	1806-1817 ; 1819 ; 1824-1830 ; 1831-1834 (Pézenas, 41 kms) ; 1835-1850
35	ILLE-ET-VILAINE	1860-1888 (Feins, 22 kms)	
36	INDRE	1859-1888 (Issoudun, 25 kms)	
37	INDRE-ET-LOIRE		1849-1870
38	ISERE	1845-1888	1808-1811 ; 1831-1833 ; 1840-1842
39	JURA		1845-1870
40	LANDES	1851-1888 (Peyrehorade, 61 kms)	1806-1818 (Saint-Sever, 16 kms)
41	LOIR-ET-CHER	1851-1888 (Vendôme, 27 kms)	1838-1841 and 1843-1846 (Pontlevoy, 19 kms) ; 1849-1850
42	LOIRE	1851-1888 (Roanne, 69 kms)	
43	HAUTE-LOIRE	1849-1888	
44	LOIRE-INFERIEURE	1835-1888	1824-1828
45	LOIRET	1849-1888	
46	LOT		1851-1870
47	LOT-ET-GARONNE		1833-1849 (Port-Sainte-Marie, 20 kms) ; 1850-1861 ; 1864 ; 1866-186 ; 1870

48	LOZERE		1857-1870 ; 1871-1873 (Le Bley-mard, 18 kms)
49	MAINE-ET-LOIRE		1842-1848 (Thouarcé, 22 kms) ; 1849-1870 (Les Ponts-de-Cé, 3 kms)
50	MANCHE	1861-1888 (Cherbourg, 64kms)	1844-1846 ; 1856-1870
51	MARNE	1852-1888	1806-1848
52	HAUTE-MARNE		1845-1858 (Bourbonne-les-Bains, 49 kms) ; 1859-1864 (Bassoncourt, 31 kms) ; 1865-1870
53	MAYENNE	1850-1888	1806-1814
54	MEURTHE-ET-MOSELLE	1872-1888	
55	MEUSE		1847-1870
56	MORBIHAN		1862 (Malestroit, 31 kms) ; 1863-1870
57	MOSELLE	1825-1871	
58	NIEVRE		1837-1859 (Decize, 30 kms) ; 1860-1870
59	NORD	1806-1888	
60	OISE		1853-1857 (Clermont, 24 kms) ; 1858-1870
61	ORNE		1865-1870
62	PAS-DE-CALAIS		1854-1869 (Hendecourt-lès-Cagnicourt, 14 kms) ; 1870-1876
63	PUY-DE-DOME	1858-1888	

64	BASSES-PYRENEES		1837-1841 ; 1843-1852 and 1855 (Bages, 34 kms) ; 1853-1854 ; 1856-1870
65	HAUTES-PYRENEES		1854-1870 (Bagnères-de-Bigorre, 29 kms)
66	PYRENEES-ORIENTALES	1850-1888	1834-1849
67	BAS-RHIN	1802-1871	
68	HAUT-RHIN	1856-1871	1849-1855 (Husseren-Wesserling, 36 kms)
69	RHONE	1841-1888	1838-1840
70	HAUTE-SAONE		1845-1869 ; 1870-1874 (La Voivre, 36 kms)
71	SAONE-ET-LOIRE		1845-1864 (Chalon-sur-Saône, 53 kms) ; 1865-1870 (Crissey, 31 kms) ; 1871-1874
72	SARTHE		1811-1814 ; 1817-1830 ; 1850-1852 ; 1855-1870
73	SAVOIE		1863-1870
74	HAUTE-SAVOIE		1861-1870 (Genève, 33 kms)
75	SEINE	1806-1888	
76	SEINE-INFERIEURE	1845-1888	1806-1812 ; 1821-1835 ; 1839-1844 (La Chapelle-du-Bourgay, 42 kms)
77	SEINE-ET-MARNE		1852 and 1854-1860 (Nemours, 32 kms) ; 1861-1870

78	SEINE-ET-OISE		1840-1846 (Champcueil, 39 kms) ; 1847-1870
79	DEUX-SEVRES	1858-1888	1806-1820 ; 1839-1852
80	SOMME		1806-1869 (Mont-didier, 32 kms) ; 1870-1875 (Albert, 27 kms)
81	TARN		1820-1850 (Sorèze, 55 kms) ; 1851-1870
82	TARN-ET-GARONNE		1843 ; 1858-1870
83	VAR		1825-1832 and 1835 and 1841-1848 (Hyères, 17 kms) ; 1833-1834 ; 1836-1840 ; 1849-1851 (Brignoles, 31 kms) ; 1852-1872
84	VAUCLUSE		1806-1840 ; 1841-1865 (Orange, 21 kms)
85	VENDEE		1864-1870 (Bouin, 55 kms)
86	VIENNE	1859-1888	1806-1818
87	HAUTE-VIENNE	1860-1888	1854-1859 (Saint-Léonard-de-Noblat, 18 kms)
88	VOSGES		1859-1870 (Contrexéville, 42 kms) ; 1871-1876 (Vagney, 26 kms)
89	YONNE		1837-1849 and 1856-1857 (Laroche-Saint-Cydroine, 21 kms) ; 1850-1855 ; 1858-1870

99	MEURTHE	1811-1818 ; 1841-1871	
90	BELFORT		

Notes: The table specifies if the rainfall data were collected from the FAO dataset or the publications from Victor Raulin. It also indicates the place where the volume of rainfall was measured and the dates. When this place was not the administrative centre of departments, the as-the-crow-flies distance from this centre is also specified.

For the Oise department, the data are coming from the town of Clermont, located 53 kilometres away from Paris, for the years 1853-1857. It was then collected from Beauvais from 1858 to 1870, which is 59 kilometres away from Paris.

For the Seine-et-Oise department, the data come from Champcueil from 1840 to 1846 and Versailles from 1847 to 1870, which are respectively 35 and 9 kilometres away from Paris.
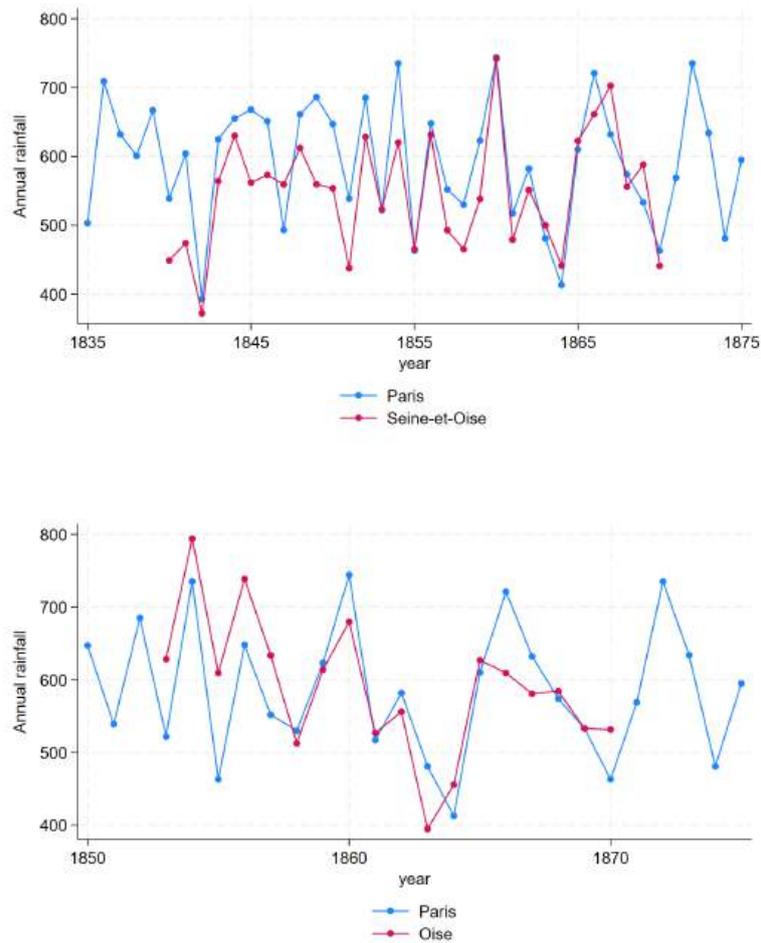
Figure A9: Annual rainfall in Paris, in the Oise and Seine-et-Oise departments

Notes: The graphs depict the annual rainfall in Paris and the surrounding departments of Oise and Seine-et-Oise. Annual rainfall is measured in millimetre or litre per square metre. One millimetre of rain corresponds to a height of water of one millimetre on a flat surface of one square metre, that is to say to a total volume of one litre of rainfall.
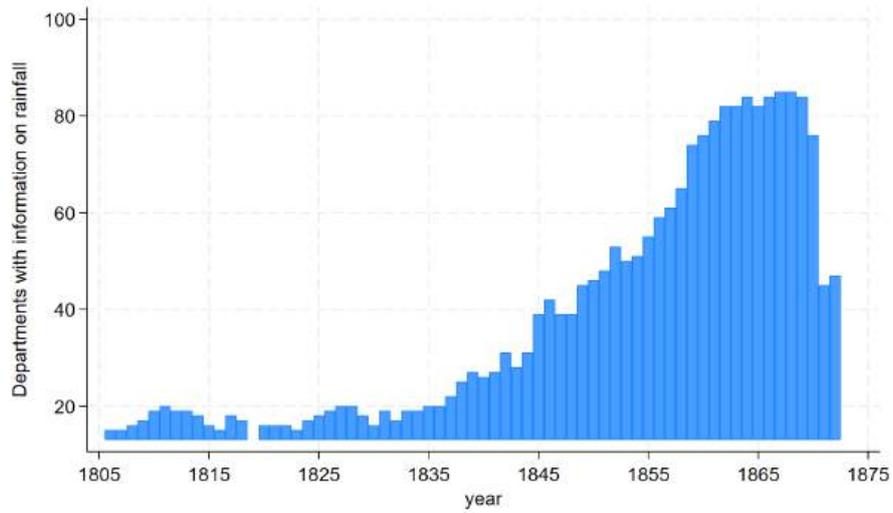
Figure A10: Number of departments with non-missing information on rainfall

Note: The figure depicts the number of departments with non-missing information on rainfall by year. This information is considered non-missing in a given year if rainfall data are available for each month of this year.

We assess the reliability of the reconstructed rainfall by comparing it to the collected annual rainfall. Figure A11 depicts the mean annual rainfall for departments available in our collected sample, this information for the same set of departments from the reconstructed data as well as the difference between the two rainfall series. One can see that the two series are highly correlated, as, on average, the reconstructed data only overestimate the true rainfall by 67.3 mm each year, which corresponds to an overestimation of 9% . Just as importantly here, this spread is constant along the nineteenth century, which entails that the quality of the reconstruction is consistent over time and that using the reconstructed data won't introduce a bias for certain sub-periods.

Running the same test within departments also shows the high quality of the reconstructed rainfall. In Figure A12 and Figure A13, we selected the Nord, Seine, Bouches-du-Rhône and Haute-Garonne departments for which collected rainfall is available all along the nineteenth century. The collected and reconstructed rainfall series are highly correlated in these departments, even if the spread is even lower for northern departments (around 0 mm on average compared to around 200 mm for the southern departments). This was expected as Pauling et al. (2006) show that the quality of the reconstruction is higher for the north fo Europe. Most importantly, the bias is constant within departments, whether they are located in the north or south of France.
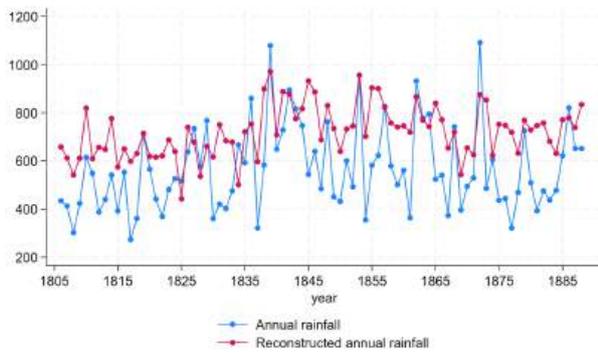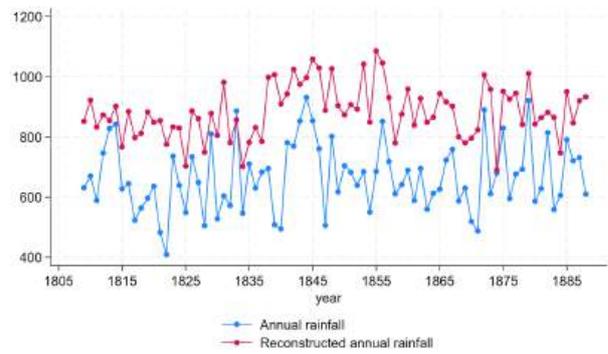

a   b
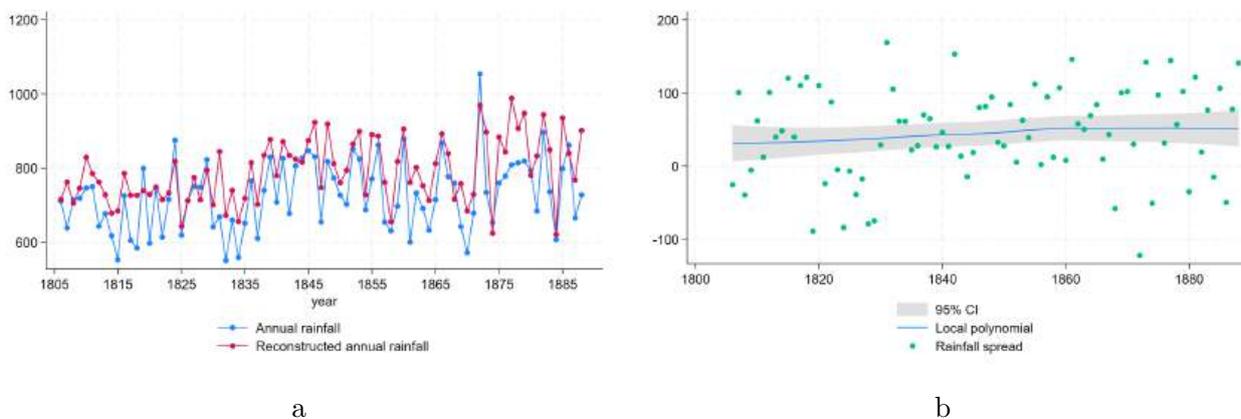
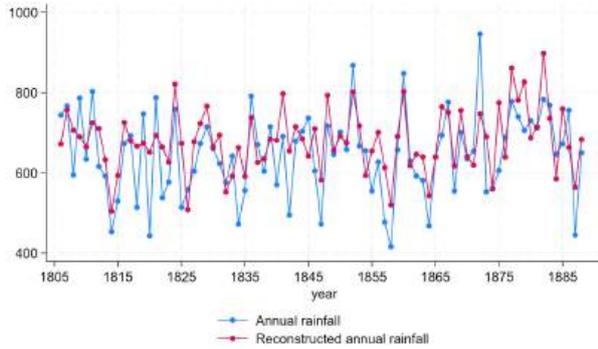Figure A11: Rainfall, reconstructed rainfall and rainfall spread

Notes: Sub-figure (a) depicts the mean annual rainfall within departments according to the data collected and the reconstructed data. For example, between all the departments for which rainfall data are available in 1806, the average annual rainfall is of around 711 mm. For the same set of departments, the reconstructed rainfall provides a value of 688 mm. Sub-figure (b) represents the rainfall spread, defined as the difference between reconstructed rainfall and actual rainfall. A local polynomial smooth plot is represented with 95% confidence intervals in shaded area. All rainfall variables are expressed in millimetre or litre per square metre.
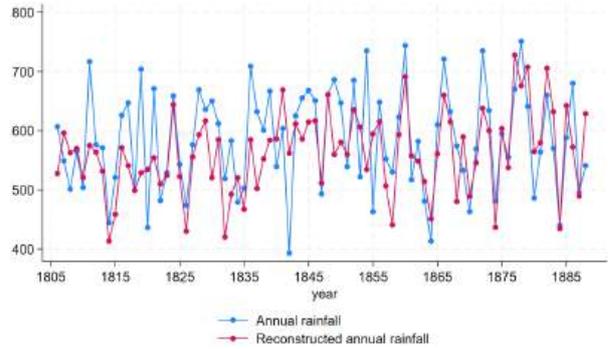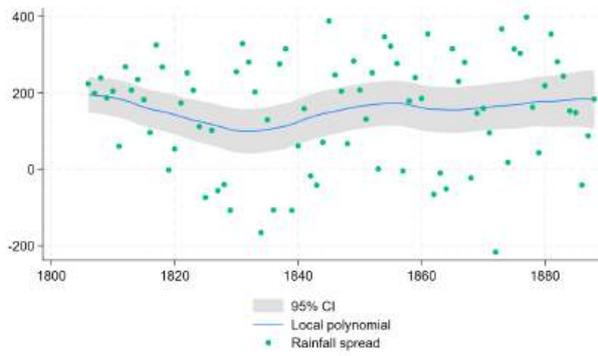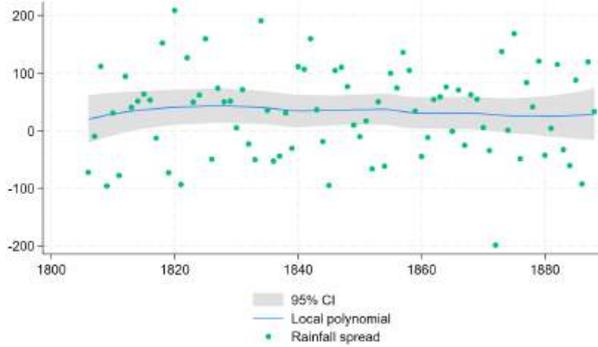
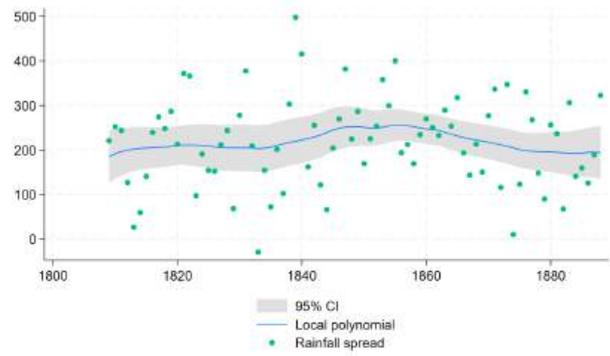Figure A12: Rainfall and reconstructed rainfall for four departments

Notes: The four departments represented are: Bouches-du-Rhône, Haute-Garonne, Nord and Seine. The figure depicts the annual rainfall within these four departments according to the data collected and the reconstructed data. All rainfall variables are expressed in millimetre or litre per square metre.
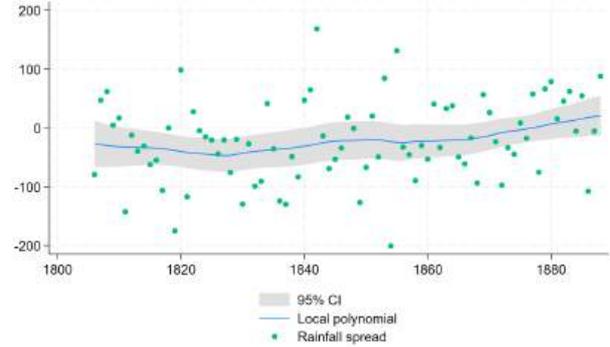
Bouches-du-Rhône

Haute-Garonne

Nord

Seine

Figure A13: Rainfall spread for four departments

Notes: The four departments represented are: Bouches-du-Rhône, Haute-Garonne, Nord and Seine. The figure depicts the rainfall spread, defined as the difference between reconstructed rainfall and actual rainfall. A local polynomial smooth plot is represented with 95% confidence intervals in shaded area. All rainfall variables are expressed in millimetre or litre per square metre.
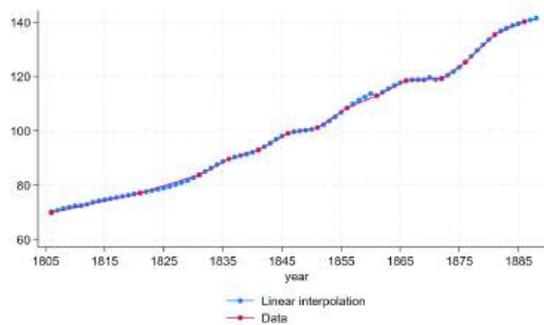
C.4 Other Variables
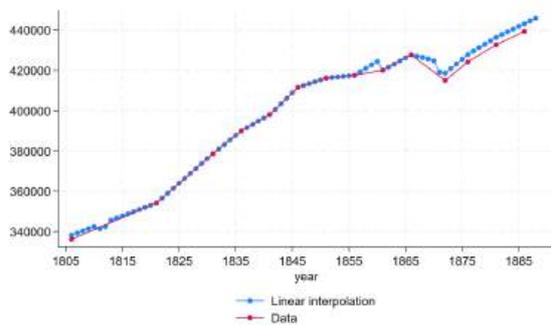
Av. population per department
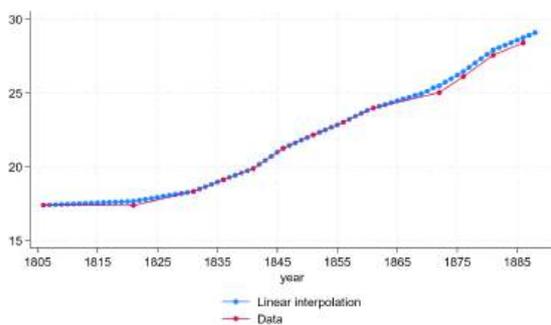
Population density (inhabitants per km²)

Urban population (%)
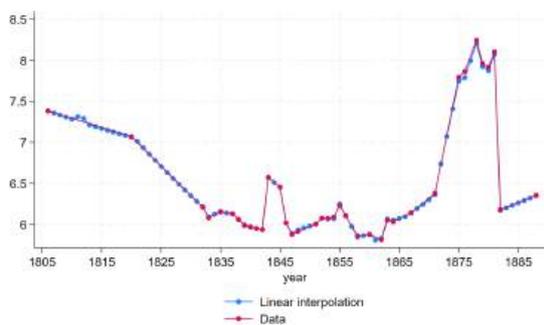
Taxes (Francs per capita)
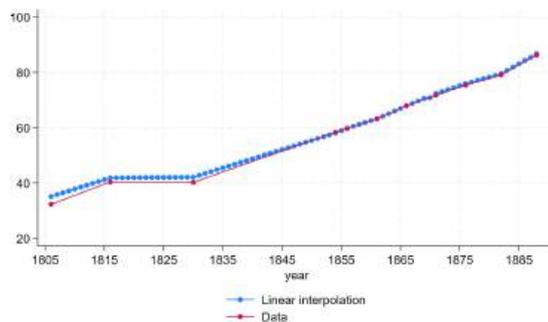
Literacy (%)

Figure A14: Control variables - Data and linear interpolation

Notes: Population is defined as the average number of inhabitants per department and population density is measured as the number of inhabitants per square kilometre. Urban population is in percentage and taxes are in francs per capita. Literacy is defined as the share of spouses that could sign their marriage contract.

C.5 Descriptive Statistics
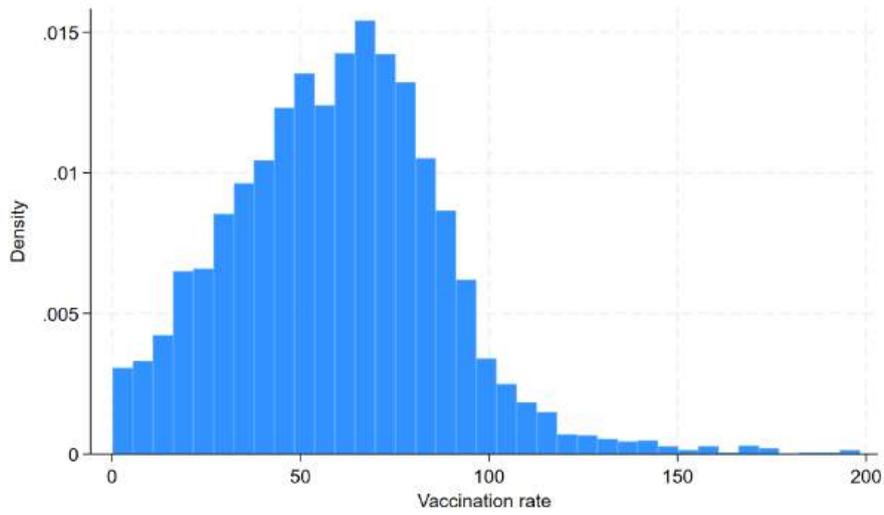
Figure A15: Histogram of the vaccination rate

Note: The 30 cases in which the vaccination rate if greater than 200% are not displayed in the histogram.

