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# Labor scarcity, technology adoption and innovation: evidence from the cholera pandemics in 19th century France

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**Abstract**
To analyze the impact of labor scarcity on technology adoption and innovation, this study uses the differential spread of cholera across France in 1832, 1849 and 1854, before the transmission mode of this disease was understood. The results suggest that a larger share of cholera deaths in the population, which can be causally linked to summer temperature levels, had a positive and significant short-run effect on technology adoption and innovation in agriculture but a negative and significant short-run impact on technology adoption in industry. These results can be explained by the positive impact of labor scarcity on human capital formation.

**Keywords** Epidemics · Labor scarcity · Technology adoption · Technology-skill complementarity

**JEL Classification** I15 · N13 · O33

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This article is dedicated to the memory of Yariv Welzman.

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## 1 Introduction

To explain technology adoption, theoretical studies have developed the macroeconomic implications of production factors which can be either complementary or substitute (see, e.g., Aghion & Howitt, 1992; Zeira, 1998; Howitt, 1999; Acemoglu, 2007; 2010; Alesina et al., 2018). If labor and technology are complementary factors of production, then labor scarcity, whereby skilled and/or unskilled workers are needed to operate machinery, is detrimental to technology adoption.[1] If they are substitute, then labor scarcity leads to high wages and is conducive to technology adoption. However, there are only a few empirical analyses for the effects of labor scarcity on technology adoption because obtaining a quasi-experimental framework that could provide causal evidence has turned out to be challenging.

This study makes use of data about the cholera pandemics in 1832, 1849 and 1854 across France to provide reduced form estimates for the effect of labor scarcity on technology adoption and innovation.[2] In so doing, it asks the following questions: (i) is labor scarcity conducive to technology adoption in agriculture and in industry or not, i.e., are production factors in agriculture and in industry complementary or substitute? (ii) is labor scarcity conducive to technological innovation? and (iii) is labor scarcity conducive to technology adoption and innovation in both the short-run and the mid-to long-run?

19th century France appears well suited for such an empirical analysis. First, the country was hit harshly by the cholera epidemics: it lost 102,739 individuals in 1832, 102,500 in 1849 and 142,749 in 1854, i.e., about 1% of the population died over 22 years.[3] However some areas were hit more intensely than others. For instance, the department of Ariège in the South-West of France lost 4.2% of its population during the 1854 pandemic. Second, it was one of the first countries to experience the industrial revolution. Third, the French territory had been divided in small administrative divisions of nearly equal size in 1790 and thus, before the spread of cholera. During the period under study, there were 85 departments which were subdivided into 357 arrondissements: the average size of departments was 6,228 km$^2$ while that of arrondissements was 1966 km$^2$.

In the course of the 19th century, scientists offered competing theories on the spread of cholera and its cure. Although English physician John Snow had already published his first findings in 1849, it was only in 1855 with the second edition of his book that he conclusively demonstrated the role of contaminated water in the spread of the disease (Snow, 1855). And while Italian scientist Filippo Pacini had isolated the Vibrio Cholerae Bacterium in 1854, it was only in 1884 that German scientist Robert Koch would identify the Vibrio Cholerae Bacterium as the source of the disease and subsequently provide a treatment (Koch, 1884). Scientists have, by now, identified the different modes of transmission of cholera (Glass & Black, 1992). In particular, for a country like France whose weather

[1] Several studies (e.g., Kremer, 1993; Ashraf & Galor, 2011) noted that historically, technological innovation occurred in densely-populated areas.

[2] This paper thus differs from studies which use CES and/or Cobb–Douglas production functions to assess the rate of substitution between labor and technology. In this literature (e.g., Knoblach & Stöckl, 2019, for a recent survey), specific assumptions on estimation equations and technology dynamics have a substantial impact on the estimated parameters. We do not attempt to reproduce our main reduced form regression results with a CES production function given the specificities of our data as we discuss below.