1815-1820

1845-1850

1865-1869

1880-1885
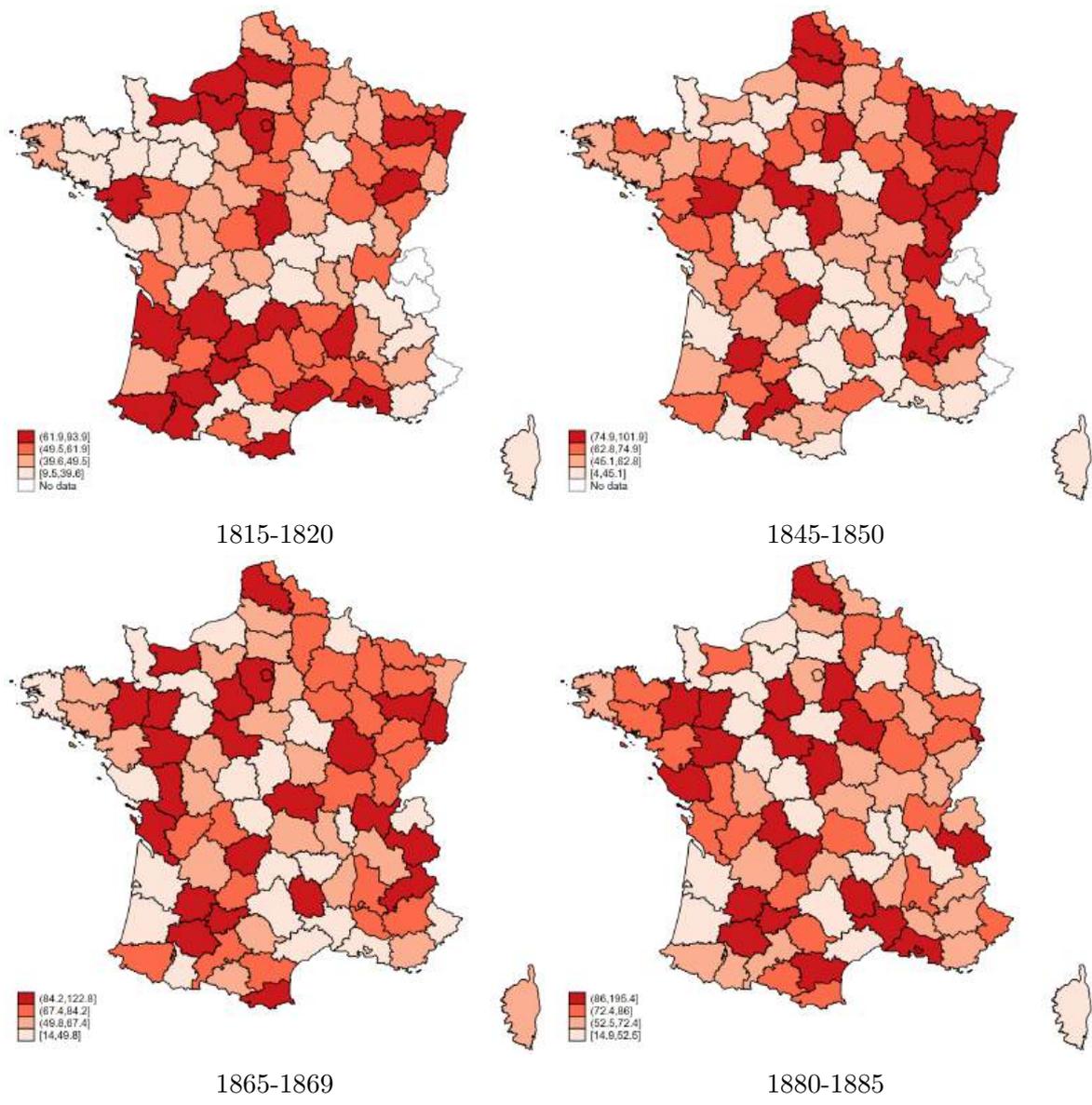
Figure A16: Vaccination rate over the nineteenth century

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births and is computed over five years in each case. The maps depict the quartiles of the vaccination rate.
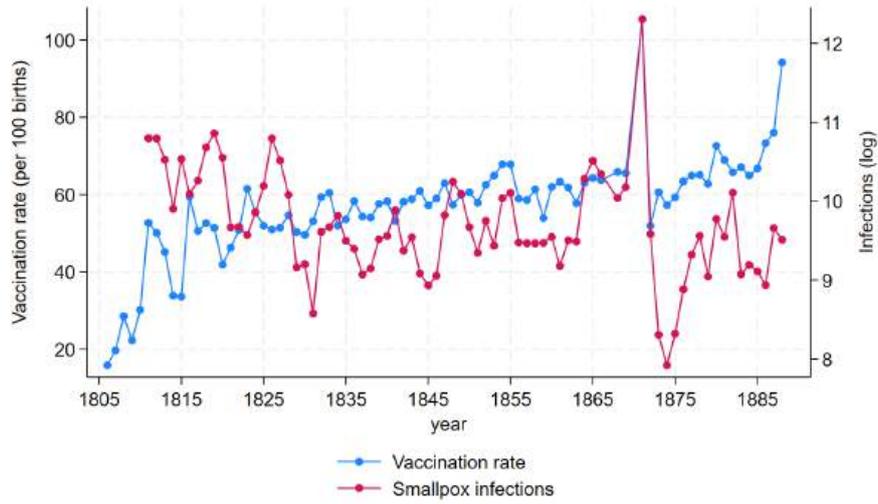
Figure A17: Vaccination rate and total infections from smallpox, 1806-1888

Note: The vaccination rate is defined as the number of vaccinations per 100 births. The log of the total number of infections from smallpox is represented on the right axis.
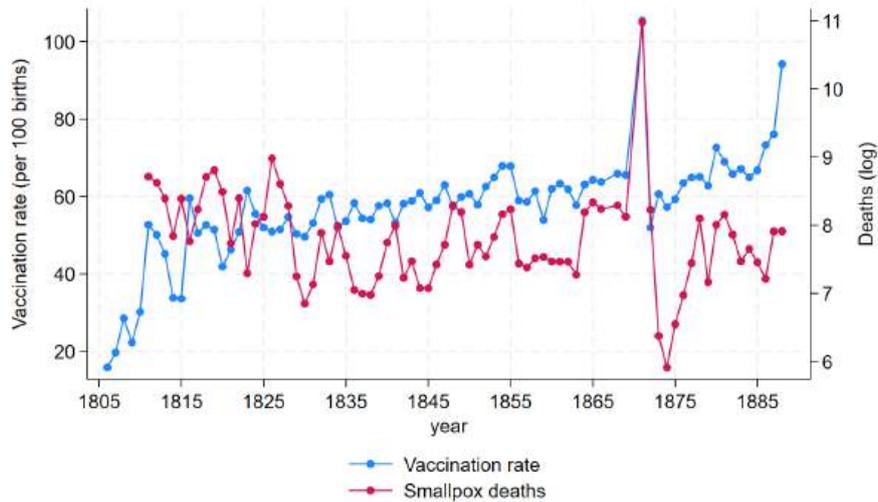
Figure A18: Vaccination rate and total deaths from smallpox, 1806-1888

Note: The vaccination rate is defined as the number of vaccinations per 100 births. The log of the total number of deaths from smallpox is represented on the right axis.

Figure A19: Yearly wheat price within departments in France - 1806-1872

Note: The price of wheat is measured in francs per hectolitre at the department level.

Figure A20: Price of wheat and vaccination rate, 1806-1888

Note: The price of wheat is measured in francs per hectolitre. The vaccination rate is computed as the number of vaccinations per 100 births.

Table A5: Summary statistics

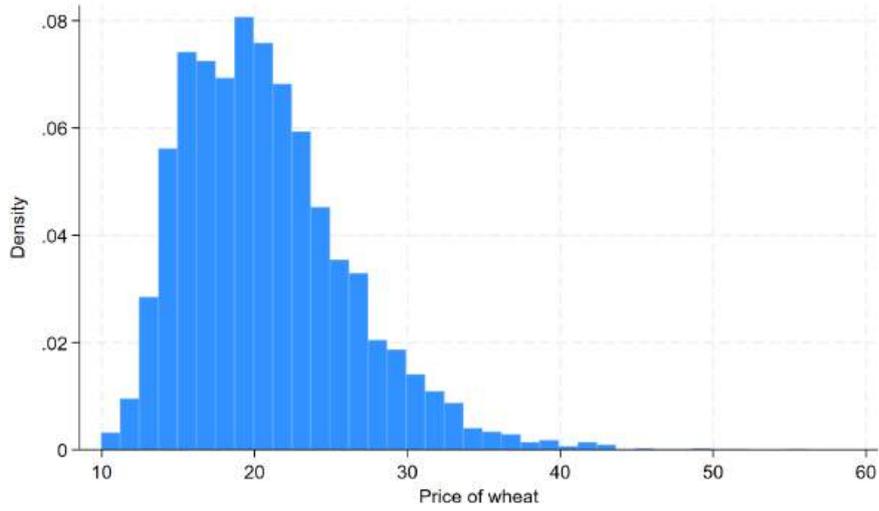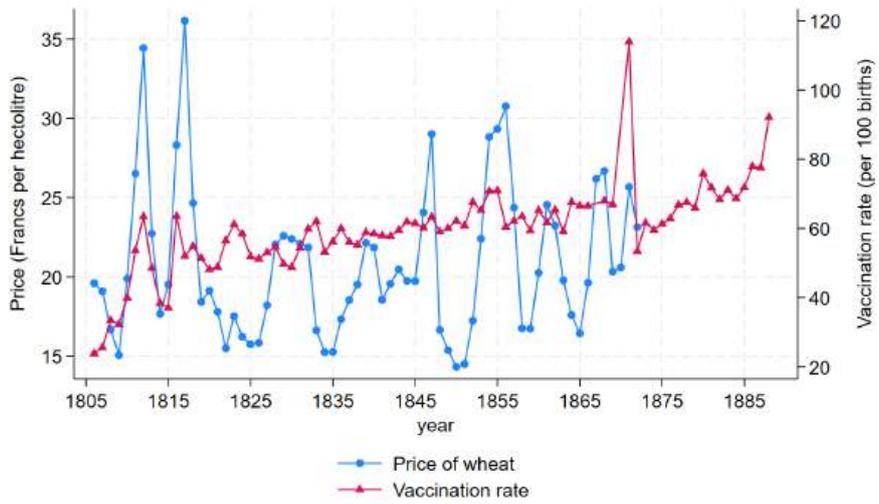| Variable	Mean	Std. Dev.	Min.	Max.	N
Vaccination rate (Vaccinations per 100 births)	60.6	30.8	0.2	386.4	6174
Smallpox vaccinations	6393.6	4954.1	31	89976	6194
Smallpox infections	384.2	819.4	1	15703	4238
Smallpox deaths	66.7	193.6	1	4052	3889
Spending in favour of vaccination	3404.5	6542.7	7.5	83000.8	3495
Price of wheat (yearly)	20.8	5.5	10	56.1	5811
Price of wheat - January	20.8	6	9.3	65.4	5789
Price of wheat - February	20.9	6.1	9.7	68.4	5796
Price of wheat - March	21	6.3	9.6	70.1	5792
Price of wheat - April	21.1	6.8	9.3	67	5802
Price of wheat - May	21.2	6.9	8.8	76.4	5795
Price of wheat - June	21.3	6.7	8.1	81.7	5800
Price of wheat - July	20.9	5.7	9.2	64.5	5798
Price of wheat - August	20.5	5.1	9.2	55.3	5796
Price of wheat - September	20.3	5.2	9.4	56.7	5792
Price of wheat - October	20.5	5.4	9.7	60.5	5789
Price of wheat - November	20.6	5.7	9.6	62.4	5791
Price of wheat - December	20.7	5.8	9.5	64.8	5782
Annual rainfall (from Victor Raulin)	734.3	233.5	174.3	1892.2	3106
Rainfall - January	56.5	42.7	0	380.5	3185
Rainfall - February	46.5	38.9	0	373	3190
Rainfall - March	54	40.5	0	359	3200
Rainfall - April	55.3	40	0	539	3210
Rainfall - May	68.6	44.5	0	393	3209
Rainfall - June	62.9	42.7	0	408	3207
Rainfall - July	53.2	38.3	0	287	3208
Rainfall - August	56.4	40.1	0	412	3201
Rainfall - September	70.5	49.9	0	471	3192
Rainfall - October	81.6	58.6	0	555	3192
Rainfall - November	70.4	50.1	0	462	3191
Rainfall - December	59.6	47.9	0	496	3185
Annual rainfall (reconstructed data)	790.7	164.6	368.3	1543.1	7221
Spring rainfall	176.4	58.7	46.8	493.5	7221
Summer rainfall	180.3	59.3	13.8	483.2	7221
Autumn rainfall	244.4	69.2	77.3	593.6	7221
Winter rainfall	189.5	57.3	27.3	528.3	7221
Phylloxera - full contamination	0.1	0.3	0	1	3078

Wine production - log	12.1	1.8	3.4	16.5	2694
Population	398297.2	217146.5	53826.3	3025793	7222
Population density	101.1	379.8	18.5	6307.6	7222
Urban population	21.8	14.7	4.4	99.3	7220
Taxes per capita	6.6	5.4	0.6	120.1	7204
Literacy	56.5	24.9	2	100	7220

Notes: All variables are defined at the department level and are measured yearly.

D Empirical Strategies

D.1 Wheat Prices and Negative Income Shocks

A point worth mentioning is why we chose to focus on wheat prices instead of variations in taxes to measure income shocks. The first reason is because consistent tax data are harder to obtain for the entire century. But more importantly, these data are expected to constitute a less accurate reflection of annual changes in income in nineteenth-century France. Indeed, the amount of direct taxes was decided one year in advance by the government. This amount is therefore less likely to have precisely followed the ups and downs of the economy. If a recession took place in year t for example, the amount of taxes collected would only be amended in year $t+1$ in order to account for the negative shock on income.

Moreover, taxes may also vary for other reasons than changes in the level of economic dynamism, such as political decisions or changes in state capacity. Using indirect taxes on consumption might improve the reliability of this measure, as well as relying on an exogenous instrument such as rainfall to get rid of the other factors that may affect the tax level. However, this strategy is often related to an issue of weak instrument, which creates additional problems regarding the reliability of the estimations (Franck, 2016). We therefore chose to stick to prices as their appear to be a better predictor of income shocks that variations in the tax level in the case of nineteenth-century France.
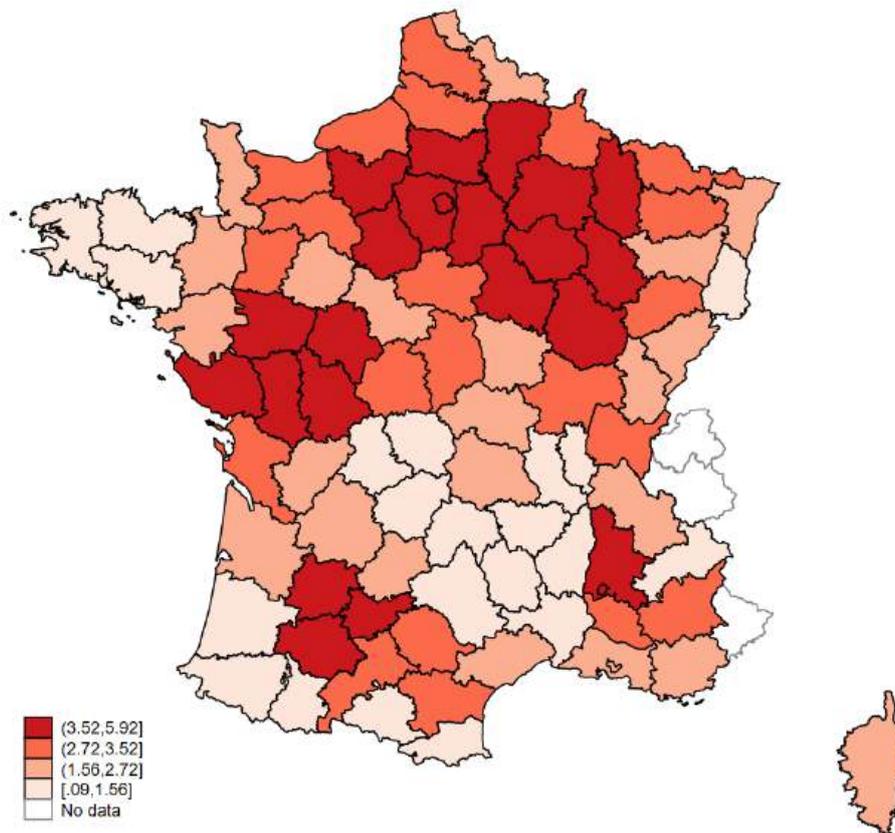
Figure A21: Wheat production in France in 1852

Note: Wheat production is measured in hectolitre per inhabitant.
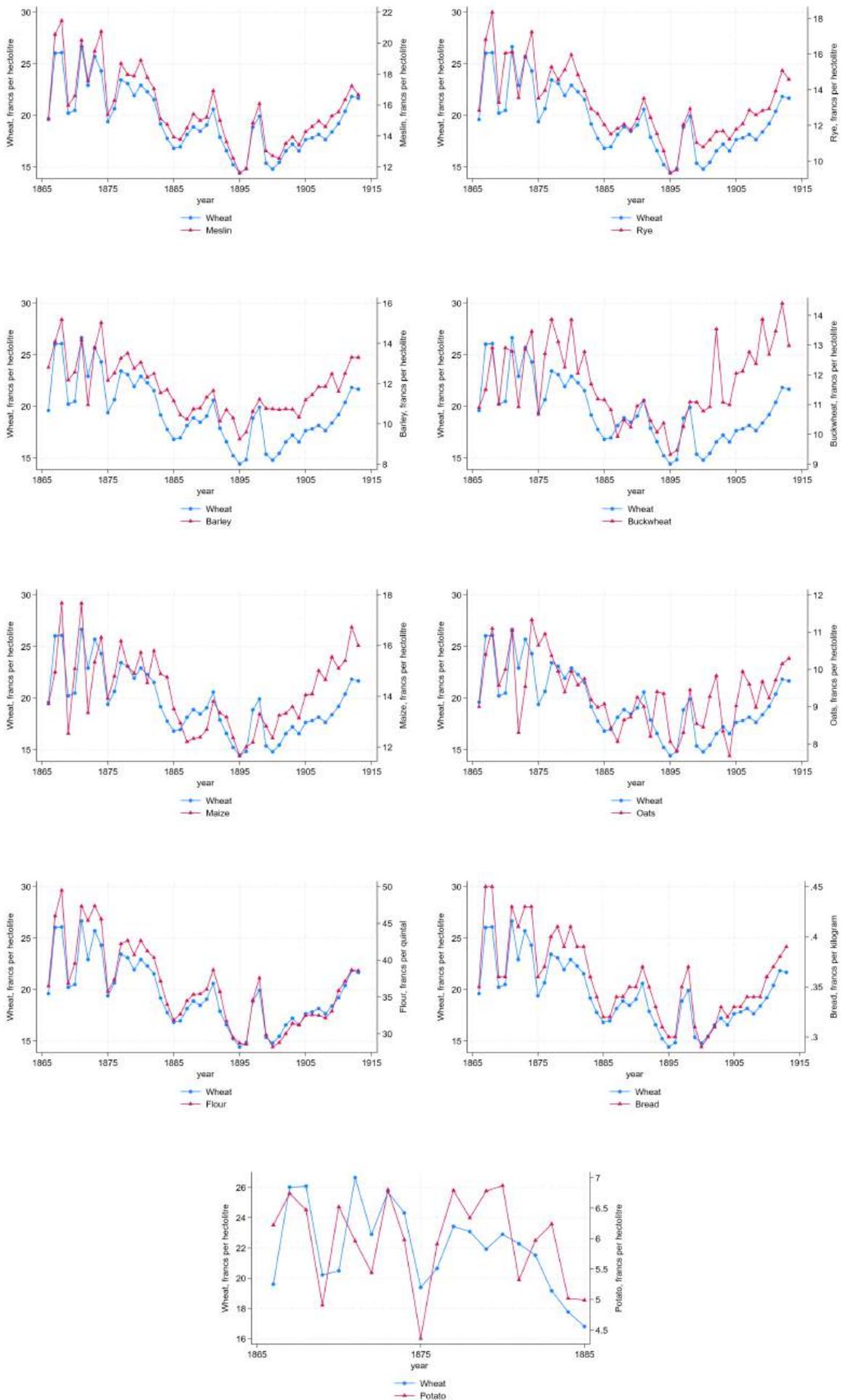
Figure A22: Price of grains, flour, bread and potato, 1866-1913

Notes: Prices are available for the 1866-1913 period. The price of potato is only available from 1866 to 1885. The price of grains and potato is measured in francs per hectolitre, the price of flour in francs per quintal and the price of bread in francs per kilogram.

Table A6: Correlation table - Price of grains, flour, bread and potato

Variables	Wheat	Meslin	Rye	Barley	Buckwheat	Maize	Oats	Flour	Bread	Potato
Wheat	1.0000									
Meslin	0.9836	1.0000								
	(0.0000)									
Nb. Obs.	48									
Rye	0.9384	0.9644	1.0000							
	(0.0000)	(0.0000)								
Nb. Obs.	48	48								
Barley	0.8792	0.8982	0.9356	1.0000						
	(0.0000)	(0.0000)	(0.0000)							
Nb. Obs.	48	48	48							
Buckwheat	0.5764	0.6054	0.6845	0.7393	1.0000					
	(0.0000)	(0.0000)	(0.0000)	(0.0000)						
Nb. Obs.	48	48	48	48						
Maize	0.7550	0.7745	0.8366	0.8768	0.8505	1.0000				
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)					
Nb. Obs.	48	48	48	48	48					
Oats	0.6791	0.7034	0.7747	0.8432	0.7011	0.7739	1.0000			
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)				
Nb. Obs.	48	48	48	48	48	48				
Flour	0.9822	0.9722	0.9204	0.8270	0.4983	0.7019	0.6102	1.0000		
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0003)	(0.0000)	(0.0000)			
Nb. Obs.	48	48	48	48	48	48	48			
Bread	0.9851	0.9789	0.9284	0.8576	0.5370	0.7375	0.6542	0.9822	1.0000	
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0001)	(0.0000)	(0.0000)	(0.0000)		
Nb. Obs.	48	48	48	48	48	48	48	48		
Potato	0.5741	0.5791	0.6061	0.5454	0.6830	0.5438	0.1866	0.5721	0.5608	1.0000
	(0.0081)	(0.0075)	(0.0046)	(0.0129)	(0.0009)	(0.0132)	(0.4307)	(0.0084)	(0.0101)	
Nb. Obs.	20	20	20	20	20	20	20	20	20	

Notes: Prices are available for the 1866-1913 period. The price of potato is only available from 1866 to 1885. The price of grains and potato is measured in francs per hectolitre, the price of flour in francs per quintal and the price of bread in francs per kilogram.

On the following graph, variations in the price of wheat are strongly correlated with variations in the number of thefts and property crimes. There is one noticeable exception with the sudden increase in property crimes in 1851. This increase is most likely linked to political turmoil which characterised the year 1851 and which culminated with the coup of Napoléon Bonaparte in December 1851.
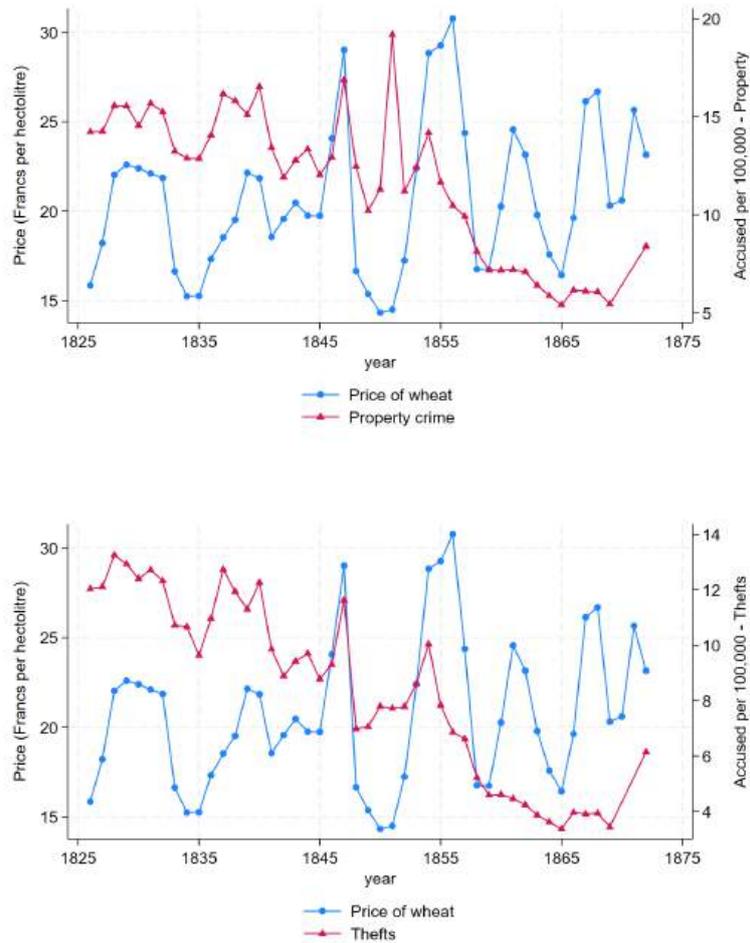

Figure A23: Price of wheat, property crimes and thefts, 1826-1872

Notes: The price of wheat is measured in francs per hectolitre. The number of people accused of theft or property crimes is measure per 100,000 inhabitants.

Table A7: Price of wheat, violent and property crimes, thefts

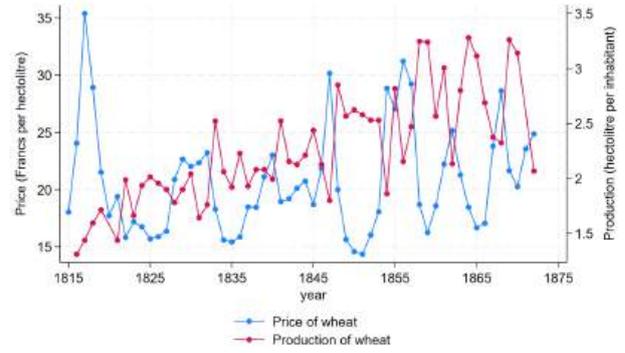|	Violent crimes		Property crimes		Thefts	
	(1)	(2)	(3)	(4)	(5)	(6)
Price of wheat	0.056	0.066	0.170**	0.161**	0.099*	0.093
	(0.059)	(0.059)	(0.064)	(0.063)	(0.058)	(0.056)
Population	–	0.029	–	-0.039	–	-0.002
		(0.080)		(0.090)		(0.067)
Population density	–	-0.002	–	-0.019***	–	-0.019***
		(0.004)		(0.004)		(0.003)
Urban population	–	-0.019	–	-0.065	–	-0.065
		(0.154)		(0.123)		(0.102)
Taxes p.c	–	-0.019	–	0.054	–	0.073*
		(0.025)		(0.038)		(0.038)
Literacy	–	0.122***	–	0.036	–	0.031
		(0.035)		(0.043)		(0.033)
Department fixed effects	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X
Observations	3807	3807	3807	3807	3807	3807
R^2	0.618	0.632	0.669	0.733	0.654	0.736

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Data on the price of wheat and on crimes are both available for the 1826-1872 period. Violent crimes, property crimes and thefts correspond to the ratio of the number of people accused of violent, property crimes or theft to the department population, per 100,000 inhabitants. The price of wheat is computed in francs per hectolitre. Population is in ten thousands of inhabitants and population density is measured as the number of inhabitants per square kilometre. Urban population is in percentage and taxes are in francs per capita. Literacy is defined as the share of spouses that could sign their marriage contract. Standard errors are clustered at the department level.
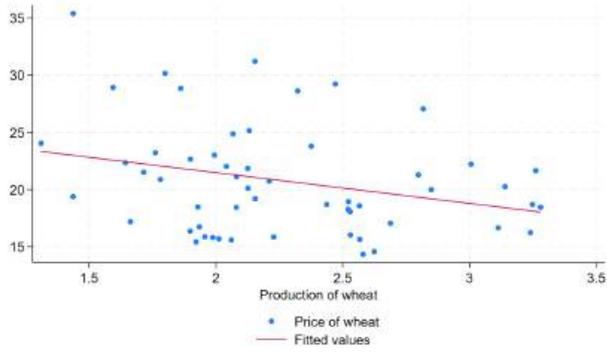
Department level - 1852   National level

Figure A24: Price of wheat and production of wheat

Notes: The price of wheat is computed in francs per hectolitre and the production of wheat in hectolitres per inhabitant. The price of wheat for a given year t is computed as the average price between July_t and July_{t+1}. The production in year t is the one stemming from the harvest taking place in July_t.

D.2 The Rainfall Instrument

Wheat was typically sown in autumn and harvested in July in nineteenth-century France. Each harvest determined the price until a new one took place. The price of wheat determined by the quality of the harvest in July$_t$ therefore remained quite stable until July$_{t+1}$. The price of wheat during calendar year t was therefore formed by two harvests, the one taking place in July$_t$ and which influenced the price until December$_t$, and the one taking place in July$_{t-1}$ and which influenced the price until July$_t$.

This fact led some historians to work with wheat prices considering "harvest-years" (from July to July) and not calendar years. We will however refrain from doing so in our main specifications as all our other variables, including our main dependent variable on vaccination, are defined over calendar years.

As our yearly measure of wheat prices is determined by two harvests, we use all the monthly rainfall that can influence these harvests to build our instrument. In Table A8, we therefore explore the potential influence of monthly rainfall from July$_{t-2}$ to December$_{t-1}$ on the price of wheat at year t. We don't include rainfall at year t to avoid having to deal with a potential direct effect of rainfall on vaccination against smallpox. One could still argue that rainfall in Autumn$_{t-1}$ might have an effect on roads at the beginning of year t and therefore also affect the vaccination rate in t. This effect might be true, but would most likely remain marginal. Moreover, as shown in Table A3 and according to the information provided in the vaccination reports, only 11% of the total number of vaccinations was taking place before April. We can therefore be sure that any effect of rainfall spreading to the next year will not significantly affect the number of vaccinations during this year[44].

It appears from these estimations that it is mainly excessive rainfall during the months that preceded the sowing of wheat in autumn and during the sprouting of the cereal in spring that contributed to increase the price of wheat. We therefore define a new rainfall variable, named $Rainfall-wheatcycle_{t-1}$, which is computed as the total rainfall over these months, which are more precisely: July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$. This variable will constitute our rainfall instrument when working with the collected rainfall data from the publications of Victor Raulin as it is the best predictor of variations in wheat prices. Figure A25 summarises the time frame considered.

When using the reconstructed rainfall information, we can't replicate the same strategy as we only have seasonal reconstructed data and not monthly ones. In Table A9, we estimate the impact of these seasonal rainfall on the price of wheat and find a similar pattern than with monthly rainfall. However, we also find now that rainfall during the autumn season negatively affects the price of wheat. This is coherent with the fact that the absence of water during the

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[44]Not including the months after December$_{t-1}$ also entails that we only instrument part of the variation in prices due to the harvest in July$_t$. However, as more than 70% of the vaccinations were taking place between January and August (Table A3), we instrument the price variations that are the most likely to impact vaccination.

sowing months has a negative effect on the grains which have just been sown.

When working with the reconstructed data, we therefore don't sum the total amount of rainfall to avoid mixing variables with an opposite effect on the price, which would decrease the strength of our instrument. We include all seasons from $Summer_{t-2}$ ($June_{t-2}$) to $Autumn_{t-1}$ ($November_{t-1}$) as instruments in this case, as in column (7) of Table A9.

Following what is done in Franck (2016) or Waldinger (2024), we also considered rainfall deviations from the average value over the century, and the absolute or square value of this deviation. However, the instrument remained weak compared to the simple measure of rainfall in millimetre, and we therefore stick to it. We also tried to use reconstructed temperature data instead of rainfall to instrument wheat prices in Table A10. However, any instrument based on temperature also remained weak compared to a simple measure of rainfall during the sprouting and before the sowing months.

Our first stage is therefore represented by column (4) of Table A8 for the collected rainfall, and by column (7) of Table A9 for the reconstructed instrument.

Table A8: Price of wheat and rainfall - OLS estimations

| | Price of wheat$_t$ | | | | | |
	(1)	(2)	(3)	(4)	(5)	(6)
Annual rainfall$_t$	0.0005*	–	0.0003	–	0.0001	–
	(0.0003)		(0.0003)		(0.0003)	
Annual rainfall$_{t-1}$	–	0.0010***	0.0011***	–	-0.0007*	–
		(0.0003)	(0.0003)		(0.0004)	
Rainfall - wheat cycle$_{t-1}$	–	–	–	0.0022***	0.0031***	–
				(0.0004)	(0.0005)	
July$_{t-2}$	–	–	–	–	–	0.0064***
						(0.0014)
August$_{t-2}$	–	–	–	–	–	0.0029***
						(0.0010)
September$_{t-2}$	–	–	–	–	–	0.0021**
						(0.0009)
October$_{t-2}$	–	–	–	–	–	0.0005
						(0.0005)
November$_{t-2}$	–	–	–	–	–	0.0000
						(0.0010)
December$_{t-2}$	–	–	–	–	–	-0.0002
						(0.0008)
January$_{t-1}$	–	–	–	–	–	0.0028***
						(0.0009)
February$_{t-1}$	–	–	–	–	–	-0.0020*
						(0.0010)
March$_{t-1}$	–	–	–	–	–	-0.0009
						(0.0014)
April$_{t-1}$	–	–	–	–	–	0.0019
						(0.0014)
May$_{t-1}$	–	–	–	–	–	0.0030**
						(0.0014)
June$_{t-1}$	–	–	–	–	–	-0.0002
						(0.0013)
July$_{t-1}$	–	–	–	–	–	0.0008
						(0.0013)
August$_{t-1}$	–	–	–	–	–	0.0028***
						(0.0010)
September$_{t-1}$	–	–	–	–	–	0.0040***
						(0.0007)
October$_{t-1}$	–	–	–	–	–	0.0005
						(0.0009)
November$_{t-1}$	–	–	–	–	–	-0.0018
						(0.0011)
December$_{t-1}$	–	–	–	–	–	-0.0016
						(0.0012)
Department fixed effects	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X
Observations	2508	2463	2330	2361	2213	2328
R^2	0.900	0.901	0.904	0.905	0.908	0.906

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes The price of wheat is computed in francs per hectolitre. Annual rainfall is computed from January to December, while rainfall - wheat cycle$_{t-1}$ is computed as the total rainfall over the months July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$. All rainfall variables are expressed in millimetre or litre per square metre.
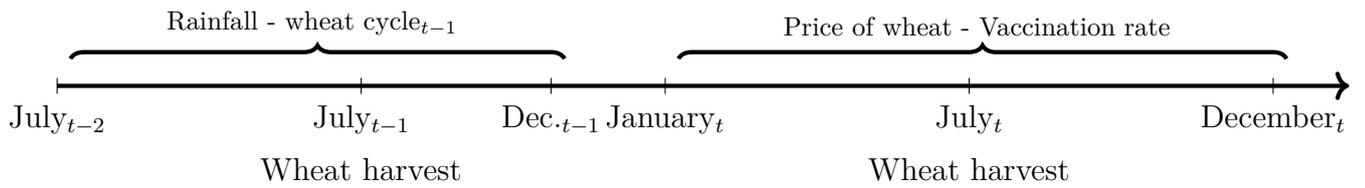
Figure A25: Time frame of the rainfall, wheat and vaccination variables

Rainfall - wheat cycle$_{t-1}$ is computed as the total rainfall over the months July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$.

Table A9: Price of wheat and reconstructed rainfall - OLS estimations

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Price of wheat$_t$						
Rainfall - summer$_{t-2}$	0.0121***	–	–	–	–	–	0.0096***
	(0.0015)						(0.0013)
Rainfall - autumn$_{t-2}$	–	-0.0048***	–	–	–	–	-0.0045***
		(0.0009)					(0.0009)
Rainfall - winter$_{t-1}$	–	–	0.0013	–	–	–	0.0048***
			(0.0010)				(0.0010)
Rainfall - spring$_{t-1}$	–	–	–	-0.0008	–	–	0.0005
				(0.0014)			(0.0014)
Rainfall - summer$_{t-1}$	–	–	–	–	0.0173***	–	0.0150***
					(0.0016)		(0.0014)
Rainfall - autumn$_{t-1}$	–	–	–	–	–	-0.0041***	-0.0032***
						(0.0009)	(0.0010)
Department fixed effects	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X
Observations	5446	5446	5530	5530	5530	5530	5445
R^2	0.879	0.878	0.876	0.876	0.879	0.876	0.883

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes The price of wheat is computed in francs per hectolitre. Spring rainfall is computed from March to May, summer rainfall from June to July, autumn rainfall from September to November and winter rainfall with the January, February and December months. All rainfall variables are expressed in millimetre or litre per square metre.

In the following Table A10, the reconstructed temperature data are coming from Schmatz et al. (2015), from which we can compute the average temperature each month at the department level. We find that a higher temperature during the autumn and winter months contributes to decrease the price, while a higher temperature during the summer increases it. This can be explained by the fact that freezing air temperature in winter is detrimental to the growth of cereals. Moreover, higher temperature in summer is likely to decrease the quality of the land on which wheat is sown in autumn, which contributes to increase the price.

Table A10: Price of wheat and temperature - OLS estimations

	Price of wheat$_t$					
	(1)	(2)	(3)	(4)	(5)	(6)
Annual temperature$_t$	0.058	–	–	–	–	–
	(0.2849)					
Annual temperature$_{t-1}$	–	0.047	–	–	–	–
		(0.2312)				
Temperature - wheat cycle$_{t-1}$ (negative)	–	–	-0.036	–	-0.102**	–
			(0.0494)		(0.0484)	
Temperature - wheat cycle$_{t-1}$ (positive)	–	–	–	0.153**	0.202***	–
				(0.0588)	(0.0580)	
July$_{t-2}$	–	–	–	–	–	0.160**
						(0.0696)
August$_{t-2}$	–	–	–	–	–	-0.350***
						(0.0485)
September$_{t-2}$	–	–	–	–	–	0.447***
						(0.1589)
October$_{t-2}$	–	–	–	–	–	-0.243*
						(0.1416)
November$_{t-2}$	–	–	–	–	–	-0.015
						(0.2945)
December$_{t-2}$	–	–	–	–	–	-0.326***
						(0.0638)
January$_{t-1}$	–	–	–	–	–	0.721***
						(0.0846)
February$_{t-1}$	–	–	–	–	–	-0.462***
						(0.0436)
March$_{t-1}$	–	–	–	–	–	0.109
						(0.1019)
April$_{t-1}$	–	–	–	–	–	-0.042
						(0.1772)
May$_{t-1}$	–	–	–	–	–	0.018
						(0.2080)
June$_{t-1}$	–	–	–	–	–	0.207
						(0.1541)
July$_{t-1}$	–	–	–	–	–	0.106**
						(0.0532)
August$_{t-1}$	–	–	–	–	–	-0.013
						(0.0465)
September$_{t-1}$	–	–	–	–	–	0.560***
						(0.1816)
October$_{t-1}$	–	–	–	–	–	-0.683***
						(0.1328)
November$_{t-1}$	–	–	–	–	–	0.261
						(0.2102)
December$_{t-1}$	–	–	–	–	–	-0.212***
						(0.0510)
Department fixed effects	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X
Observations	5809	5722	5722	5722	5722	5634
R^2	0.869	0.873	0.873	0.873	0.873	0.881

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes The price of wheat is computed in francs per hectolitre. Annual temperature are computed from January to December. Temperature - wheat cycle$_{t-1}$ (negative) is computed as the average temperature in August$_{t-2}$, October$_{t-2}$, December$_{t-2}$, February$_{t-1}$, October$_{t-1}$ and December$_{t-1}$, that is the months whose temperature has a negative effect on wheat prices. Temperature - wheat cycle$_{t-1}$ (positive) is computed as the average temperature in July$_{t-2}$, September$_{t-2}$, January$_{t-1}$, July$_{t-1}$ and September$_{t-1}$, that is the months whose temperature has a positive effect on wheat prices. Temperature is measured in Celsius degree.

In Table A11, we investigate the potential link between rainfall and smallpox diffusion. The prevalence of the disease could indeed be associated with the level precipitation. For example, if high precipitation decreases the time members from the same locality spend together, this would most likely reduce the spread of smallpox. This would also contribute to a lower number of vaccinations, as people seek for less protection when the number of smallpox cases is low. We find that annual rainfall, either considering the collected or reconstructed measures at time t or $t-1$, is not significantly linked to smallpox infections or deaths at time t. We can therefore be sure that the diffusion of smallpox was not influenced by the level of precipitation.

Table A11: Smallpox diffusion and climate conditions - OLS estimations

|	Infections$_t$				Deaths$_t$			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Annual rainfall - collected$_t$	-0.002	–	–	–	-0.000	–	–	–
	(0.0033)				(0.0006)			
Annual rainfall - collected$_{t-1}$	–	0.001	–	–	–	0.000	–	–
		(0.0029)				(0.0007)			
Annual rainfall - reconstructed$_t$	–	–	-0.008	–	–	–	-0.001	–
			(0.0051)				(0.0011)	
Annual rainfall - reconstructed$_{t-1}$	–	–	–	0.001	–	–	–	-0.001
				(0.0055)				(0.0012)
Department fixed effects	X	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X	X
Observations	1921	1906	4044	4044	1819	1802	3718	3718
R^2	0.438	0.477	0.363	0.362	0.502	0.547	0.453	0.453

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes Infections and deaths from smallpox are measured per 10,000 inhabitants. Collected and reconstructed rainfall is computed as the total rainfall. All rainfall variables are expressed in millimetre or litre per square metre.

In Figure A26, we investigate the potential effect of our rainfall instrument computed over the wheat cycle and of annual rainfall on infant and child mortality. As our second instrument is composed of several variables, we use the first one to gather the outcomes in a single figure. We do the same in Figure A27 and Figure A28. Infant mortality is defined as the number of children from 0 to 1 year of age who die in year t, per 1,000 births. Child mortality is defined as the number of children from 0 to 5 years of age who die in year t, per 1,000 births. Both variables are computed over the periods 1855-1868 and 1875-1884.

We consider the potential effect of rainfall from $t - 10$ to t. We do so to be sure to capture any impact of rainfall on mortality. Indeed, if a higher level of precipitation is for example associated with a higher mortality risk from infectious diseases (other than smallpox), children may not die from these diseases during the year of infection. Doing so, we don't find any significant and consistent association between rainfall and infant or child mortality.
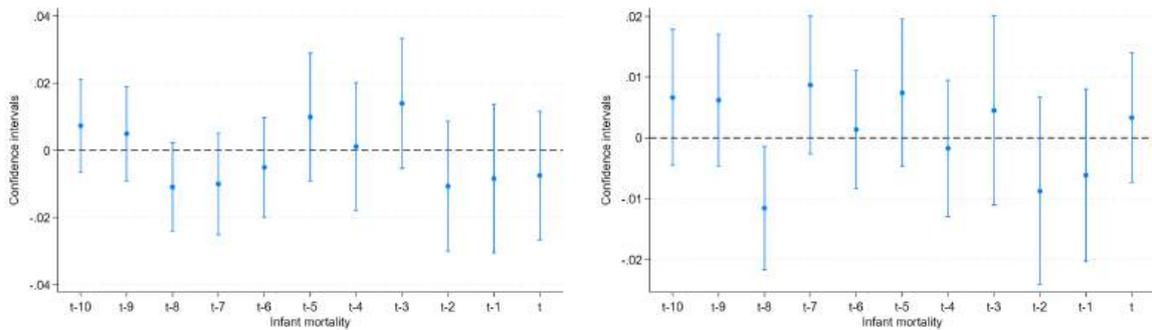
Effect of the rainfall instrument on infant mortality at t

Effect of annual rainfall on infant mortality at t
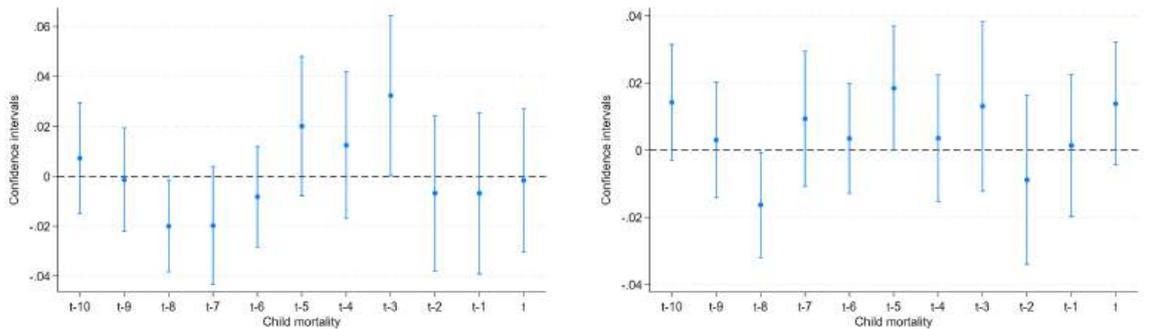
Effect of the rainfall instrument on child mortality at t

Effect of annual rainfall on child mortality at t

Figure A26: Effect of the rainfall instrument and of annual rainfall on infant and child mortality at time t

Notes: The figures depict OLS estimation coefficients of the effect of the rainfall instrument and of annual rainfall, both based on collected rainfall , from $t - 1$ to $t + 10$ on infant and child mortality in t. The rainfall instrument corresponds to the volume of rainfall over the wheat cycle and is computed as the total rainfall over the months July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$. Infant mortality is defined as the number of children from 0 to 1 year of age who die in year t, per 1,000 births. Child mortality is defined as the number of children from 0 to 5 years of age who die in year t, per 1,000 births. 95% confidence intervals are reported.

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In Figure A27, we look at the potential link between rainfall and the number of births. Such a link could exist if, for example, families observing heavy precipitation would anticipate bad upcoming harvests and adjust their fertility accordingly. We consider the potential effect of rainfall from $t-10$ to t, as the decision to adjust the fertility level may take time or may only be taken after several bad harvest. We do not find any effect of rainfall on the number of births.
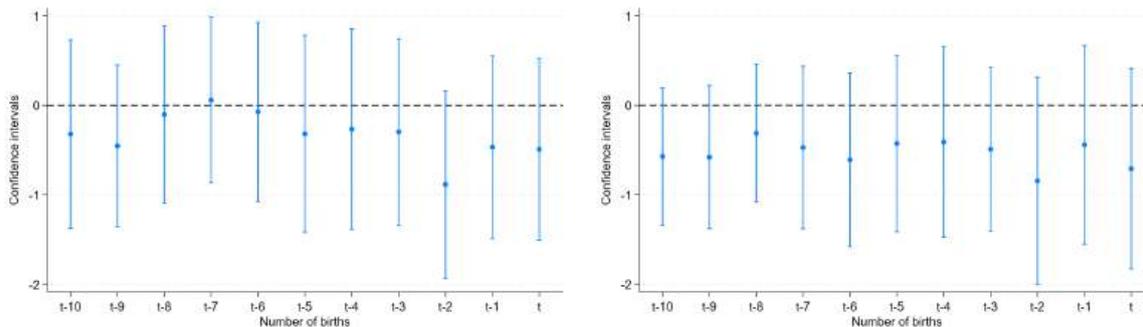
Effect of the rainfall instrument on the number of births at t

Effect of annual rainfall on the number of births at t

Figure A27: Effect of the rainfall instrument and of annual rainfall on the number of births at time t

Notes: The figures depict OLS estimation coefficients of the effect of the rainfall instrument and of annual rainfall, both based on collected rainfall , from $t-1$ to $t+10$ on the number of births in t. The rainfall instrument corresponds to the volume of rainfall over the wheat cycle and is computed as the total rainfall over the months July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$. 95% confidence intervals are reported.

The falsification tests presented in Figure A28 investigates the impact of future rainfall on the price of wheat. They rely on our rainfall instrument computed over the wheat cycle and on annual rainfall. As the variable $Rainfall-wheatcycle_{t-1}$ is defined over two wheat cycles from $July_{t-2}$, we expect $Rainfall-wheatcycle_{t-1}$, $Rainfall-wheatcycle_t$ and $Rainfall-wheatcycle_{t+1}$ to have an effect on the price at time t. Indeed, this last rainfall measure starts in $July_t$ and end in $December_{t+1}$. It could therefore still influence the price, as excessive rainfall from $July_t$ to $December_t$ might for example increase transportation costs and ultimately the price of wheat. This effect is however expected to be weaker than for $Rainfall-wheatcycle_{t-1}$ and $Rainfall-wheatcycle_t$. Finally, our instrument should not be related to the price level afterwards.

Reassuringly, this is exactly what we find in the estimations. A standard deviation in rainfall contributes to increase the price by 0.4 francs per hectolitre of wheat, and this effect is logically divided by two when only considering rainfall from $July_t$. When our instrument starts in year $t + 1$ and for later years, there is no significant impact of rainfall on the price.