[3] To put these figures in perspective, estimates suggest that the Spanish flu in France killed about 0.61% of the population after WWI (238,000 out of 39,108,000 inhabitants) while the Covid-19 pandemic had killed 0.19% by 31 December 2021 (123,805 out of 66,314,842 inhabitants) (Ansart et al., 2009)

is not warm throughout the year, cholera is particularly prone to transmission in the summer and specifically, in regions which are humid. In such an environment, transmission is often possible because the Vibrio cholerae bacterium can survive for six to seven weeks on dry clothes which were previously damp and sweaty. In fact, because the basic rules of microbe transmission and social distancing were unknown at the time, cholera was often spread during funeral wakes when mourners would touch the body of the dead and his/her dry clothes, thereby leading to the mistaken belief that the disease spread through airborne "miasmas".

But even if the spread of cholera before 1855 was not understood and could not be prevented, it is possible to conjecture in hindsight that the diffusion of the pandemics was correlated with local characteristics. While our empirical strategy controls for time-invariant characteristics with fixed effects, it might be the case that cholera spread more easily in areas near rivers where population density increased between 1832 and 1854. Moreover, the relationship between labor scarcity and technology adoption may ultimately reflect the potential effect of institutional, geographical, and cultural characteristics on the joint evolution of the labor supply and technological progress. Given the potential endogeneity in the relationship between labor scarcity and technology, and in light of the historical evidence linking summer temperature levels and humidity to the spread of cholera in France (Delaporte, 1986; Bourdelais & Raulot, 1987), this paper uses the historical weather data of Luterbacher et al. (2004), Luterbacher et al. (2006) and Pauling et al. (2006) to establish the causal impact of the cholera on technology adoption. The empirical analysis shows that summer temperatures in 1832, 1849 and 1854 have a causal impact in the local intensity of cholera deaths in the population of each department. This finding is robust to using Acemoglu et al. (2020)'s maximum likelihood strategy that accounts for interpolation concerns in the measurement of temperature across geographic units. More generally, our results are robust to falsification tests showing that the share of cholera deaths cannot be explained by other seasonal temperature and rainfall levels in other years as well as to pre-trends tests for observable demographic and economic characteristics.

The results establish that in the short-run, a larger share of cholera deaths in the population had a positive and significant effect on technology adoption and innovation in agriculture but a negative and significant impact on technology adoption in industry. As such, our results suggest that labor and capital are substitute factors of production in agriculture and complementary in the industrial sector, in line with recent studies on the impact of labor scarcity that rely on policy variations in migration (e.g., Abramitzky et al., 2023; San, 2023). However our findings indicate that the effects of the cholera pandemics on technology adoption and innovation were quantitatively limited.[4] A department experiencing a median loss in population because of the cholera epidemics (0.057%) would have adopted 0.28 additional mechanized ploughs per day laborer over the following years but would have had 3.68 fewer steam-powered machines per worker in the year after each epidemic. These results are robust to accounting for spatial autocorrelation using Colella et al. (2020)'s approach as well as for heterogeneous treatment effects using the two-way fixed effects estimators of de Chaisemartin and D'Haultfoeuille (2020).

[4] It is possible that pandemics only have a major economic effect on economies when the death toll reaches a high threshold, e.g., when one third of the population died during the Black Death in the Middle Ages. However, since the 19th century, no pandemic in countries out of the Malthusian trap has killed that many people. The public policy implications of our results therefore call for a careful approach as the economic consequences of pandemics may not be as disruptive as one would think.

Moreover, our study suggests that the positive impact of labor scarcity on human capital accumulation can explain our main results. As population loss increased the expected returns to literacy and literate workers were sought out in industrial work (e.g., Katz & Margo, 2014; Atack et al., 2019; Franck & Galor, 2022), the rise in the share of literacy workers in the population offset the immediate negative effect of the population losses on technology adoption in industry. In parallel, this increase in literate workers, who would most likely avoid low-paying work in agriculture, fostered agricultural mechanization. Additional regressions show that this human capital channel for our results is robust to accounting for migration, urbanization, a cultural shift as proxied by a change in religiosity, fertility and nuptiality patterns as well as local financial intermediation.