We also find no effect of variations in annual rainfall from $t+1$ to $t+10$ on the price of wheat at time t.
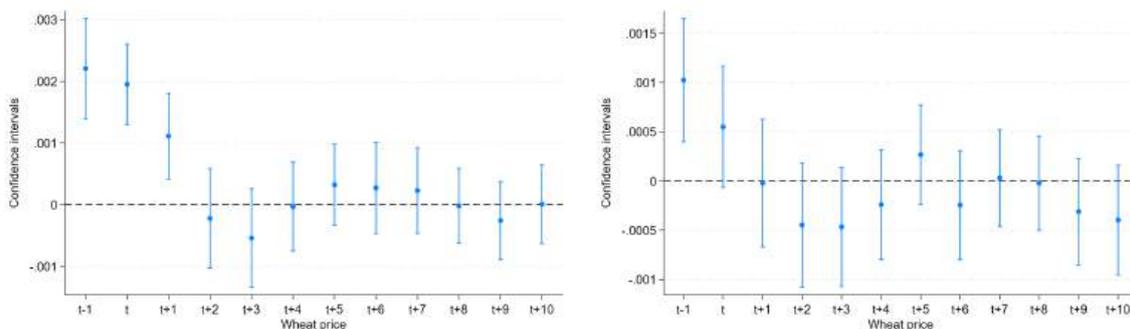
Effect of the rainfall instrument on the price of wheat at t

Effect of annual rainfall on the price of wheat at t

Figure A28: Falsification test: impact of future rainfall on the price of wheat at time t

Notes: The figures depict OLS estimation coefficients of the effect of the rainfall instrument and of annual rainfall, both based on collected rainfall , from $t-1$ to $t+10$ on the price of wheat at time t. The rainfall instrument corresponds to the volume of rainfall over the wheat cycle and is computed as the total rainfall over the months $July_{t-2}$, $August_{t-2}$, $September_{t-2}$, $March_{t-1}$, $April_{t-1}$, May_{t-1}, $June_{t-1}$, $July_{t-1}$, $August_{t-1}$, and $September_{t-1}$. 95% confidence intervals are reported.

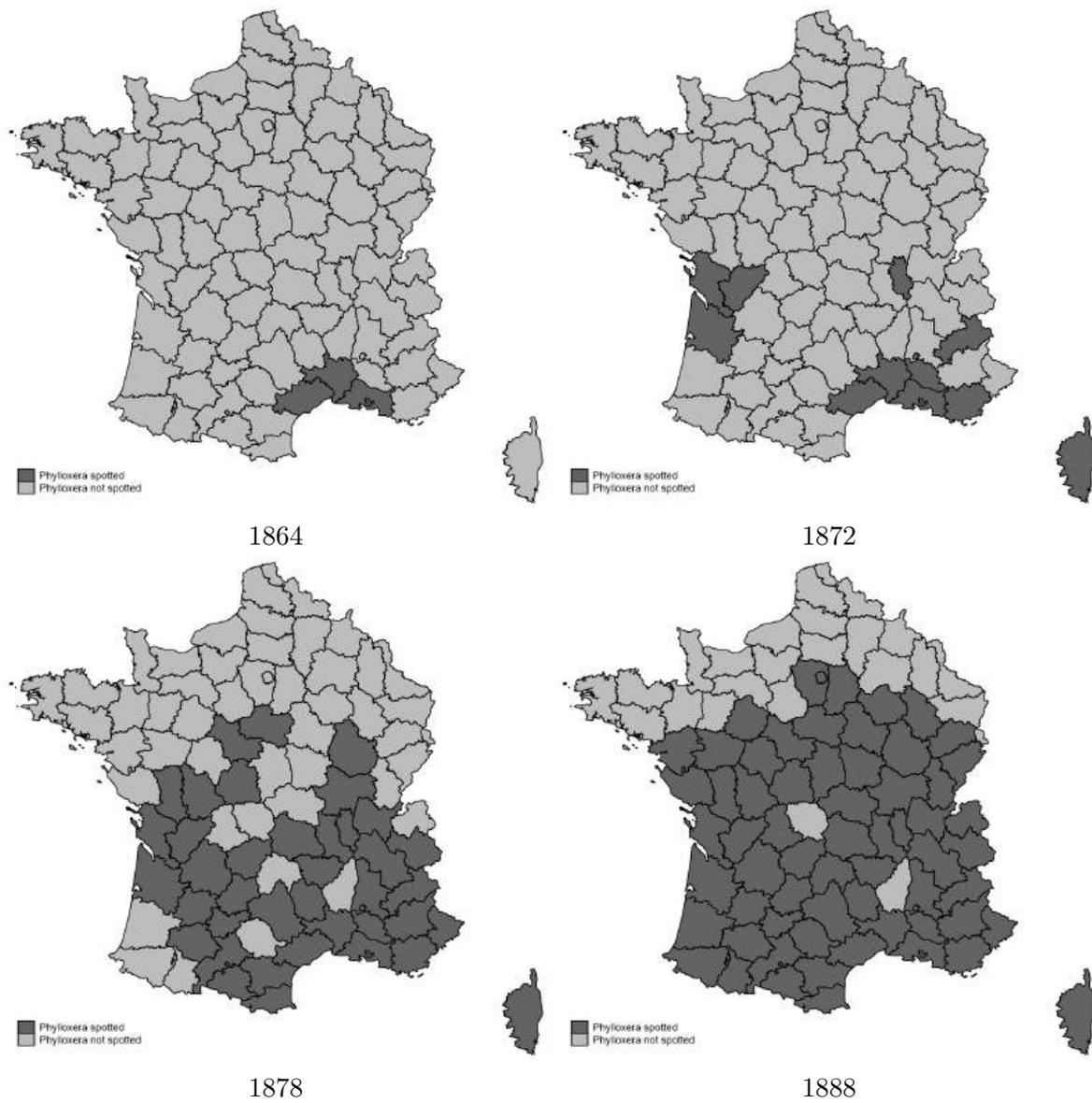## D.3   The Phylloxera Crisis

1864

1872

1878

1888

Figure A29: The diffusion of phylloxera in France

Notes: The maps depict the diffusion of phylloxera over French departments. If the phylloxera was spotted in at least one municipality, then it is considered to be present in the department at stake.
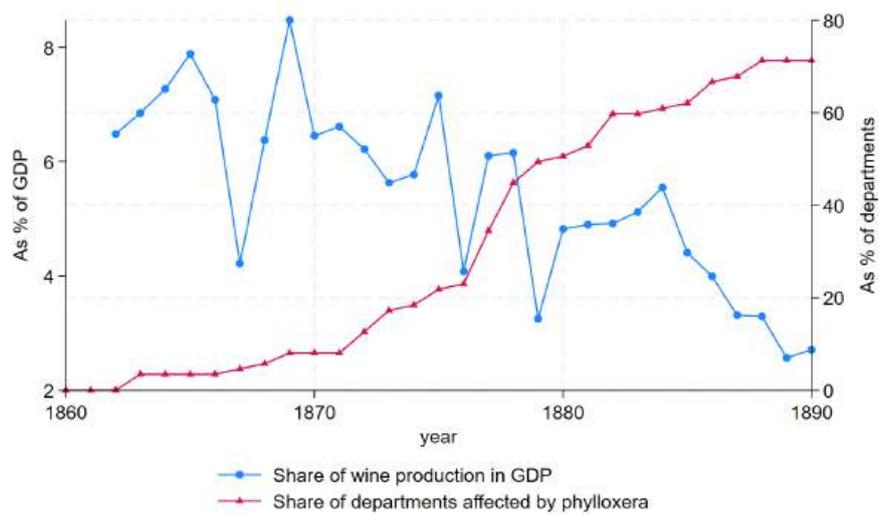
Figure A30: Phylloxera and share of wine production in GDP, 1862–90

Source: (Bignon et al., 2017).

Note: A department is considered to be affected by phylloxera if the insect has been spotted in at least one municipality.

E Empirical Results

E.1 Wheat Prices and Vaccination Against Smallpox
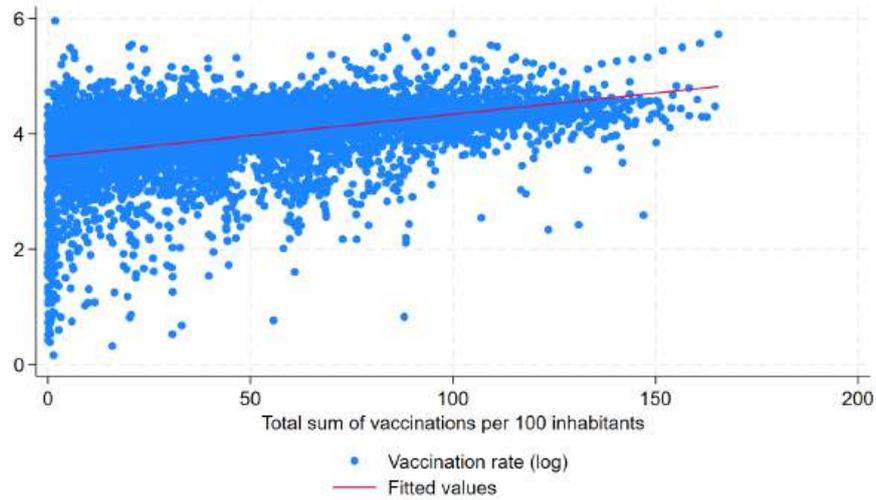
Figure A31: Total sum of vaccinations until $t - 1$ and vaccination rate at time t

Note: The total sum of vaccinations is measured per 100 inhabitants and corresponds to the sum of vaccinations administered until $t - 1$.
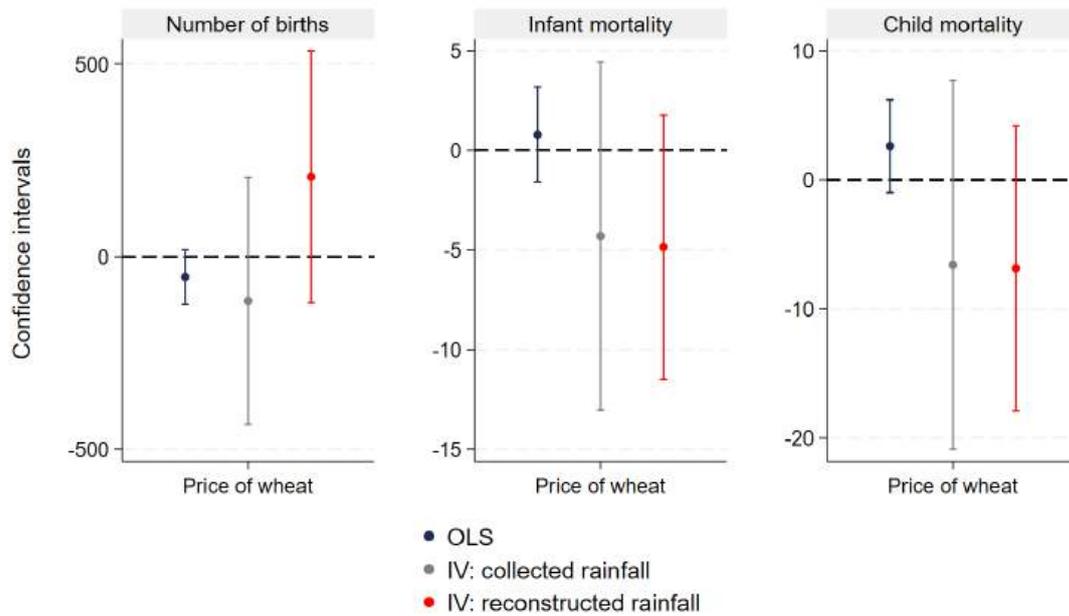
Figure A32: Effect of wheat price on the number of births, infant and child mortality. OLS and IV estimations

Note: The figure depicts OLS and IV estimation coefficients of the effect of wheat price on the number of births, infant and child mortality. The price of wheat is computed in francs per hectolitre. Collected rainfall is computed as the total rainfall over the months July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$. Reconstructed rainfall is measured as the total rainfall over the seasons Summer$_{t-2}$, Autumn$_{t-2}$, Spring$_{t-1}$, Summer$_{t-1}$ and Autumn$_{t-1}$. Infant mortality is defined as the number of children from 0 to 1 year of age who die in year t, per 1,000 births. Child mortality is defined as the number of children from 0 to 5 years of age who die in year t, per 1,000 births. 95% confidence intervals are reported.

E.1.1   Heterogeneity Analysis

In Table A12, we conduct an heterogeneity analysis to test if the impact of negative income shocks on vaccination against smallpox differed depending on various characteristics of the departments. To do so, we rely on OLS estimations and interact the price of wheat with binary variables equal to 1 when the second term of the interaction is above the median level across departments. We consider the average urban population over the century, the production of wheat, the consumption of wheat, cereals, and the the share of landowners from the Agricultural Survey of 1852, GDP in 1850 from Bazot (2014), disposable income in 1864 from Delefortrie and Morice (1959) and the subscriptions to the Quarto edition of the *Encyclopédie* from Squicciarini and Voigtländer (2015). Through all specifications, the effect of wheat price remains significant at the 10% or 5% level.

Its impact on vaccination is not affected by urban population and a potential easier access to vaccinators and vaccination centres. This is coherent with the absence of correlation between medical practitioners and vaccination found in Table A14. It also indicates that the effect of economic shocks was not concentrated in urban centres but spread though the countryside too.

The level of wheat production doesn't modify the effect of prices, although one could have expected to find a higher level of production to be associated with a lower effect of wheat prices. Indeed, producers could have benefited from selling at a higher price, which would have reduced the intensity of the negative income shock linked to high prices. If these high prices were welfare-improving for a large enough share of the population, their effect should be reduced or even close to zero. Finding a stable and significant effect of wheat prices on vaccination therefore reinforces the idea that they constitute a very good proxy for negative income shocks.

A high consumption of wheat or cereals doesn't affect the impact of price either. One could have thought that people whose diet depended more strongly on cereals would be more affected by variations in wheat prices. However, bread accounted for a very significant part of food spending within all departments in France. This percentage was always higher than 45% for agricultural workers, with a mean and median value of 65%. A higher price of wheat and cereals therefore represented a strong negative income shocks in all departments, and affected vaccination the same way across different forms of diet.

The level of economic resources, either measured through GDP per capita or disposable income, was not associated with the effect of negative shocks either. A higher proportion of wealthy individuals might have decreased the effect of wheat prices, as these people would be less affected by the increase in the cost of food. The absence of effect is most likely due to the fact that this proportion was never high enough to protect the majority of the population from being impacted by changes in the price of staple food.

By introducing the share of landowners, we want to more formally control for the fact part of the agricultural workers might have benefited from an increase in the cost of food. Indeed, by selling wheat at a higher price, landowners could have increased their profits, even with a lower production of wheat. This effect could reduce the reliability of using price variations as a measure of income shocks. The outcomes however confirm that this issue was marginal in nineteenth-century France. Indeed, we don't find any significant impact of the concentration of landowners on the effect of wheat prices on vaccination against smallpox.

The last variable we use in this analysis is the subscriptions to the *Encyclopédie*, taken as a proxy for the concentration of an enlightened elite within departments. One might hypothesise that a higher

proximity of the elite to science, and therefore medical studies, would have favoured the dissemination of positive information on vaccination and increased the willingness of people to vaccination their children. We however see no impact of this proximity on the relationship between negative income shocks and vaccination.

We also examine whether the effect of negative income shocks depended on the prevalence of child labour or the proportion of children in the population. First, one might expect parents to have been more inclined to protect their children in areas where children contributed more significantly to household resources. From an intertemporal perspective, the loss of a child implied a reduction in future income, or at least a delay in accessing it. Second, a lower proportion of children in the population was associated with higher wealth levels (Cummins, 2013) and with greater investment in children's human capital in nineteenth-century France (see Figure A33). One could therefore expect stronger effects of shocks in departments where parental investment in children was higher, and where parents would have been even more motivated to protect their children from smallpox. However, the results presented in Table A13 indicate that neither reliance on child labour nor the share of children in the population altered the effect of negative shocks. Parents generally responded to shocks by increasing vaccination, regardless of the extent of child labour or their level of investment in children's human capital.

Table A12: Price of wheat and vaccination against smallpox. Heterogeneity analysis

	Vaccination rate							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Price of wheat	0.744**	0.851**	0.775**	0.841**	0.742**	0.867**	0.727*	0.765**
	(0.325)	(0.364)	(0.367)	(0.379)	(0.365)	(0.365)	(0.369)	(0.369)
× High urban population	-0.086	–	–	–	–	–	–	–
	(0.144)							
× High production of wheat	–	-0.299	–	–	–	–	–	–
		(0.186)						
× High consumption of wheat	–	–	-0.163	–	–	–	–	–
			(0.190)					
× High consumption of cereals	–	–	–	-0.288	–	–	–	–
				(0.185)				
× High GDP	–	–	–	–	-0.052	–	–	–
					(0.194)			
× High disposable income	–	–	–	–	–	-0.303	–	–
						(0.194)		
× High share of landowners	–	–	–	–	–	–	-0.062	–
							(0.196)	
× High subscriptions to the Encyclopédie	–	–	–	–	–	–	–	-0.140
								(0.198)
Controls	X	X	X	X	X	X	X	X
Department fixed effects	X	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X	X
Observations	4501	4472	4472	4472	4420	4501	4501	4501
R^2	0.358	0.358	0.357	0.358	0.350	0.358	0.357	0.358

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. For all variables used in the interaction terms, a high value is defined as above the median level. The consumption of wheat and cereals are measured in kilogram per inhabitant, the production of wheat in hectolitres per inhabitant and GDP is measured in francs per capita, as well as disposable income. The share of landowners is defined as the share of agricultural workers that own the land they exploit. Subscriptions to the *Encyclopédie* are measured as the number of subscriptions to the Quarto edition per 1,000 inhabitants. The price of wheat is computed in francs per hectolitre. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level.
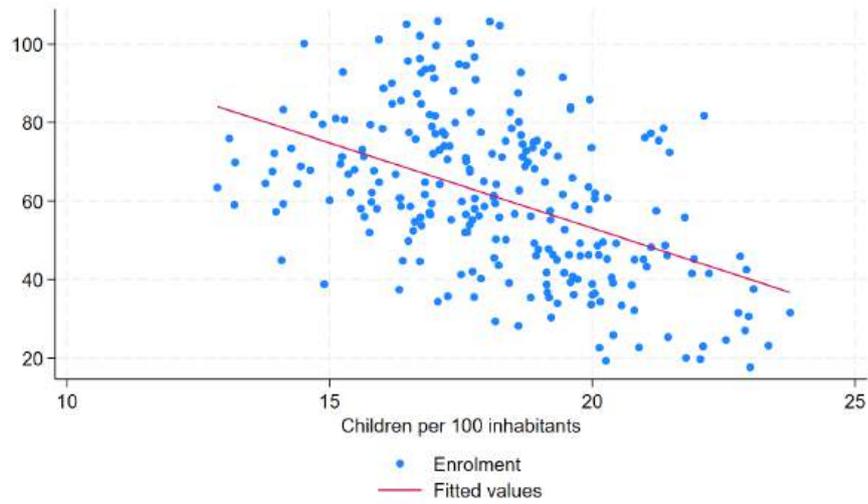
Figure A33: Proportion of children in the population and enrolment rate

Note: The proportion of children in the population is measured as the number of children per 100 inhabitants. Enrolment rates are measured as the number of children enrolled in primary schools per 100 children age 5 to 15 years old. The data used to measure enrolment and the proportion of children cover the years 1821 (1833 for enrolment), 1851, 1861, 1866 and 1872.

In the following table, we consider two proxies for the intensity of child labour: the share of children in factories and the intensity of agricultural child labour.

The first is defined as the percentage of children from 8 to 15 year old working within factories and is coming from the Industrial Survey of 1839-1847. The second is measured as the ratio between the number of days worked in a year by children in the agricultural sector and the number of days worked by adults. This information is coming from the 1852 Agricultural Survey. Both are imperfect proxies, but should give a good indication of the degree of reliance on child labour, both for families involved in the industrial and agricultural sectors.

The proportion of children is measured as the number of children per 100 inhabitants. The data used to measure this proportion cover the years 1821, 1851, 1861, 1866 and 1872.

Table A13: Price of wheat and vaccination against smallpox depending on the intensity of child labour and the proportion of children in the population

	Vaccination rate					
	(1)	(2)	(3)	(4)	(5)	(6)
Price of wheat	0.764*	0.790**	0.890**	0.858**	0.708*	0.704**
	(0.402)	(0.375)	(0.386)	(0.358)	(0.358)	(0.341)
× High share of children in factories	-0.089	-0.134	–	–	–	–
	(0.193)	(0.193)				
× High intensity of agricultural child labour	–	–	-0.359*	-0.318	–	–
			(0.193)	(0.195)		
× High proportion of children	–	–	–	–	-0.021	-0.024
					(0.201)	(0.203)
Controls		X		X		X
Department fixed effects	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X
Observations	4420	4420	4472	4472	4503	4501
R^2	0.337	0.351	0.345	0.358	0.344	0.357

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. The share of children in factories is defined as the percentage of children from 8 to 15 year old working within factories. The intensity of agricultural child labour is measured as the ratio between the number of days worked in a year by children in the agricultural sector and the number of days worked by adults. The proportion of children is measured as the number of children per 100 inhabitants. The data used to measure the proportion of children cover the years 1821, 1851, 1861, 1866 and 1872. A high share of children in factories, intensity of child labour or proportion of children is defined as above the median level. The price of wheat is computed in francs per hectolitre. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level.

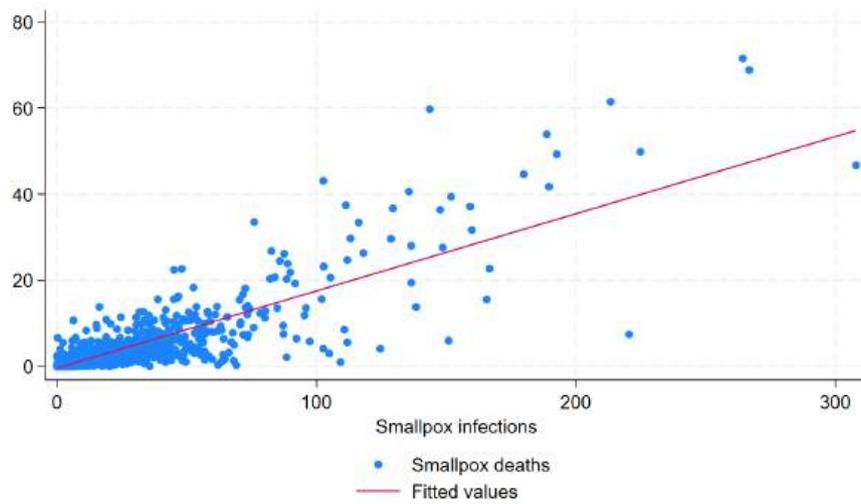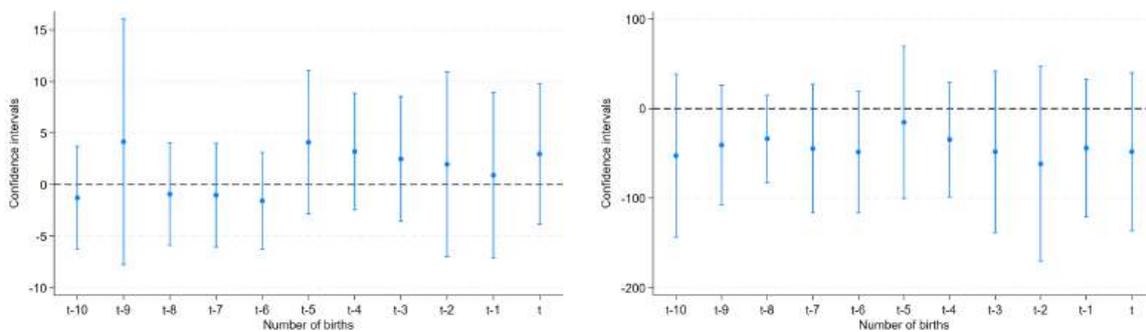## E.1.2 Past and Contemporaneous Epidemics

Figure A34: Infections and deaths from smallpox per 10,000 inhabitants

Note: Infections and deaths are measured per 10,000 inhabitants.

Infections per 10,000 inhabitants   Deaths per 10,000 inhabitants

Figure A35: Infections, deaths from smallpox and number of births

Notes: The figure depicts OLS estimation coefficients of the effect of smallpox infections and deaths from smallpox from $t-10$ to t on the number of births in t. Infections and deaths are measured per 10,000 inhabitants. 95% confidence intervals are reported.

E.1.3 Medical Practitioners and Other Determinants of Vaccination

An important factor that could have influenced the spread of vaccination is the concentration of medical practitioners. From 1803, the list of all doctors, surgeons, *officiers de santé* and pharmacists should be kept by departments. Unfortunately, it is hard to find this information before the middle of the century and the publication of *L'Annuaire médical et pharmaceutique de la France* (Medical and pharmaceutical directory of France) by Félix Roubaud. Thanks to these publications, we were able to collect information on the number of medical practitioners from 1854 to 1878 (except for 1871), which should provide a good approximation for the number of vaccinators. There were on average 6.2 practitioners per 10,000 inhabitants in France over this period (see Figure A36). Their presence was relatively stable within departments, and we therefore expect most of their influence on the spread of vaccination to be captured by the department fixed effects. Moreover, there is no visible correlation between the concentration of practitioners and the rate of vaccination (see Figure A37)[45].

In Table A14, we look at the influence of practitioners on vaccination. We run the OLS and IV estimations controlling for the number of practitioners, and interact the price of wheat with an indicator of a high presence of medical practitioners. None of the specifications used returns a significant effect of potential vaccinators on vaccination, and the effect of economic shocks is still significant despite running the estimations with a restricted number of years. We can therefore assert that the effect of income shocks is robust to controlling for the concentration of medical practitioners, and that parents didn't react differently to economic shocks when the number of potential vaccinators available was higher.

Other epidemics than smallpox could also have prompted people into vaccinating more. They could indeed have had a strong psychological impact and worked as an additional incentive for parents to protect their children against infectious diseases, especially if the number of deaths among the people living in the same department was high. To test this hypothesis, we consider the major epidemics that took place in nineteenth-century France, the cholera outbreaks of 1832, 1849 and 1854[46]. These epidemics caused the deaths of respectively 102,739, 102,500 and 142,749 individuals, which corresponds to around 1% of the population in total. There is however no significant correlation between the number of cholera deaths and the subsequent vaccination rate. Controlling for the number of cholera deaths doesn't affect the significance of the effect of income shocks on vaccination either (see Figure A38 and Table A15).

Distrust towards the ruling elite could also have fuelled vaccine hesitancy (Kennedy, 2019) and contributed to decrease vaccination against smallpox. It is hard to control for this factor, and especially to obtain variations in political distrust over the nineteenth century. However, as the political colour of departments remained quite stable during the century in France (Montalbo, 2023), the effect of distrust should be captured by the department fixed effects. We also find no correlation between the support for the Republicans during the legislative election of 1849, taken as a proxy for distrust towards the Monarchists and Bonapartists who ruled during most of the 1806-1888 period, and vaccination.

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[45]This absence of correlation is most likely due to the fact that the number of vaccinators was high enough in every departments to match the demand for vaccination.

[46]Tuberculosis is another major infectious disease of the nineteenth century. It is estimated to have caused around 80,000 deaths per year in France during that period. However, measuring its impact on vaccination against smallpox is tricky as there is no yearly data available on the number of people dying from tuberculosis at the department level.

The same is true when looking at the correlation with the turnout level, taken as a proxy for civic-mindedness (Figure A39).

Finally, even if religion doesn't seem to have played a role in influencing vaccination against smallpox (Bercé, 1984; Darmon, 1986), it could be interesting to control for religious intensity. It is however hard to obtain a proxy for religion that varies over time. Moreover, religious practice remained quite stable geographically speaking from the beginning of the nineteenth century to WWII in France (Squicciarini, 2020). The effect of religion is therefore very likely to be mostly captured in the department fixed effects too. Moreover, there is no correlation between the share of constitutional clergy, taken as a proxy for secularisation, during the Revolution in France and vaccination against smallpox (Figure A40).
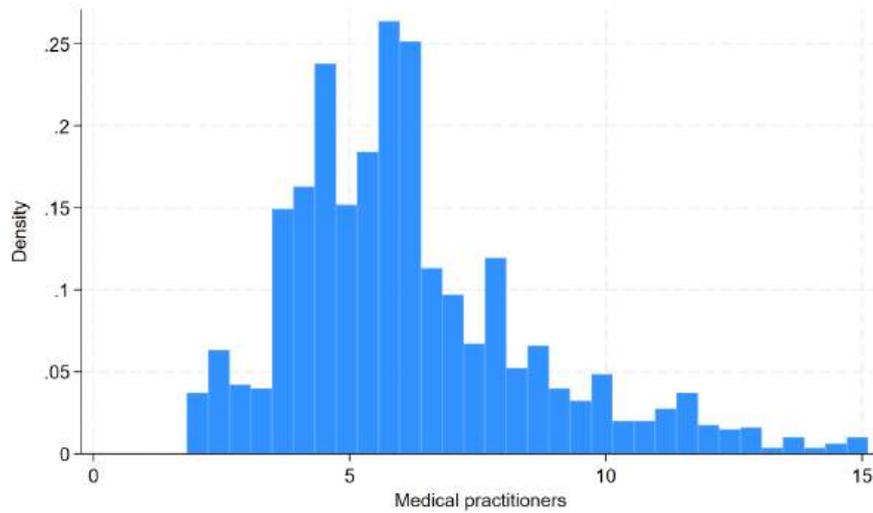
Figure A36: Medical practitioners per 10,000 inhabitants in France (1854-1878)

Note: The number of medical practitioners is defined as the sum of doctors, *officiers de santé* and pharmacists. The concentration of these practitioners is measured as their total number per 10,000 inhabitants.
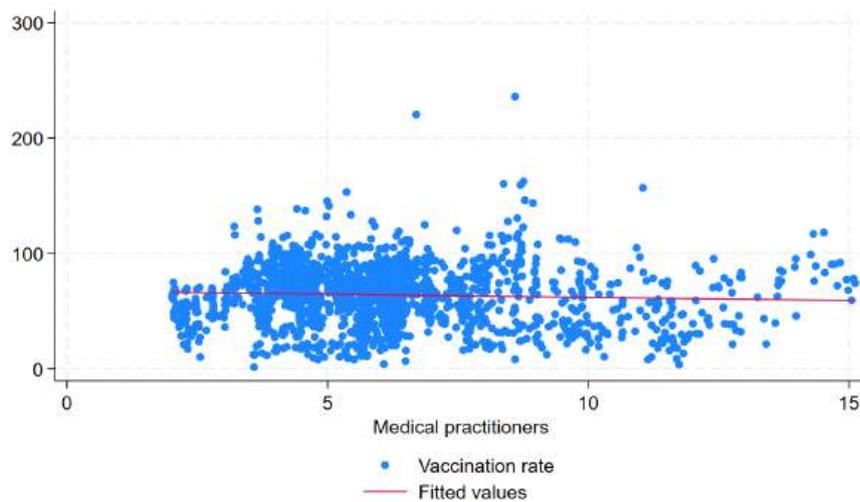

Figure A37: Vaccination rate and the concentration of medical practitioners

Note: The vaccination rate is defined as the number of vaccinations per 100 births. The number of medical practitioners is defined as the sum of doctors, *officiers de santé* and pharmacists. The concentration of these practitioners is measured as their total number per 10,000 inhabitants.

In [Table A14](#) in the Appendix, we look at the influence of practitioners on vaccination. We run the OLS and IV estimations controlling for the number of practitioners, and interact the price of wheat with an indicator of a high presence of medical practitioners. We stick to the IV estimations based on reconstructed rainfall, since using the collected precipitation would reduce the number of observations too drastically. This number is reduced when introducing the price of wheat as this variable is only available until 1872.

Table A14: Price of wheat and vaccination against smallpox. Additional control: number of medical practitioners

	Vaccination rate							
	OLS						IV: Rainfall$_{t-1}$	
							Reconstructed	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Price of wheat	–	–	0.874*	0.883*	0.928*	0.944*	2.883*	2.920*
			(0.519)	(0.520)	(0.509)	(0.512)	(1.683)	(1.727)
× High presence of practitioners	–	–	–	–	-0.110	-0.119	–	–
					(0.110)	(0.103)		
Medical practitioners	0.929	1.192	0.007	0.200	–	–	-0.033	0.135
	(1.464)	(1.446)	(1.323)	(1.405)			(1.291)	(1.374)
Controls		X		X		X		X
Department fixed effects	X	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X	X
Observations	1608	1608	1098	1098	1098	1098	1098	1098
R^2	0.593	0.596	0.665	0.669	0.666	0.669		
$F-stat$							17.581	15.951

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. The price of wheat is computed in francs per hectolitre. The number of medical practitioners is defined as the sum of doctors, *officiers de santé* and pharmacists. The concentration of these practitioners is measured as their total number per 10,000 inhabitants. A high presence of practitioners is defined as above the median value. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level. Reconstructed rainfall is measured as the total rainfall over the seasons Summer$_{t-2}$, Autumn$_{t-2}$, Spring$_{t-1}$, Summer$_{t-1}$ and Autumn$_{t-1}$.
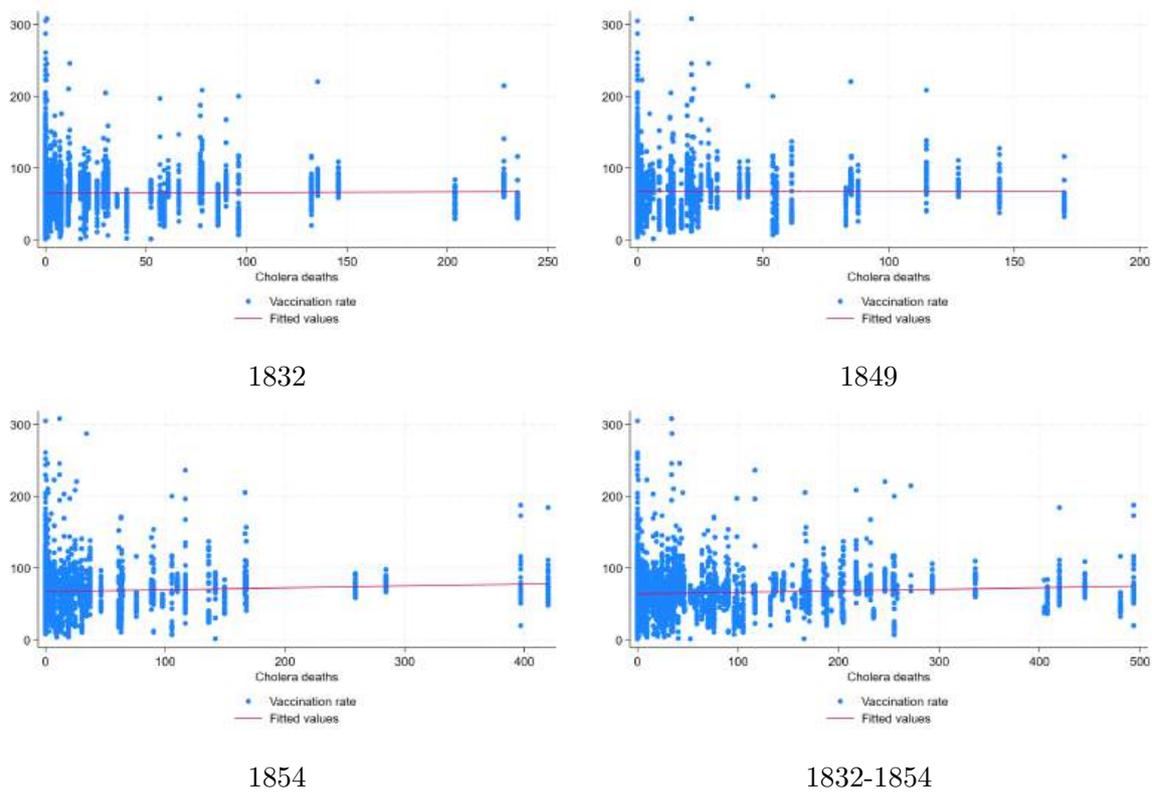
Figure A38: Vaccination rate and cholera deaths

Source: The number of cholera deaths is coming from Franck (2024).

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. Cholera deaths are measure per 10,000 inhabitants. The graphs depict the number of cholera deaths in 1832, 1849 or 1854 and its link with the vaccination rates from the year after the epidemics took place. For example, the first sub-graph shows the relationship between the number of deaths from cholera in 1832 and the vaccination rates within departments from 1833 to 1888. The last sub-graph does the same thing, but the number of deaths is measure as the total sum of deaths from cholera over time.

Table A15: Price of wheat and vaccination against smallpox. Additional control: number of cholera deaths

| | OLS | | IV: Rainfall$_{t-1}$ | | OLS | | IV: Rainfall$_{t-1}$ | |
| | | | Collected | | | | Reconstructed | |
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Price of wheat	1.297***	1.149**	3.768**	3.855**	0.699*	0.687**	2.372*	2.680**
	(0.474)	(0.465)	(1.834)	(1.866)	(0.355)	(0.338)	(1.368)	(1.268)
Cholera deaths	–	0.028	–	0.028	–	0.003	–	-0.003
		(0.019)		(0.017)		(0.013)		(0.012)
Controls		X		X		X		X
Department fixed effects	X	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X	X
Observations	2010	2010	2010	2010	4503	4501	4503	4501
R^2	0.575	0.583			0.344	0.357		
$F-stat$			29.209	27.692			20.682	20.063

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

*Notes*: Vaccination rate is defined as the percentage of vaccinations over the number of births. The price of wheat is computed in francs per hectolitre. Cholera deaths are measure per 10,000 inhabitants. They are computed as the sum of deaths from cholera in 1832, 1849 and 1854. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level. In columns (1) and (2), the number of observations used in the OLS estimations is restricted to the sample used in the IV estimations, and for which rainfall data are available. Collected rainfall is computed as the total rainfall over the months July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$. Reconstructed rainfall is measured as the total rainfall over the seasons Summer$_{t-2}$, Autumn$_{t-2}$, Spring$_{t-1}$, Summer$_{t-1}$ and Autumn$_{t-1}$.
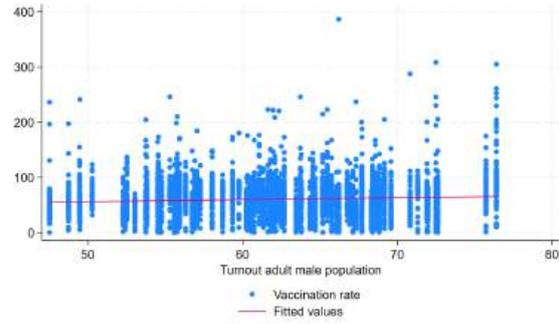
Support for the *Démocrates-socialistes*
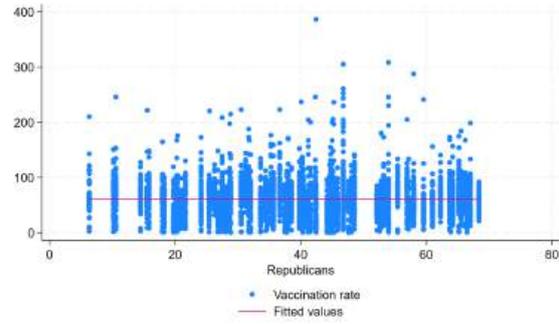
Support for the Republicans
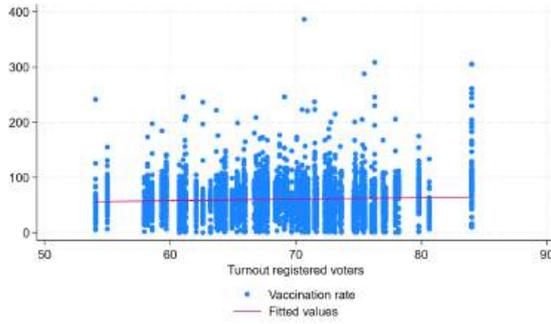
Turnout - registered voters

Turnout - adult male population

Figure A39: Vaccination rate, Republican support and voter turnout (in 1849)

Source: Turnout and support for the Republicans are coming from Montalbo (2023).

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. *Démocrates-socialistes* stands for the politicians belonging to the political party called the *Montagne*. Moderate republicans are included alongside the *Démocrates-socialistes* in the Republican variable. Turnout registered voters is defined as the share of voters over all registered people. Turnout adult male population stands for the share of voters over the adult male population (older than 21 years old). All political variables are measured during the 1849 legislative election.

We use the share of constitutional clergy to measure religious intensity in Figure A40. The Civil Constitution of the Clergy passed on 12 July 1790 during the French Revolution deeply restructured the French Church. It abolished tithes, nationalised Church lands, reduced the number of religious corps, and had citizens elect bishops and priests. The National Assembly required the clergy to take an oath of allegiance to this Constitution, which was refused by a significant percentage of all priests, around 44% over all French departments. A high share of constitutional clergy is therefore considered to be a very good proxy for secularisation at that time.
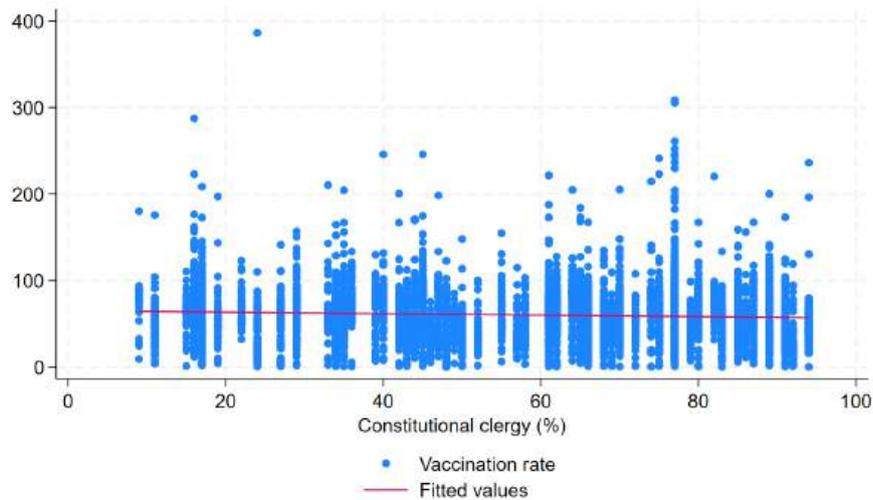

Figure A40: Vaccination rate and share of constitutional clergy

Source: The share of constitutional clergy is coming from Tackett (1986).
Note: The vaccination rate is defined as the number of vaccinations per 100 births. The constitutional clergy corresponds to the clergy who agreed to sign the Civil Constitution of the clergy during the Revolution in France.

E.1.4 Robustness Checks

In this subsection, we document a series of robustness checks for our IV estimates.

Alternative dependent and independent variables

In Table A16, we measure the price of wheat in t from the harvest taking place the year before, that is to say in July_{t-1}. One might indeed think that a change in price during the second part of $t - 1$ (and especially the very end of the year) could have also influenced the vaccination rate in t. Since children usually didn't get vaccinated during the winter season, any end-of-the-year variation in price would most likely increase vaccination during the spring season in year t.

In Table A17, we compute the vaccination rate as the number of vaccinations divided by the number of births in t and $t - 1$ instead of only t. This accounts for the fact that vaccination was mainly administered to young children between 0 and 2 years old. A larger part of the pool of potential candidates to vaccination is therefore taken into account in this case. In both cases, our results remain significant.

Finally, in Table A18, we use a spline instead of a linear interpolation to construct our control variables, which doesn't affect the outcomes.

Alternative instrument

In Table A19 and Table A20, we modify our instruments in two ways. Firstly, we consider rainfall over all the months from the harvest in $t - 2$, and therefore don't select the months that had the strongest influence on the harvests in $t - 1$ and t (see subsection D.2 in the Appendix for additional details on the instruments). This reduces the strength of the instruments, but does not modify the significance of the outcomes. Secondly, we consider our baseline instrument based on collected rainfall, but introduce all the months separately in the econometric specification instead of taking the sum of rainfall over these months. The results remain significant under this specification. We also run an over-identification test in this case and can't reject the exogeneity of the instruments used.

Falsification and robustness checks on vaccination

We run a falsification test in order to check that negative income shocks don't impact past vaccination rates. In Figure A41, we run the IV estimations on the vaccination rates from $t - 10$ to $t - 1$ and find no significant effect.

As there is some missing information on the number of vaccinations, we also want to be sure that this doesn't introduce a bias in the estimations. This might for example be the case if departments that don't report vaccinations each year tend to report the sum of vaccinations across several years. In Figure A42, we compute the percentage of non-missing observations on vaccination within departments and show that this percentage is reassuringly very high, with an average and median value of 86% and 87%. Nonetheless, we exclude in Table A21 the 25% of departments with a percentage of non-missing observations lower than 82%. This doesn't affect the significance of the outcomes.

Table A16: Price of wheat and vaccination against smallpox. Alternative price of wheat computed over the wheat cycle from July_{t-1} to December_t

	Vaccination rate							
	OLS		IV: Rainfall_{t-1}		OLS		IV: Rainfall_{t-1}	
			Collected				Reconstructed	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Price of wheat from last harvest	1.300**	1.123**	3.394**	3.480**	0.881**	0.879**	1.961	2.399**
	(0.517)	(0.510)	(1.717)	(1.719)	(0.389)	(0.367)	(1.219)	(1.160)
Controls		X		X		X		X
Department fixed effects	X	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X	X
Observations	2034	2034	2034	2034	4566	4564	4566	4564
R^2	0.574	0.580			0.345	0.358		
$F-stat$			37.132	34.783			26.165	25.967

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. The price of wheat is computed in francs per hectolitre and from July_{t-1} to December_t. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level. In columns (1) and (2), the number of observations used in the OLS estimations is restricted to the sample used in the IV estimations, and for which rainfall data are available. Collected rainfall is computed as the total rainfall over the months July_{t-2}, August_{t-2}, September_{t-2}, March_{t-1}, April_{t-1}, May_{t-1}, June_{t-1}, July_{t-1}, August_{t-1}, and September_{t-1}. Reconstructed rainfall is measured as the total rainfall over the seasons Summer_{t-2}, Autumn_{t-2}, Spring_{t-1}, Summer_{t-1} and Autumn_{t-1}.

Table A17: Price of wheat and vaccination against smallpox. Alternative vaccination rate: number of births over two years

	Vaccination rate							
	OLS		IV: Rainfall$_{t-1}$		OLS		IV: Rainfall$_{t-1}$	
			Collected				Reconstructed	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Price of wheat	0.649**	0.578**	1.696*	1.745*	0.338*	0.337**	1.155*	1.372**
	(0.247)	(0.245)	(0.924)	(0.919)	(0.178)	(0.169)	(0.668)	(0.642)
Controls		X		X		X		X
Department fixed effects	X	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X	X
Observations	2010	2010	2010	2010	4503	4501	4503	4501
R^2	0.564	0.570			0.344	0.357		
$F - stat$			29.209	27.651			20.682	19.111

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the sum of births in year t and $t-1$. The price of wheat is computed in francs per hectolitre. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level. In columns (1) and (2), the number of observations used in the OLS estimations is restricted to the sample used in the IV estimations, and for which rainfall data are available. Collected rainfall is computed as the total rainfall over the months July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$. Reconstructed rainfall is measured as the total rainfall over the seasons Summer$_{t-2}$, Autumn$_{t-2}$, Spring$_{t-1}$, Summer$_{t-1}$ and Autumn$_{t-1}$.

Table A18: Price of wheat and vaccination against smallpox. Spline interpolation to construct the control variables

	Vaccination rate							
	OLS		IV: Rainfall$_{t-1}$		OLS		IV: Rainfall$_{t-1}$	
			Collected				Reconstructed	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Price of wheat	1.297***	1.159**	3.768**	3.624*	0.699*	0.709**	2.372*	2.893**
	(0.474)	(0.456)	(1.834)	(1.859)	(0.355)	(0.334)	(1.368)	(1.327)
Controls		X		X		X		X
Department fixed effects	X	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X	X
Observations	2010	2010	2010	2010	4503	4501	4503	4501
R^2	0.575	0.582			0.344	0.358		
$F-stat$			29.209	27.978			20.682	18.918

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. The price of wheat is computed in francs per hectolitre. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. The control variables are estimated using a spline interpolation and not a linear one as in Figure A14. Standard errors are clustered at the department level. In columns (1) and (2), the number of observations used in the OLS estimations is restricted to the sample used in the IV estimations, and for which rainfall data are available. Collected rainfall is computed as the total rainfall over the months July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$. Reconstructed rainfall is measured as the total rainfall over the seasons Summer$_{t-2}$, Autumn$_{t-2}$, Spring$_{t-1}$, Summer$_{t-1}$ and Autumn$_{t-1}$.

Table A19: Price of wheat and vaccination against smallpox. Alternative instrument: rainfall computed over all the months from the harvest in $t-2$

	Vaccination rate							
	OLS		IV: Rainfall$_{t-1}$		OLS		IV: Rainfall$_{t-1}$	
			Collected				Reconstructed	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Price of wheat	1.271***	1.132**	3.703*	3.820*	0.699*	0.693**	2.044	2.465**
	(0.478)	(0.472)	(2.051)	(2.070)	(0.355)	(0.336)	(1.272)	(1.236)
Controls		X		X		X		X
Department fixed effects	X	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X	X
Observations	2000	2000	2000	2000	4503	4501	4503	4501
R^2	0.575	0.581			0.344	0.357		
$F-stat$			21.792	20.168			18.140	16.563

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. The price of wheat is computed in francs per hectolitre. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level. In columns (1) and (2), the number of observations used in the OLS estimations is restricted to the sample used in the IV estimations, and for which rainfall data are available. Collected rainfall is computed as the total rainfall over the months July$_{t-2}$ to September$_{t-1}$. Reconstructed rainfall is measured as the total rainfall over the seasons Summer$_{t-2}$, Autumn$_{t-2}$, Winter$_{t-1}$ Spring$_{t-1}$, Summer$_{t-1}$ and Autumn$_{t-1}$.

Table A20: Price of wheat and vaccination against smallpox. Alternative instrument: monthly rainfall variables

	Vaccination rate					
	OLS				IV: Rainfall$_{t-1}$	
					Collected	
	(1)	(2)	(3)	(4)	(5)	(6)
Price of wheat	0.699*	0.693**	1.297***	1.154**	2.702*	2.810*
	(0.355)	(0.336)	(0.474)	(0.468)	(1.517)	(1.531)
Controls		X		X		X
Department fixed effects	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X
Observations	4503	4501	2010	2010	2010	2010
R^2	0.344	0.357	0.575	0.581		
$F-stat$					11.127	10.174
Sargan chi²					8.961	9.368
Sargan p-value					0.441	0.404

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. The price of wheat is computed in francs per hectolitre. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level. In columns (3) and (4), the number of observations used in the OLS estimations is restricted to the sample used in the IV estimations, and for which rainfall data are available. Collected rainfall consists in the total rainfall for the months July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$. Each month is introduced separately in the first stage.
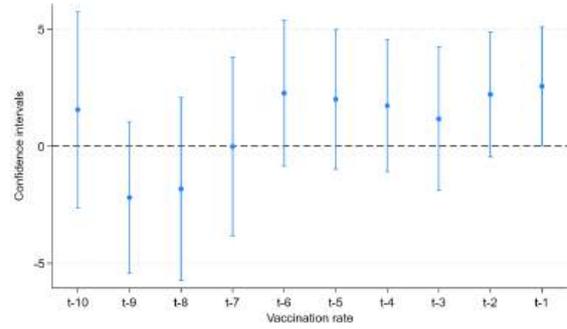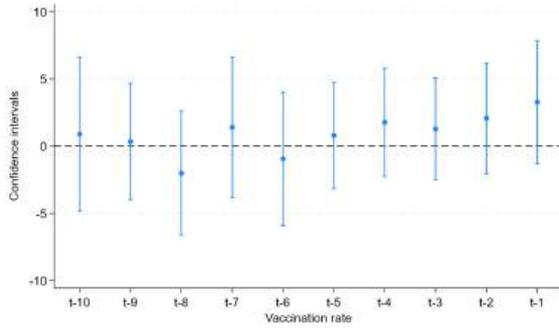
IV: collected rainfall$_{t-1}$;, wheat price   IV: reconstructed rainfall$_{t-1}$;, wheat price

Figure A41: Falsification tests: impact of wheat prices on past vaccination rates

Notes: Sub-figures depict IV estimation coefficients of the effect of wheat prices in t on vaccination rates from $t-1$ to $t-10$. Collected rainfall is computed as the total rainfall over the months July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$. Reconstructed rainfall is measured as the total rainfall over the seasons Summer$_{t-2}$, Autumn$_{t-2}$, Spring$_{t-1}$, Summer$_{t-1}$ and Autumn$_{t-1}$. 95% confidence intervals are reported.
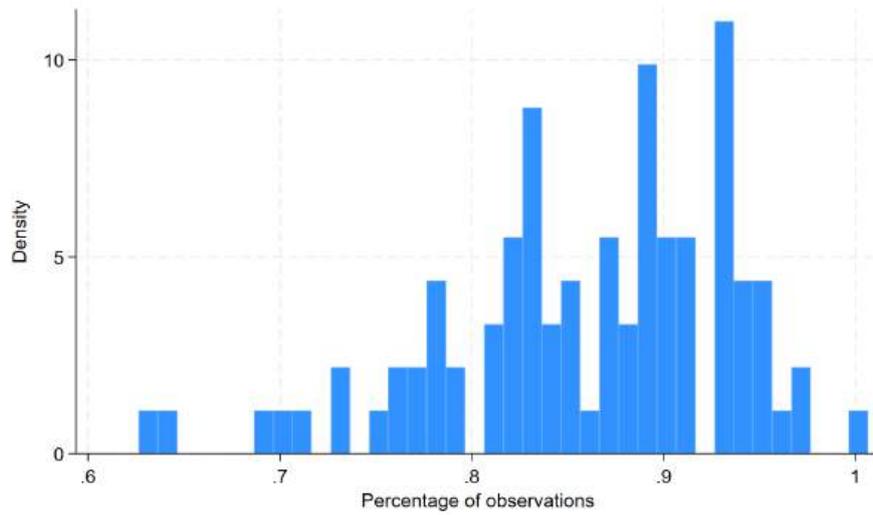
Figure A42: Percentage of non-missing observations on vaccination within departments

Note: The figure depicts the histogram of the percentage on non-missing observations of vaccination within departments. There is for example 0% of the departments for which the percentage of non-missing observations on vaccination is lower than 60%. There is 1.1% of the departments for which the percentage of non-missing observations is equal to 100%.

Table A21: Price of wheat and vaccination against smallpox. Exclusion of the bottom 25% departments as regards missing observations on vaccinations

	Vaccination rate							
	OLS		IV: Rainfall$_{t-1}$		OLS		IV: Rainfall$_{t-1}$	
			Collected				Reconstructed	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Price of wheat	1.526***	1.397***	5.747**	5.722**	0.659	0.587	2.585*	2.756*
	(0.470)	(0.466)	(2.299)	(2.438)	(0.407)	(0.387)	(1.469)	(1.468)
Controls		X		X		X		X
Department fixed effects	X	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X	X
Observations	1626	1626	1626	1626	3642	3640	3642	3640
R^2	0.586	0.591			0.376	0.389		
$F-stat$			19.909	22.183			17.936	15.574

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: The bottom 25% departments as regards the percentage of missing observations on vaccinations is excluded from the estimations. Vaccination rate is defined as the percentage of vaccinations over the number of births. The price of wheat is computed in francs per hectolitre. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level. In columns (1) and (2), the number of observations used in the OLS estimations is restricted to the sample used in the IV estimations, and for which rainfall data are available. Collected rainfall is computed as the total rainfall over the months July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$. Reconstructed rainfall is measured as the total rainfall over the seasons Summer$_{t-2}$, Autumn$_{t-2}$, Spring$_{t-1}$, Summer$_{t-1}$ and Autumn$_{t-1}$.

E.2 Phylloxera, Wine Crisis and Vaccination

E.2.1 Event Study Outcomes

Log of wine production
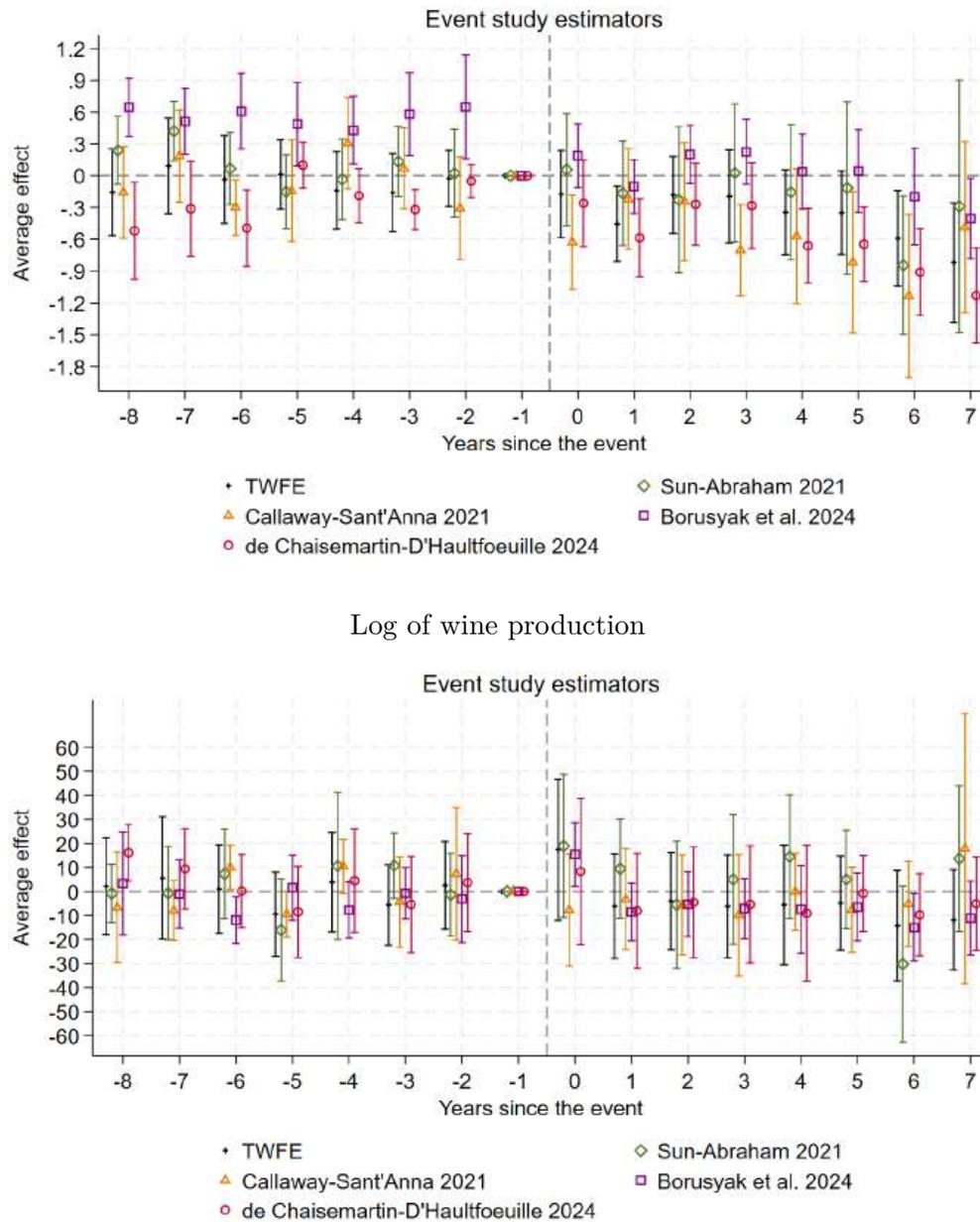
Vaccination rate

Figure A43: Event-study plot: effect of phylloxera on wine production and vaccination rate within non-wine-intensive departments

Notes: The event-study plot is built using five different estimators: a dynamic TWFE model (black cross markers), Sun and Abraham (2021) (green diamond markers), Callaway and Sant'Anna (2021) (orange triangle markers), Borusyak, Jaravel, and Spiess (2024) (purple square markers) and de Chaisemartin and D'Haultfoeuille (2024) (pinkish-red circle markers). The treatment variable is full contamination by phylloxera. The time span of the data covers eight years before full infestation, and seven afterwards. The reference period considered is $\tau = -1$, one year before full contamination. The outcome variables are respectively the log of wine production and the vaccination rate. Wine production is measured in hectolitres and the vaccination rate is defined as the number of vaccinations per 100 births. Non-wine-intensive departments are defined as the departments in which wine production represented less than 15% of agricultural production in 1862. 95% confidence intervals are reported. Standard errors are clustered at the department level.
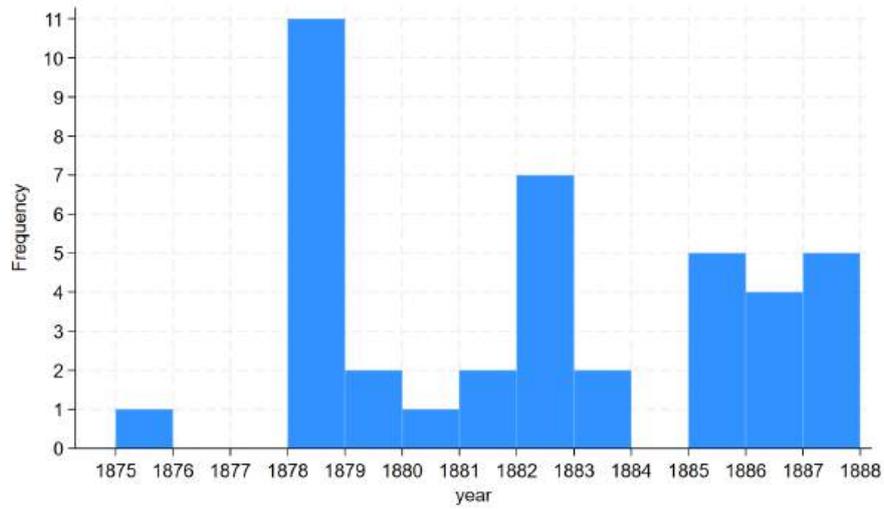
Figure A44: First year of full contamination by phylloxera

Notes: The graph corresponds to the histogram of the first year when phylloxera fully contaminated a given department. One department was for example reported as fully contaminated in 1875, and remained so until the end of the period, while 11 departments were fully contaminated from 1878.
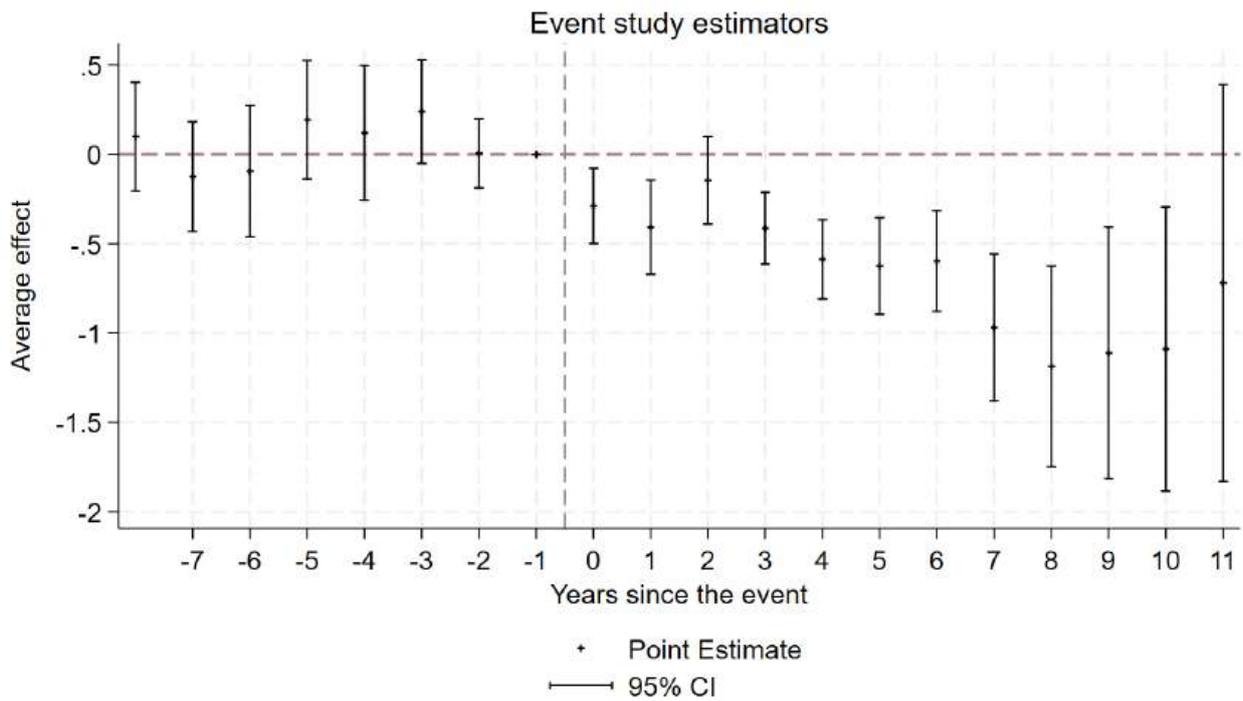
Figure A45: Event-study plot: effect of phylloxera on wine production within wine-intensive departments

Notes: The event-study plot is built using a dynamic TWFE model. The treatment variable is full contamination by phylloxera. The time span of the data covers eight years before full infestation, and eleven afterwards. The reference period considered is $\tau = -1$, one year before full contamination. The outcome variable is the log of wine production, which is measured in hectolitres. Wine-intensive departments are defined as the departments in which wine production represented at least 15% of agricultural production in 1862. 95% confidence intervals are reported. Standard errors are clustered at the department level.

E.2.2 Robustness checks

In this subsection, we document a series of robustness checks for our phylloxera estimates.

Tt is important to mention first that the baseline results are already robust to controlling for the potential effect of the Franco-Prussian War of 1870-71. As visible in Figure 1, the war and ensuing smallpox pandemic contributed to dramatically increase the number of vaccinations. One might firstly fear that these vaccinations were mostly performed on soldiers and not children, as smallpox caused around 25,000 deaths in the French army in 1870-71 (Smallman-Raynor and Cliff, 2002). The strong rise in vaccinations in 1871 might therefore be considered as an outlier that should not be included in the estimations. Secondly, as the number of births declined from around 996,000 in 1870 to 826,000 in 1871 (before increasing again to reach 966,00 in 1872) (Biraben, 1979), the war could also have impacted the vaccination rate through its effect on births. Because of these two reasons, and following what was already done in Bignon et al. (2017), we therefore chose to exclude the year 1871 from the estimations. As for the IV estimations with wheat prices, 1870 is also excluded as the number of births within departments is not available for this year. All in all, the estimations are therefore not driven or affected by the potential impact of the Franco-Prussian War on smallpox vaccination.

Vaccination rates adjusted for infant and child morality

In Figure A46, we explore the effect of phylloxera on vaccination rates adjusted for infant and child mortality. Since information on mortality by age groups is only available for the 1855–1868 and 1875–1884 periods, and that most departments were fully contaminated by phylloxera from 1878, we restrict the analysis to four pre-periods and six periods of full contamination. The results remain significant. The presence of a significant coefficient in $\tau = -3$ using the Callaway and Sant'Anna (2021) and de Chaisemartin and D'Haultfœuille (2024) estimators is hard to explain. However, these estimators return non-significant pre-trends for the other periods and all other estimators are always non-significant.

Never-treated or not-yet-treated as a control group

In our baseline estimations, the control group varies across the heterogeneity-robust estimators used. While the Borusyak et al. (2024) and de Chaisemartin and D'Haultfœuille (2024) estimators rely on both the never treated and not-yet treated as a control group, the Callaway and Sant'Anna (2021) estimator only uses the never treated. Finally, when using the Sun and Abraham (2021) estimator, we chose to focus on the last treated as a control group. Choosing among potential control groups depends on the belief about which of them will provide the most reliable counter-factual. As stated in Miller (2023), picking the not-yet treated would be based on the idea that among those treated, the timing of treatment is essentially random. Choosing the never treated on the other hand would amount considering as more plausible the assumption that control units represent the counterfactual changes over time.

Our results are not sensitive to the approach chosen. Indeed, in Figure A47, we reproduce the baseline outcomes using the Callaway and Sant'Anna (2021) estimator which allows to consider only the never treated or the not-yet treated (*notyet* option) as a control group. In Figure A48, we instead rely on the de Chaisemartin and D'Haultfœuille (2024) estimator, which allows to consider both the never and not-yet treated or only the never treated (*only_never_switchers* option). The outcomes

remain very close to the baseline ones in each case.

Balanced panel

The panel of departments we consider in the event-study is unbalanced. Some departments are only fully contaminated by phylloxera after 1881, and are therefore not observed every year during the seven periods after contamination that we consider in our baseline specification. A department fully contaminated in 1885 will for example be observed during three periods after contamination.

The heterogeneity-robust estimators we use don't require a balanced panel, and therefore not all groups have to be observed at every period. However, one might still want to only consider a balanced panel of departments, and thus carry the estimations only with departments that can be observed at every period. One might indeed think that departments that are fully contaminated towards the end of the period under scrutiny could have some particular characteristics that could bias the estimations.

In Figure A49, we therefore restrict the sample to departments observed at every period. We only report the outcomes from the Borusyak et al. (2024) and de Chaisemartin and D'Haultfœuille (2024) estimators using the *hbalance* and *same_switchers* options. Indeed, if the panel is unbalanced, the Callaway and Sant'Anna (2021) estimator converts it into a balanced panel by removing units with missing observations for any time period. The baseline results relying on this estimator are therefore already robust to controlling for unbalancedness. The Sun and Abraham (2021) estimator doesn't include a balanced-panel option. In spite of an increase in the confidence intervals associated with the reduction in sample size, the outcomes remain significant and mostly unchanged when working with a balanced panel of departments.

Other baseline periods

In Figure A50, we consider different baseline periods for the even-study, using the standard TWFE estimator. We stick to this estimator here, as the more recent ones don't always allow to change the baseline. We consider reference periods from $\tau = -2$ to $\tau = -7$, that is to say from two to seven years before full contamination by phylloxera. The results are mostly unchanged compared to using a baseline period of $\tau = -1$.

Standard difference in differences model

We also reproduce the difference in differences strategy based on a standard TWFE model used in Banerjee et al. (2010b) and Bignon et al. (2017), and which exploits the variation in the timing of the spread of phylloxera between departments. We start the analysis in 1850, as it is from this year that data on wine production at the department level starts to be available. The main estimation model is the following:

$$Vacc_{d,t} = \beta_1 Phyllox_{d,t} + \beta_2 X_{d,t} + \alpha_d + \gamma_t + \epsilon_{d,t} \tag{4}$$

with subscripts d and t corresponding to department and time. $Phyllox_{d,t}$ corresponds to the phylloxera variables we use. Department and time fixed effects α_d and γ_t are included in the estimations and the $\epsilon_{d,t}$ standard errors are clustered at department level. The $X_{d,t}$ control variables are the same than the ones used when using wheat prices.

We use several $Phyllox_{d,t}$ variables to assess the impact of phylloxera on vaccination, all of them

being used either in Banerjee et al. (2010b) or in Bignon et al. (2017). We first define a binary variable equal to 1 if a department was fully contaminated by phylloxera, that is to say if all municipalities were infected. We then scale this variable by interacting it with three other factors: the hectares of vine measured per 100 inhabitants in 1862, the share of wine in agricultural production in 1862 and a proxy for the share of people affected by a shock on wine production (that we name "importance of wine"), which is defined as the share of people employed in agriculture according to the 1861 census multiplied by the share of wine in agricultural production in 1862. These variables are measured in 1862 as this is the last year before the phylloxera was first spotted in France.

Scaling the binary variable of full contamination enables us to evaluate if phylloxera impacted vaccination more when departments heavily depended on wine production. We also make a distinction between wine-growing departments and the other ones by taking the median value of the percentage of wine in agricultural production in 1862 (15%). Wine-intensive departments will be defined as above this median value (Banerjee et al., 2010b).

In Table A22, we use the indicator of full contamination to look at the effect of phylloxera on wine production and vaccination. The outcomes reveal that the crisis mostly affected production within wine-intensive departments. Compared to the reference period with zero or partial contamination, full contamination by phylloxera generated a decrease in wine production of about 48% within these departments. Phylloxera didn't impact wine production significantly within departments where wine growing didn't represent a high share of agricultural production. The negative income shock caused by phylloxera was therefore concentrated within wine-intensive departments.

In compliance with these results, full contamination by phylloxera within these departments is linked to a 17.5 percentage-point increase in the vaccination rate. Using the full sample and information on wine production instead of focusing only on wine-intensive departments leads to similar results. An increase of one percentage point in the share of wine production, the hectares of vine per capita or the importance of wine production in 1862 contributes to increase the effect of full contamination by phylloxera by respectively 0.4, 1 and 0.7 percentage points. The negative income shock associated with the phylloxera crisis therefore strongly contributed to the end-of-the-century increase in vaccination against smallpox. Within wine-intensive departments, the fall in wine production was linked to an increase in vaccination corresponding to around 30% of the average vaccination rate over the century. The effect is extremely high and confirms that negative shocks were one of the main drivers of vaccination.

We also use this specification to further consider the potential effect of infant or child mortality on our outcomes. This information is only available for the 1855–1868 and 1875–1884 periods, which restricts the number of observations. Infant mortality is defined as the number of children from 0 to 1 year of age who die in year t. Child mortality is defined as the number of children from 0 to 5 years of age who die in year t. In columns (1) and (2) of Table A23, the vaccination rate is defined as the percentage of vaccinations over the number of births from which infant mortality has been subtracted. In columns (3) and (4), child mortality is subtracted from the number of births. The outcomes remain significant when accounting either for infant or child mortality.

The effect of phylloxera on vaccination is also robust to two important checks. In Table A24, we include department-specific trends, as done in Banerjee et al. (2010b). This controls for a potential

omitted time-trend in vaccination. It also alleviates the concern that the end-of-the-century increase in uptake could be due to time-varying factors correlated with phylloxera. The results remain significant under this specification, which strongly reinforces the reliability of our estimations.

In Table A25, we amend our main specification by restricting the sample to the 1863-1888 years. We therefore start the analysis the year when phylloxera was first spotted in France. We do so to focus more precisely on the crisis and to avoid adding too many non-phylloxera years in the sample, which would increase the probability that vaccination was influenced by other shocks. This doesn't modify the significance of our results.

We also reproduce the robustness checks used on wheat prices and that can also be implemented in the phylloxera context. The outcomes of Table A22 are replicated using the number of births over two years to construct the vaccination rate and using controls constructed with a spline interpolation. This doesn't modify the outcomes (see Table A26 and Table A27). As the number of observations is lower when working on the phylloxera crisis, we don't include the number of infections and of medical practitioners as additional controls. This latter is for example only available until 1878, which corresponds to three years after the first department was fully contaminated by phylloxera. This prevents any reliable quantitative analysis.

Alternative Specification Based on IV Estimations

We also estimate the effect of phylloxera by implementing the IV specification used by Bignon et al. (2017) as an alternative estimation strategy. Within this framework, phylloxera indicators are used to instrument wine production. We focus on wine-intensive departments only, as the negative impact of phylloxera on wine production was concentrated within these counties. The estimation model is therefore the following:

$$Wine_{d,t} = \delta_1 Phllox_{d,t} + \delta_2 X_{d,t} + \alpha_d + \gamma_t + \epsilon_{d,t} \tag{5}$$

$$Vacc_{d,t} = \beta_1 Wine_{d,t} + \beta_2 X_{d,t} + \alpha_d + \gamma_t + \epsilon_{d,t} \tag{6}$$

where (5) corresponds to the first stage equation, (6) to the second stage and subscripts d and t to department and time. $Phllox_{d,t}$ is the instrument used and corresponds to the "Phylloxera - full contamination" variable. $Wine_{d,t}$ corresponds to the log of wine production.

In Table A28, we present the outcomes for the main specification and also directly include robustness checks using department-specific trends and restricting the sample to the 1863-1888 years (after phylloxera was first spotted). All the estimations highlight a consistent and negative impact of a higher wine production on vaccination against smallpox, which is coherent with our previous results showing a positive effect of negative income shocks on vaccination. The OLS estimates indicate that, over the 1850-1888 period and within department where the wine sector represented a significant share of agricultural output, a one-percent increase in wine production was accompanied by a decrease in vaccine uptake of around 3 percentage points. The effect is much stronger, with a magnitude oscillating between 20 and 30 percentage points, when wine production is instrumented by phylloxera. This can be explained by the fact that contamination by phylloxera entailed a disruption of the entire wine industry (barrel or cork producers for example), and not only a reduction in wine production. This also explains the very high effect found in Table A22, as phylloxera created a shock that posed a threat

on the very economic viability of wine-intensive departments. These outcomes therefore confirm that vaccine uptake in nineteenth-century France was strongly determined by the variations in economic activity and the intensity of negative income shocks.
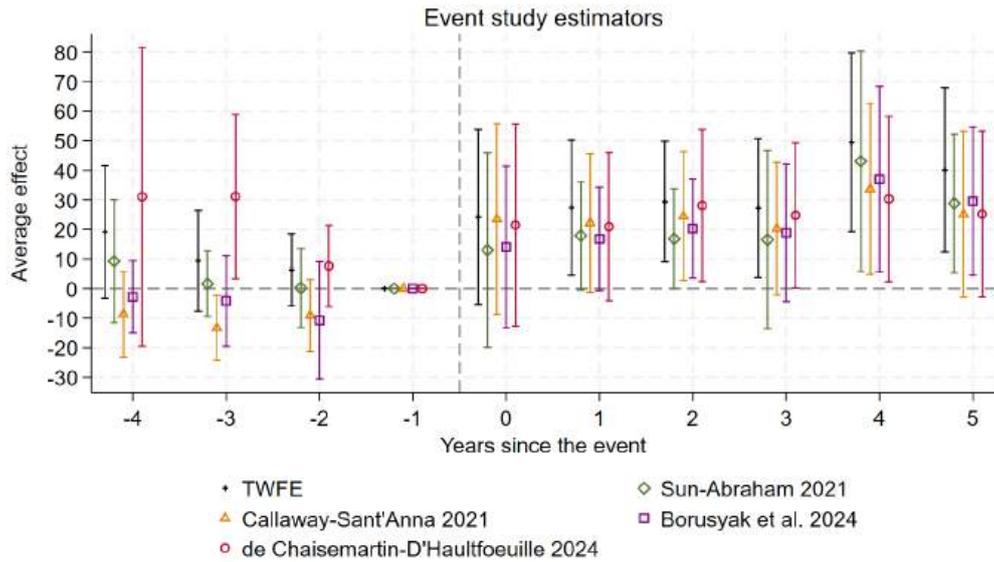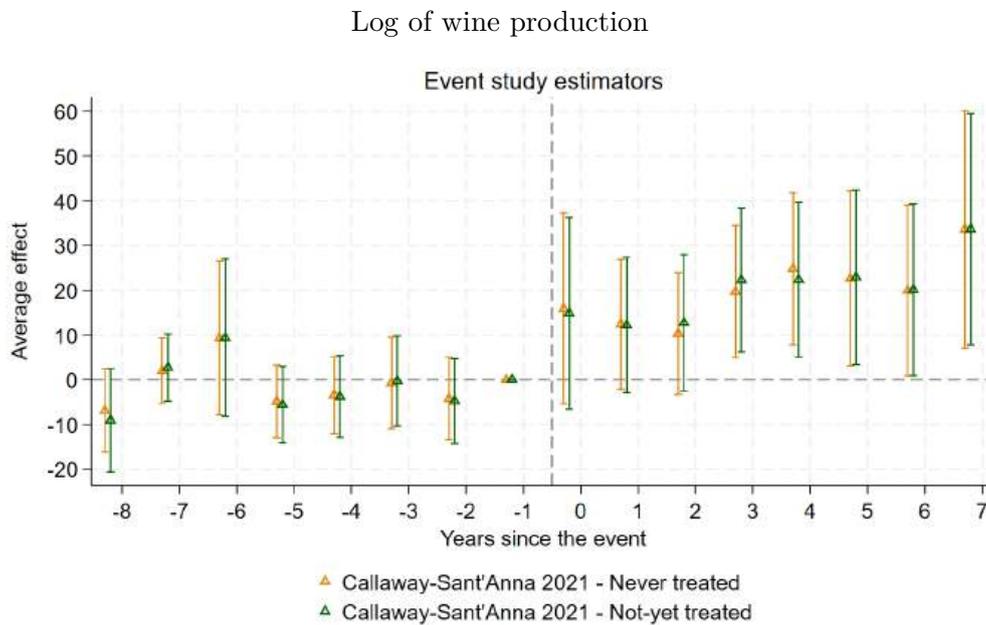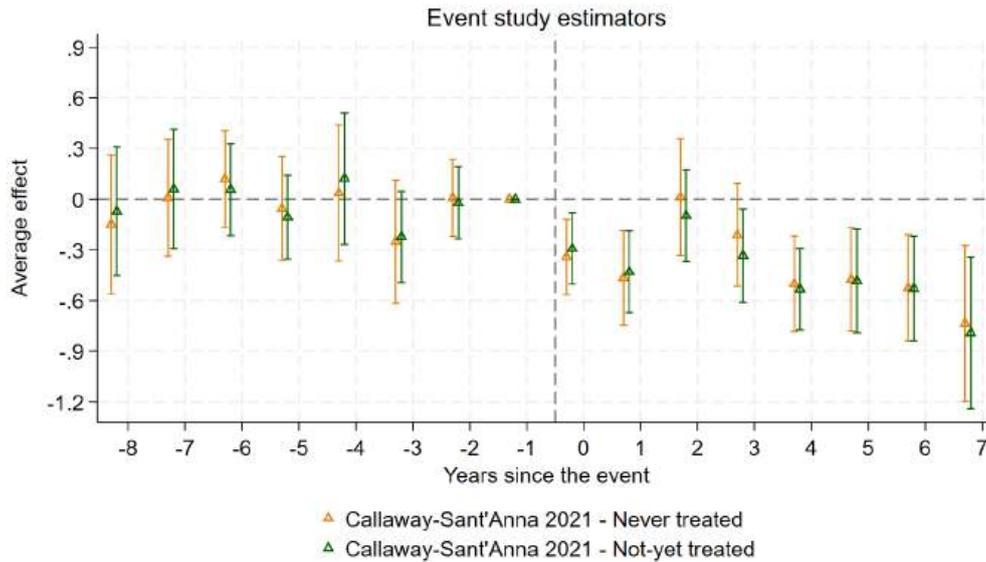
Vaccination rate adjusted for infant mortality
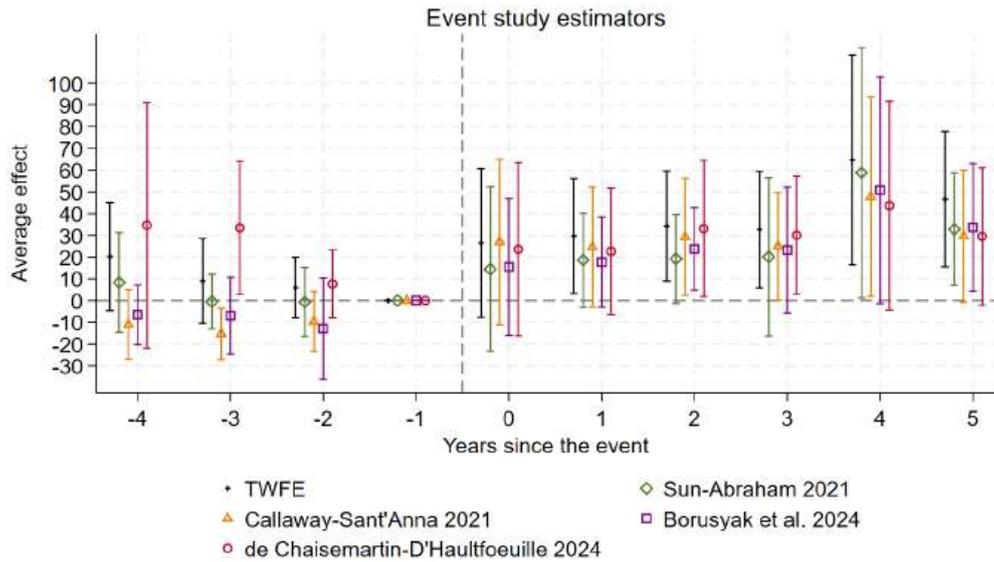
Vaccination rate adjusted for child mortality

Figure A46: Event-study plot: effect of phylloxera on vaccination rates adjusted for infant and child mortality within wine-intensive departments

Log of wine production

Vaccination rate

Figure A47: Event-study plot: effect of phylloxera on wine production and vaccination rate within wine-intensive departments. Never treated or not-yet treated as control groups

Notes: The event-study plot is built using the Callaway and Sant'Anna (2021) estimator. Orange markers correspond to estimations run with never treated departments as a control group, and green markers to not-yet treated ones as a control group. The treatment variable is full contamination by phylloxera. The time span of the data covers eight years before full infestation, and seven afterwards. The reference period considered is $\tau = -1$, one year before full contamination. The outcome variables are respectively the log of wine production and the vaccination rate. Wine production is measured in hectolitres and the vaccination rate is defined as the number of vaccinations per 100 births. Wine-intensive departments are defined as the departments in which wine production represented at least 15% of agricultural production in 1862. 95% confidence intervals are reported. Standard errors are clustered at the department level.
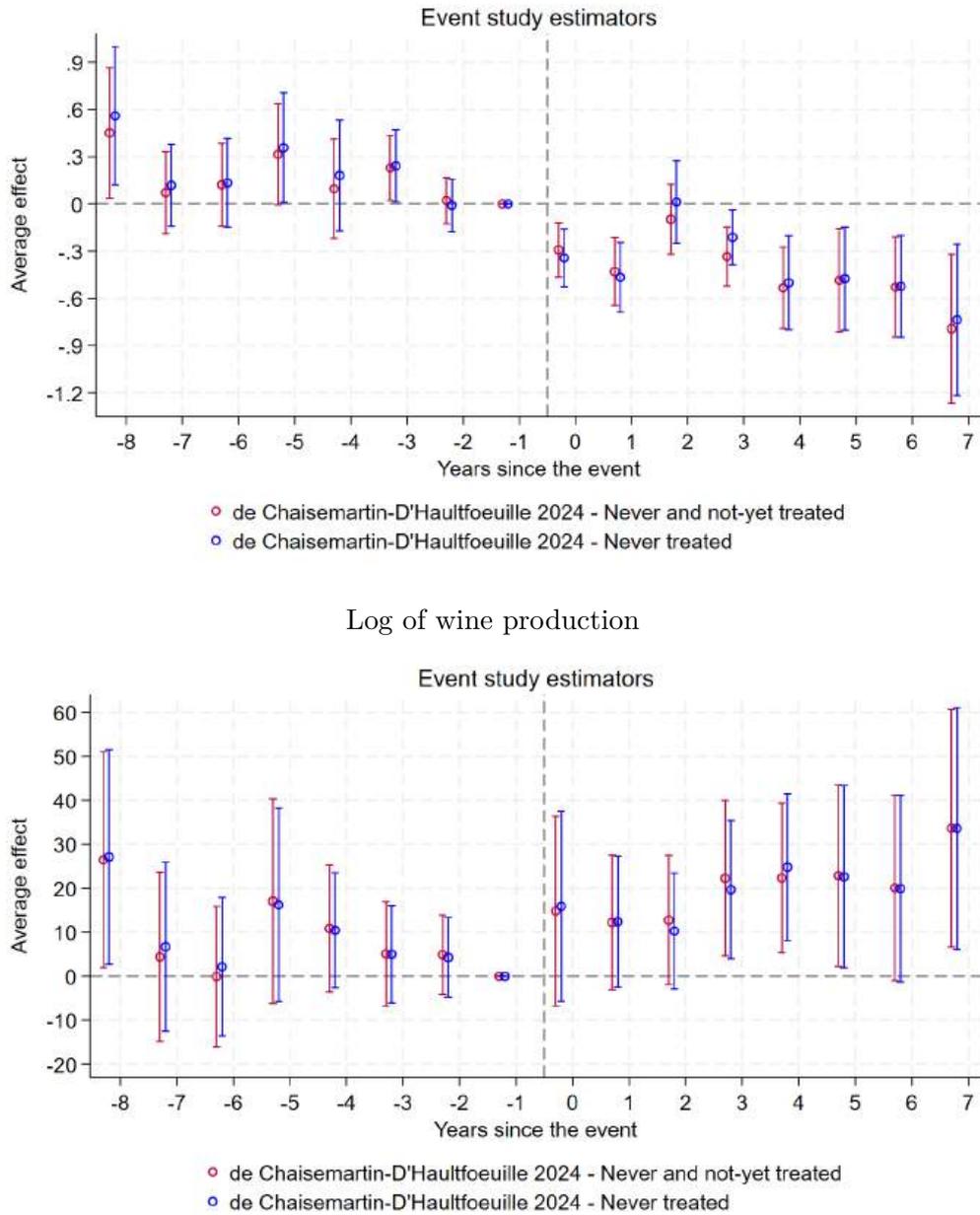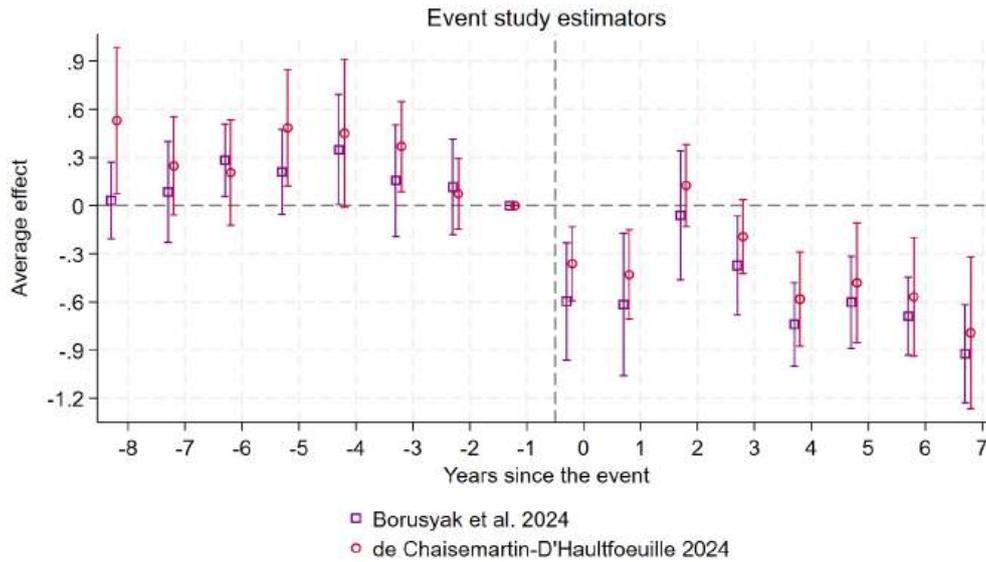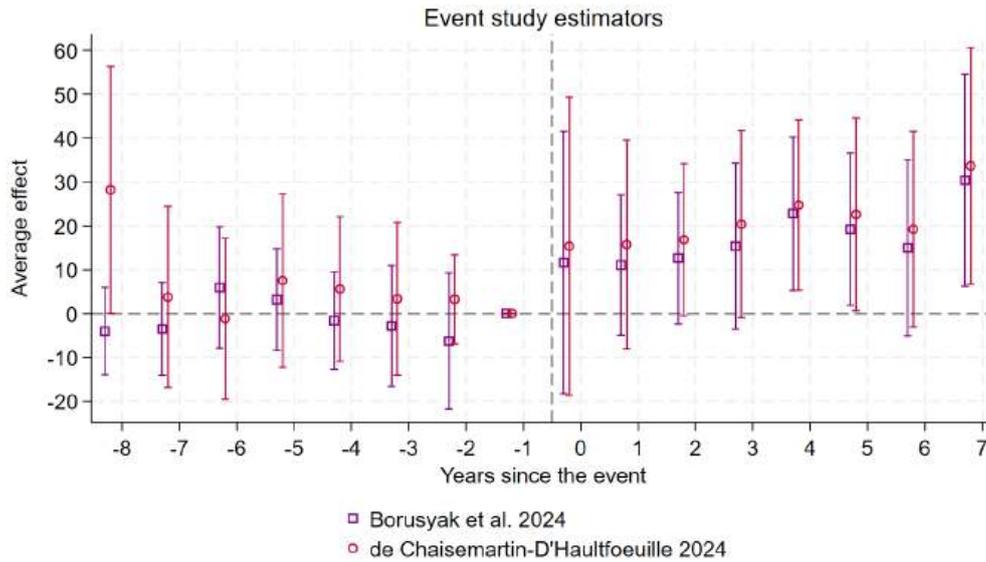
Log of wine production

Vaccination rate

Figure A48: Event-study plot: effect of phylloxera on wine production and vaccination rate within wine-intensive departments. Never treated or not-yet treated as control groups

Notes: The event-study plot is built using the de Chaisemartin and D'Haultfoeuille (2024) estimator. Red markers correspond to estimations run with never treated and not-yet departments as a control group, and blue markers to never treated ones as a control group. The treatment variable is full contamination by phylloxera. The time span of the data covers eight years before full infestation, and seven afterwards. The reference period considered is $\tau = -1$, one year before full contamination. The outcome variables are respectively the log of wine production and the vaccination rate. Wine production is measured in hectolitres and the vaccination rate is defined as the number of vaccinations per 100 births. Wine-intensive departments are defined as the departments in which wine production represented at least 15% of agricultural production in 1862. 95% confidence intervals are reported. Standard errors are clustered at the department level.

Log of wine production

Vaccination rate

Figure A49: Event-study plot: effect of phylloxera on wine production and vaccination rate within the balanced panel of wine-intensive departments.

Notes: The event-study plot is built using two different estimators: Borusyak, Jaravel, and Spiess (2024) (purple square markers) and de Chaisemartin and D'Haultfoeuille (2024) (pinkish-red circle markers). The treatment variable is full contamination by phylloxera. The time span of the data covers eight years before full infestation, and seven afterwards. The reference period considered is $\tau = -1$, one year before full contamination. The outcome variables are respectively the log of wine production and the vaccination rate. Wine production is measured in hectolitres and the vaccination rate is defined as the number of vaccinations per 100 births. Wine-intensive departments are defined as the departments in which wine production represented at least 15% of agricultural production in 1862. The estimations are conducted on a balanced panel of departments. 95% confidence intervals are reported. Standard errors are clustered at the department level.
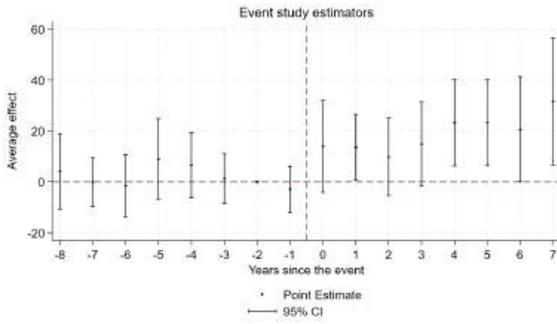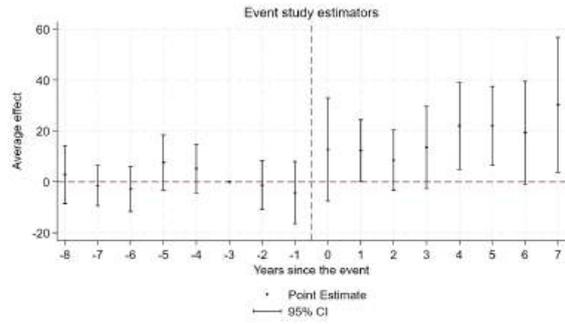
Baseline: $\tau = -2$ 　　　　 Baseline: $\tau = -3$
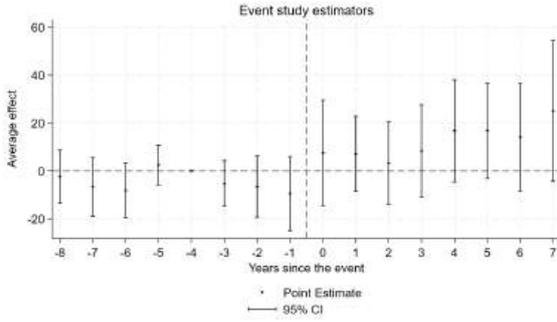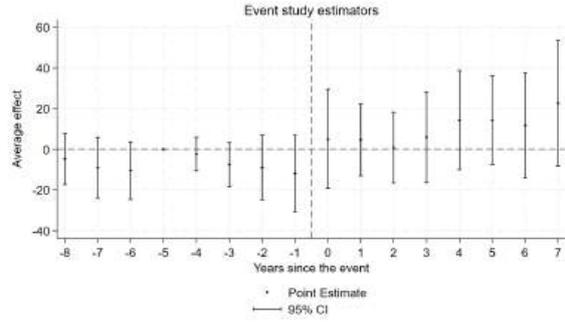
Baseline: $\tau = -4$ 　　　　 Baseline: $\tau = -5$
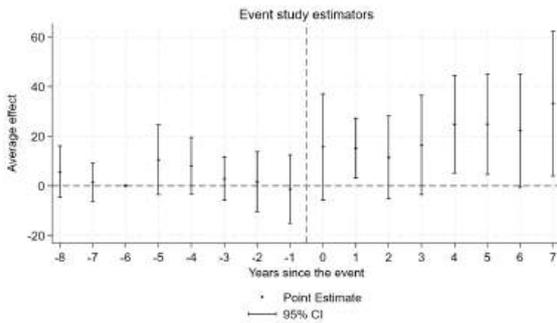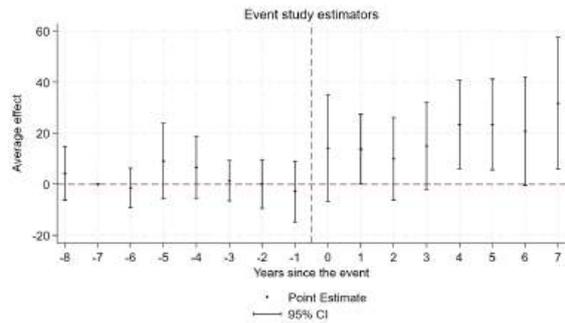
Baseline: $\tau = -6$ 　　　　 Baseline: $\tau = -7$

Figure A50: Event-study plot: effect of phylloxera on vaccination rates within wine-intensive departments

Notes: The event-study plot is built using a dynamic TWFE model. The treatment variable is full contamination by phylloxera. The time span of the data covers eight years before full infestation, and seven afterwards. The reference period considered is varying from $\tau = -2$, two years before full contamination, to $\tau = -7$, seven years before full contamination. The outcome variable is the vaccination rate, which is defined as the percentage of vaccinations over the number of births. Wine-intensive departments are defined as the departments in which wine production represented at least 15% of agricultural production in 1862. 95% confidence intervals are reported. Standard errors are clustered at the department level.

Table A22: Impact of phylloxera on wine production and vaccination against smallpox

	Log(Wine production)		Vaccination rate				
	Wine-intensive departments	Other departments	Wine-intensive departments	Other departments			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Phylloxera - full contamination	-0.482***	-0.011	17.544**	-13.187	-9.004	-12.763*	-8.724
	(0.131)	(0.197)	(7.097)	(9.132)	(7.447)	(7.250)	(8.177)
Phylloxera - full contamination*share of wine	–	–	–	–	0.415**	–	–
					(0.192)		
Phylloxera - full contamination*hectares of vine p.c	–	–	–	–	–	0.983**	–
						(0.406)	
Phylloxera - full contamination*importance of wine	–	–	–	–	–	–	0.696*
							(0.381)
Controls			X	X	X	X	X
Department fixed effects	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X
Observations	1275	1360	1181	1252	2433	2433	2433
R^2	0.733	0.867	0.540	0.410	0.451	0.455	0.451

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Wine production is measured in hectolitres. Vaccination rate is defined as the percentage of vaccinations over the number of births. A department is considered as fully contaminated by phylloxera when all the municipalities within this department are affected. Wine-intensive departments are defined as the departments in which wine production represented at least 15% of agricultural production in 1862. The share of wine corresponds to the share of wine in agricultural production in 1862. The hectares of vine are measured per 100 inhabitants in 1862 and the importance of wine is defined as the share of people employed in agriculture according to the 1861 census multiplied by the share of wine in agricultural production in 1862. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level.

Table A23: Impact of phylloxera on vaccination against smallpox. Vaccination rate accounting for infant and child mortality

	Vaccination rate			
	Wine-intensive departments	Other departments	Wine-intensive departments	Other departments
	(1)	(2)	(3)	(4)
Phylloxera - full contamination	25.027**	-14.501	30.854**	-69.323
	(9.742)	(8.948)	(12.981)	(50.179)
Controls			X	X
Department fixed effects	X	X	X	X
Year fixed effects	X	X	X	X
Observations	767	815	767	815
R^2	0.551	0.379	0.510	0.094

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Infant mortality is defined as the number of children from 0 to 1 year of age who die in year t. Child mortality is defined as the number of children from 0 to 5 years of age who die in year t. In columns (1) and (2), the vaccination rate is defined as the percentage of vaccinations over the number of births from which infant mortality has been subtracted. In columns (3) and (4), child mortality is subtracted from the number of births. A department is considered as fully contaminated by phylloxera when all the municipalities within this department are affected. Wine-intensive departments are defined as the departments in which wine production represented at least 15% of agricultural production in 1862. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level.

Table A24: Impact of phylloxera on vaccination against smallpox with department-specific trends

	Vaccination rate				
	Wine-intensive departments	Other departments			
	(1)	(2)	(3)	(4)	(5)
Phylloxera - full contamination	11.424**	-9.703	-6.774	-4.910	-7.817
	(4.891)	(6.605)	(5.603)	(5.706)	(6.049)
Phylloxera - full contamination*share of wine	–	–	0.349**	–	–
			(0.163)		
Phylloxera - full contamination*hectares of vine p.c	–	–	–	0.435	–
				(0.312)	
Phylloxera - full contamination*importance of wine	–	–	–	–	0.668**
					(0.333)
Controls	X	X	X	X	X
Department-specific trend	X	X	X	X	X
Department fixed effects	X	X	X	X	X
Year fixed effects	X	X	X	X	X
Observations	1181	1252	2433	2433	2433
R^2	0.682	0.514	0.587	0.586	0.587

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. A department is considered as fully contaminated by phylloxera when all the municipalities within this department are affected. Wine-intensive department are defined as the departments in which wine production represented at least 15% of agricultural production in 1862. The share of wine corresponds to the share of wine in agricultural production in 1862. The hectares of vine are measured per 100 inhabitants in 1862 and the importance of wine is defined as the share of people employed in agriculture according to the 1861 census multiplied by the share of wine in agricultural production in 1862. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level.

Table A25: Impact of phylloxera on vaccination against smallpox, 1863-1888

	Vaccination rate				
	Wine-intensive departments	Other departments			
	(1)	(2)	(3)	(4)	(5)
Phylloxera - full contamination	16.908***	-12.507	-9.477	-9.697	-9.262
	(5.447)	(9.080)	(7.236)	(6.989)	(7.847)
Phylloxera - full contamination*share of wine	–	–	0.432**	–	–
			(0.176)		
Phylloxera - full contamination*hectares of vine p.c	–	–	–	0.754**	–
				(0.348)	
Phylloxera - full contamination*importance of wine	–	–	–	–	0.723**
					(0.354)
Controls	X	X	X	X	X
Department fixed effects	X	X	X	X	X
Year fixed effects	X	X	X	X	X
Observations	771	835	1606	1606	1606
R^2	0.577	0.500	0.510	0.510	0.509

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. A department is considered as fully contaminated by phylloxera when all the municipalities within this department are affected. Wine-intensive department are defined as the departments in which wine production represented at least 15% of agricultural production in 1862. The share of wine corresponds to the share of wine in agricultural production in 1862. The hectares of vine are measured per 100 inhabitants in 1862 and the importance of wine is defined as the share of people employed in agriculture according to the 1861 census multiplied by the share of wine in agricultural production in 1862. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level.

Table A26: Impact of phylloxera on vaccination against smallpox. Alternative vaccination rate: number of births over two years

	Vaccination rate				
	Wine-intensive departments	Other departments			
	(1)	(2)	(3)	(4)	(5)
Phylloxera - full contamination	8.645**	-6.665	-4.724	-6.564*	-4.498
	(3.467)	(4.510)	(3.665)	(3.553)	(4.047)
Phylloxera - full contamination*share of wine	–	–	0.211**	–	–
			(0.095)		
Phylloxera - full contamination*hectares of vine p.c	–	–	–	0.496**	–
				(0.199)	
Phylloxera - full contamination*importance of wine	–	–	–	–	0.349*
					(0.190)
Controls	X	X	X	X	X
Department fixed effects	X	X	X	X	X
Year fixed effects	X	X	X	X	X
Observations	1181	1252	2433	2433	2433
R^2	0.544	0.416	0.457	0.461	0.456

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births in year t and $t-1$. A department is considered as fully contaminated by phylloxera when all the municipalities within this department are affected. Wine-intensive department are defined as the departments in which wine production represented at least 15% of agricultural production in 1862. The share of wine corresponds to the share of wine in agricultural production in 1862. The hectares of vine are measured per 100 inhabitants in 1862 and the importance of wine is defined as the share of people employed in agriculture according to the 1861 census multiplied by the share of wine in agricultural production in 1862. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level.

Table A27: Impact of phylloxera on vaccination against smallpox. Spline interpolation to construct the control variables

	Vaccination rate				
	Wine-intensive departments	Other departments			
	(1)	(2)	(3)	(4)	(5)
Phylloxera - full contamination	18.247**	-12.545	-7.645	-11.724	-7.372
	(7.439)	(8.867)	(7.346)	(7.157)	(8.096)
Phylloxera - full contamination*share of wine	–	–	0.395**	–	–
			(0.190)		
Phylloxera - full contamination*hectares of vine p.c	–	–	–	0.968**	–
				(0.411)	
Phylloxera - full contamination*importance of wine	–	–	–	–	0.661*
					(0.383)
Controls	X	X	X	X	X
Department fixed effects	X	X	X	X	X
Year fixed effects	X	X	X	X	X
Observations	1181	1252	2433	2433	2433
R^2	0.538	0.407	0.448	0.453	0.448

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. A department is considered as fully contaminated by phylloxera when all the municipalities within this department are affected. Wine-intensive department are defined as the departments in which wine production represented at least 15% of agricultural production in 1862. The share of wine corresponds to the share of wine in agricultural production in 1862. The hectares of vine are measured per 100 inhabitants in 1862 and the importance of wine is defined as the share of people employed in agriculture according to the 1861 census multiplied by the share of wine in agricultural production in 1862. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level.

Table A28: Impact of phylloxera on vaccination against smallpox - IV estimations on wine-intensive departments

												Vaccination rate
									Year $\geq$ 1863			
	OLS	IV	OLS	IV	OLS	IV	OLS	IV	OLS	IV	OLS	IV
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Log(Wine production)	-3.211**	-33.697*	-2.844	-30.238**	-3.176**	-19.045**	-3.121*	-23.856**	-4.730**	-29.081**	-4.766**	-29.490***
	(1.502)	(17.738)	(1.747)	(13.095)	(1.511)	(8.496)	(1.587)	(9.623)	(2.025)	(13.175)	(1.867)	(10.803)
Controls			X	X			X	X			X	X
Department-specific trend					X	X	X	X				
Department fixed effects	X	X	X	X	X	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X	X	X	X	X	X
Observations	1181	1181	1181	1181	1181	1181	1181	1181	771	771	771	771
R^2	0.507		0.526		0.672		0.681		0.545		0.567	
$F-stat$		13.547		18.104		28.157		19.731		19.708		15.252

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Vaccination rate is defined as the percentage of vaccinations over the number of births. Wine production is measured in hectolitres. A department is considered as fully contaminated by phylloxera when all the municipalities within this department are affected, which constitute the instrument used in the IV estimations. Wine-intensive departments are defined as the departments in which wine production represented at least 15% of agricultural production in 1862. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level.

F Transmission Channels

F.1 Data Sources for Eighteenth-Century Smallpox Deaths and Prices

For London, we collected information on mortality and the number of smallpox deaths from the London Bills of Mortality and Krylova and Earn (2020). These weekly mortality statistics were introduced at the end of the sixteenth century and report the number of burials and baptisms for London. From 1629 onwards, the cause of deaths is specified and five infectious diseases (tuberculosis, smallpox, measles, French pox, and plague) are identified from 1632. The quality of these reports has been criticised, especially the identification of the cause of deaths by the searchers of the dead. An abnormal high number of deaths was for example reported as being due to consumption (Rusnock, 2002). However, smallpox presents some characteristics that are easy to identify as the death always follows the very particular pustular rash covering the entire body. Smallpox is therefore considered with plague as one of the most reliable cause of deaths identified (Galloway, 1985). Figure A51 reports the number of smallpox deaths from the mid-seventeenth century to 1930. From these sources, we can measure the percentage of deaths attributable to smallpox from 1664. We stopped the collection in 1800, when vaccination started to spread in England. We matched this information with data on wheaten bread price taken from Mitchell and Deane (1962).

These authors also provide data on the price of wheat for the city of Eton, located 37 kms as the crow flies from Tower Bridge. Both series of prices are available for the same years than smallpox deaths. We also complement them with wheat prices for London over the period 1723-1793 from Granger and Elliott (1967).

For Edinburgh, the data on smallpox deaths are collected from Brunton (1990) for the period 1739-1776. The corresponding information for Copenhagen is collected from the *First Report of the Royal Commission Appointed to Inquire into the Subject of Vaccination (1889)* over the period 1751-1798. For these two cities, staple food prices are collected from Allen and Unger (2019).

We use Edwardes (1902) to obtain smallpox mortality in Berlin for the years 1758-1774 and 1784-1794. Prices for Berlin are coming from GESIS - Leibniz Institute for the Social Sciences (Statistisches Reichsamt, 2008).
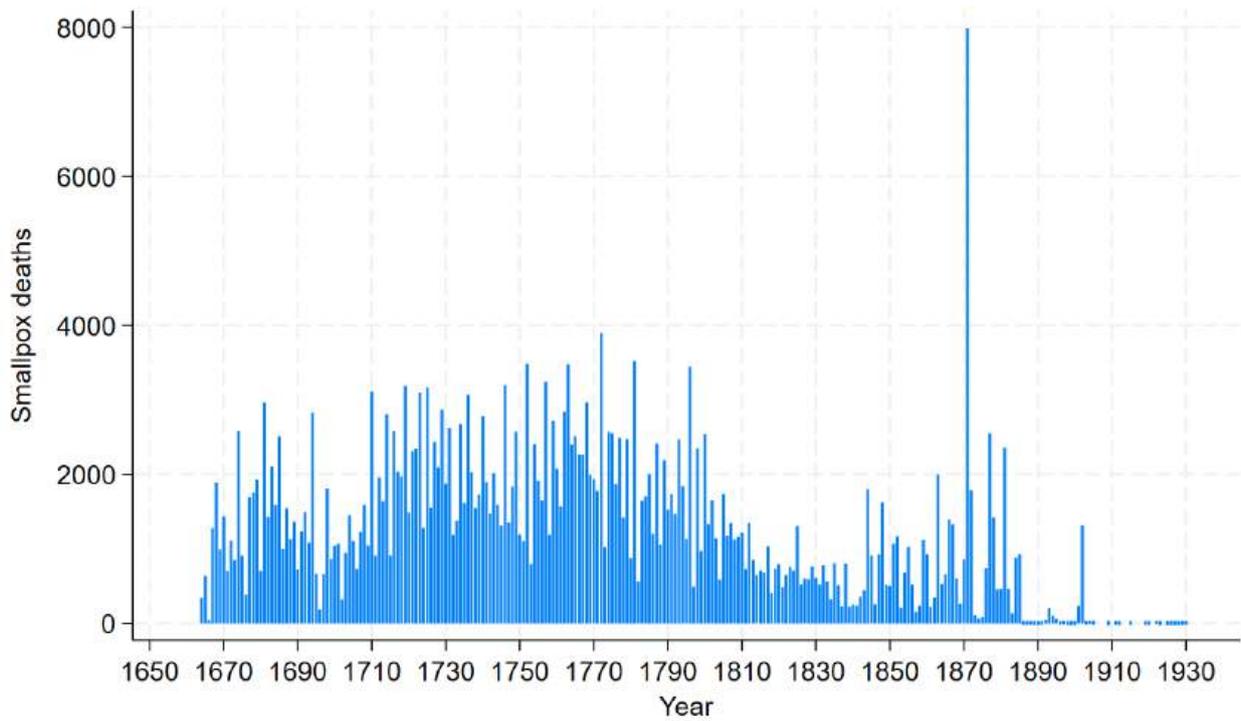
Figure A51: Annual number of smallpox deaths in London, 1661-1930

Source: (Krylova and Earn, 2020) and London Bills of mortality.

Note: The number of smallpox deaths is not divided by the population. From 1661 to 1930, the population of Inner London increased from 392,400 to 4,397,003 inhabitants.

F.2 Public Spending in Favour of Vaccination

There is historical evidence that authorities made payments to indigent populations in order to raise vaccination rates. Sarlangue (2022) provides the example of the second district of Paris which promised indigents a reward of 3 francs for each child vaccinated in 1848. The authorities of the district also threatened indigents to deny them the benefits provided by the local welfare offices if they didn't get their children vaccinated[47]. However, coercive measures remained marginal as it was never legal in France to deny social benefits to families because of a lack of diligence in vaccinating their children (Darmon, 1986).

From this historical evidence, one could imagine that, when negative income shocks struck, families more often used vaccination as an additional source of income within departments where financial rewards were associated with it. Local authorities might also have seized the opportunity created by negative shocks to implement these rewards and increase vaccination. If this is true, we should see an increase in the departments' funds allocated to vaccination when negative shocks took place.

For around half of the observations on vaccination, the national reports also specified the departments' budget allocated to vaccination. They spent on average 3,400 francs per year in favour of vaccination over the century, which corresponded to 78 francs per 10,000 inhabitants. This is extremely low as it represented only 0.13% of the amount of taxes collected by departments. The probability for departments' funding to have significantly influenced vaccination is therefore very small.

This is confirmed by the absence of any significant relationship between spending and vaccination during the nineteenth century (Figure A52). Using wheat prices or the phylloxera crisis also shows that there was no significant association between negative income shocks and the level of spending in favour of vaccination (Table A29 and Figure A53). The impact of shocks on vaccination was therefore not coming from a stronger intervention of departments and a higher opportunity cost of non-vaccinating children.

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[47]3 francs roughly corresponded to 150% of a male industrial worker daily wage at this time. The welfare offices, called *bureaux de bienfaisance*, were established in 1796 and provided relief and health services to the sick and the elderly. Each city could freely choose to establish an office, which were funded through donations.
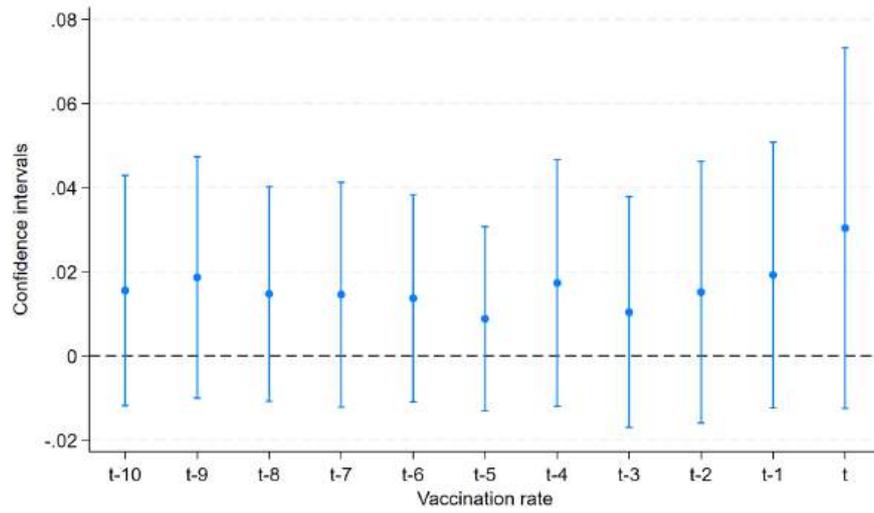
Figure A52: Effect of departments' spending in favour of vaccination on the vaccination rate

Note: The figure depicts OLS estimation coefficients of the effect of departments' spending in favour of vaccination from $t-10$ to t on the vaccination rate in t. Spending is measured in francs per 10,000 inhabitants. 95% confidence intervals are reported.

Table A29: Price of wheat and departments' spending in favour of the vaccination against smallpox

	Spending in favour of vaccination							
	OLS		IV: Rainfall$_{t-1}$		OLS		IV: Rainfall$_{t-1}$	
			Collected				Reconstructed	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Price of wheat	0.428	-0.330	-13.546	-14.148	0.127	0.170	3.716	3.916
	(1.334)	(1.252)	(11.775)	(11.322)	(0.720)	(0.746)	(8.855)	(7.398)
Controls		X		X		X		X
Department fixed effects	X	X	X	X	X	X	X	X
Year fixed effects	X	X	X	X	X	X	X	X
Observations	1275	1275	1275	1275	2584	2582	2584	2582
R^2	0.680	0.704			0.510	0.534		
$F-stat$			38.642	34.508			7.474	7.434

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Spending in favour of vaccination is measured in francs per 10,000 inhabitants. The price of wheat is computed in francs per hectolitre. Controls include: past vaccinations, population, population density, urban population, taxes per capita and literacy. Standard errors are clustered at the department level. In columns (1) and (2), the number of observations used in the OLS estimations is restricted to the sample used in the IV estimations, and for which rainfall data are available. Collected rainfall is computed as the total rainfall over the months July$_{t-2}$, August$_{t-2}$, September$_{t-2}$, March$_{t-1}$, April$_{t-1}$, May$_{t-1}$, June$_{t-1}$, July$_{t-1}$, August$_{t-1}$, and September$_{t-1}$. Reconstructed rainfall is measured as the total rainfall over the seasons Summer$_{t-2}$, Autumn$_{t-2}$, Spring$_{t-1}$, Summer$_{t-1}$ and Autumn$_{t-1}$.
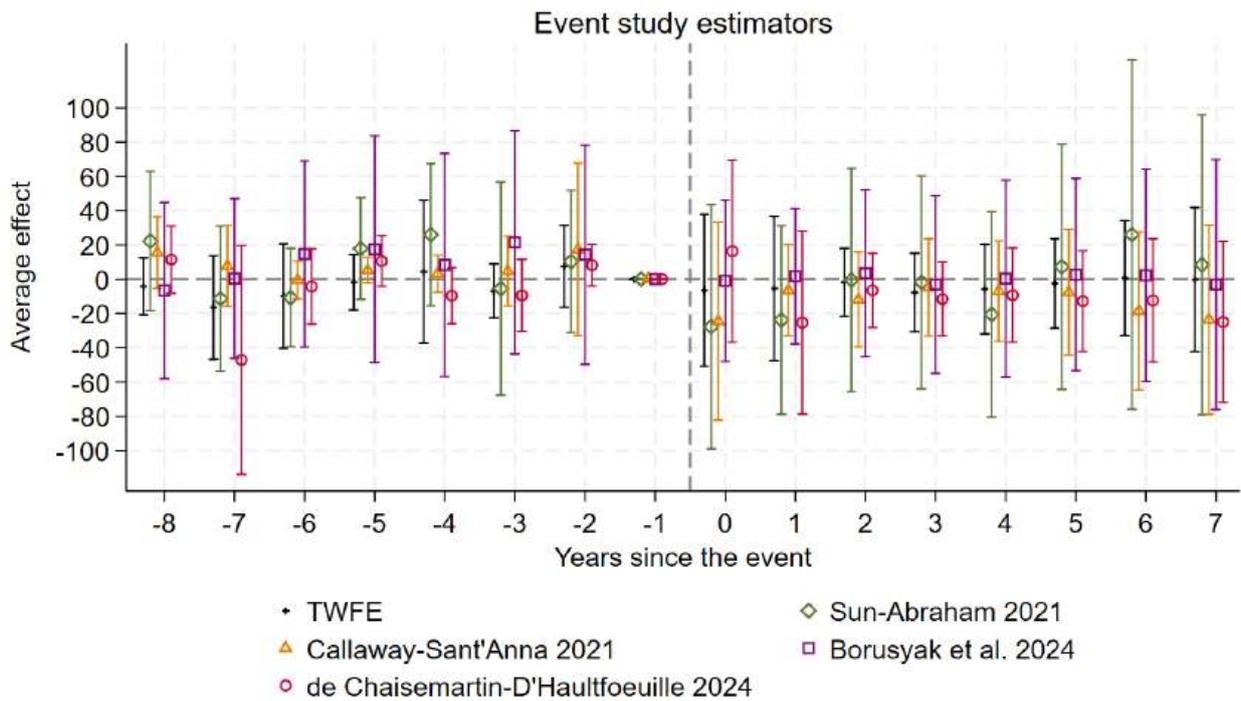
Figure A53: Event-study plot: effect of phylloxera on departments' spending in favour of vaccination against smallpox

Notes: The event-study plot is built using five different estimators: a dynamic TWFE model (black cross markers), Sun and Abraham (2021) (green diamond markers), Callaway and Sant'Anna (2021) (orange triangle markers), Borusyak, Jaravel, and Spiess (2024) (purple square markers) and de Chaisemartin and D'Haultfoeuille (2024) (pinkish-red circle markers). The treatment variable is full contamination by phylloxera. The time span of the data covers eight years before full infestation, and seven afterwards. The reference period considered is $\tau = -1$, one year before full contamination. The outcome variable is the amount of spending in favour of vaccination made by departments, which is measured in francs per 10,000 inhabitants. 95% confidence intervals are reported. Standard errors are clustered at the department level.

F.3 A Change in the Number of Hours Worked

At first sight, it seems unlikely that negative shocks impacted vaccination through a change in the number of hours worked. Indeed, negative income shocks should increase the need of people to find work and additional sources of income, which would increase the relative cost of taking time to have the children vaccinated. This would increase the opportunity cost of vaccination and reduce the vaccination rate.

However, this effect might also work in the opposite direction. Higher prices are indeed correlated with a lower production of cereals, and the phylloxera crisis was linked to a strong negative shock on wine production. In this context, it seems rational to imagine that the demand for agricultural workers would decline. This would leave people with more time to get their children vaccinated and therefore decrease the opportunity cost of vaccination associated with travel time and the reduction in the number of hours worked.

It seems impossible to know what the net effect would be, and if the positive impact on vaccination would dominate. It is in any case hard to believe that the positive effect would be high enough to compensate for the negative one and explain the very strong positive impact of income shocks on vaccination. This idea is reinforced by the fact that, using the data from the Agricultural Survey of 1852 in Figure A54, we don't find any correlation between the price of wheat and the total number of hours worked by agricultural workers. We are only able to study this correlation for one year, and we would ideally like to see if within-department variations in prices were related to changes in the hours worked. But it is a good indication that agricultural workers were not granted with more free time when production was lower[48].
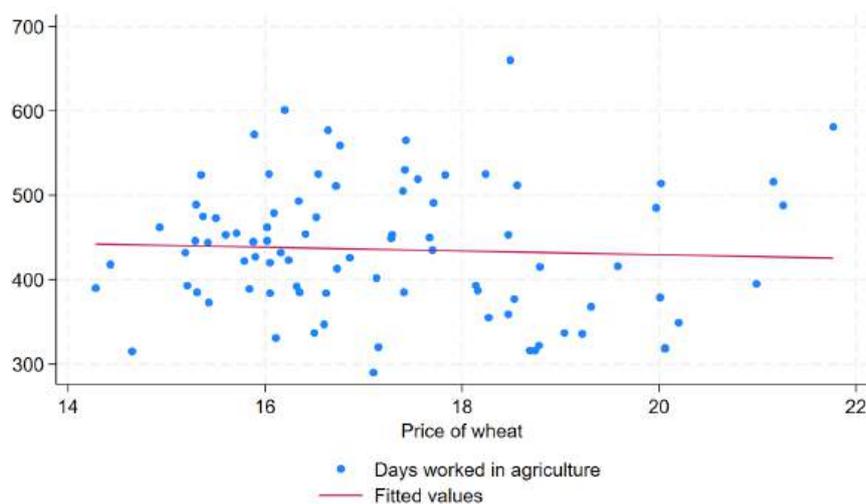

Figure A54: Price of wheat and number of days worked in the agricultural sector (1852)

Note: The number of days worked in agriculture corresponds to the sum of the number of days worked by men, women and children in the agricultural sector in 1852.

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[48]It is also hard to believe that a sufficiently high amount of agricultural workers could face a reduction in the number of hours worked so easily, and that they would first vaccinate their children rather than looking for work.

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