This study is related to three strands of the economics literature but seeks to provide a different perspective. First, it is related to research on pandemics, income shocks and economic growth (e.g., Chakraborty et al., 2010; Adda, 2016; Rasul, 2020; Albanesi & Kim, 2021). Pandemics could spur growth by increasing available resources to surviving individuals, especially for economies at the Malthusian stage of development (Lagerlöf, 2003; Young, 2005; Siuda & Sunde, 2021).[5] However, it is difficult to ascertain the impact of pandemics for countries out of the Malthusian trap: while Ambrus et al. (2020) find a long-term impact of the 1854 cholera pandemic on poverty within London, studies on the 1918–1920 Spanish flu (e.g., Barro et al., 2020; Jordà et al., 2020; Lin & Meissner, 2020) concur that it had short-term negative effects but differ as to its actual long-run persistence.

Second, this paper is related to research seeking to explain technology adoption during the industrial revolution in the 19th century (e.g., Mokyr, 2009; Akcigit et al., 2017; Juhász, 2018; Caprettini & Voth, 2020; Franck & Galor, 2022). Research starting with Habakukk (1962) has argued that labor scarcity, and the ensuing high wages, led to the adoption of machinery. It is however unclear whether high wages in England and the USA actually stemmed from the relative abundance of coal or land, or from the presence of skilled workers with high levels of productivity(see, e.g., Kelly et al., 2014; Stephenson, 2018). Relatedly, the recent study of Voth et al. (2022) uses exogeneous local variation in gender imbalance triggered by mass conscription in England during the Revolutionary and Napoleonic wars, and finds that this type of labor scarcity fostered technology adoption in the early phase of the industrial revolution.

Third, this study is related to research assessing the impact of labor market conditions on the adoption of labor-saving technology: these include Acemoglu and Finkelstein (2008) on healthcare, Manuelli and Seshadri (2014) and Hornbeck and Naidu (2014) on agriculture, Lewis (2011) on manufacturing, Acemoglu and Restrepo (2022) on the link between demographic factors and technology adoption as well as Dechezleprêtre et al. (2019) on the effects of labor costs on automation.[6] In this respect, most of the recent literature on labor scarcity takes advantage of changes in migratory policies in the short- and mid-run (e.g., Moser et al., 2014; Clemens et al., 2018; Abramitzky et al., 2023; San, 2023). This study however seeks to give a different perspective by providing causal evidence over a 50-year period for the effects of labor scarcity caused by a disease whose transmission mode was then not understood and which had no cure.

[5] The Black Death in Western Europe seems to have been conducive to growth in the long-run but its effects were different in Eastern Europe (e.g., Voigtländer & Voth, 2013; Jedwab et al., 2019).

[6] Other studies dealing with the relative scarcity of production factors on technological adoption include Newell et al. (1999) and Hassler et al. (2021) on the rise of energy prices and scarce natural resources as well as Hanlon (2015) on cotton.

The remainder of this article is as follows. Section 2 presents the data and Sect. 3 the empirical strategy. Section 4 discusses the main results. Section 5 shows that the increase in human capital explains our main results and establishes that alternative mechanisms do not provide convincing explanations. Section 6 concludes.

## 2 Data

The dataset comprises information on the 85 departments and 357 arrondissements in mainland France, as well as on individuals living across the country, during and after the 1832, 1849 and 1854 cholera pandemics.[7] As we note below, information is sometimes missing for some outcome variables immediately after 1832 and in those instances, we are therefore compelled to restrict the sample to the aftermath of the 1849 and 1854 pandemics. Table A.1 reports the descriptive statistics for the variables in the empirical analysis across the departments and arrondissements as well as for the variables used in the individual-level analysis. Tables A.2 and A.3 provide descriptive statistics for the additional variables employed in falsification tests and robustness analyses.

### 2.1 Cholera outbreaks

#### 2.1.1 Cholera transmission channels

Cholera is a waterborne disease which is most vibrant between 15 and 25 Celsius degrees. But if drinking contaminated water remains the most well-known mode of catching the disease because of Snow (1855)'s seminal study, modern research (Glass & Black, 1992) has demonstrated that there are several transmission channels for the cholera. The bacterium can indeed survive and adapt to different environments so that it is not only observed in populated located maritime areas, rivers and lakes, but also in dry areas, notably in Africa (Stock, 1976; Cliff et al., 1986).

Transmission modes of the disease other than contaminated water include contaminated food, fomites (inanimate objects such as clothes that have been exposed to the infection) as well as person-to-person transmission. All these transmission channels interact with one another under various weather conditions to spread the disease. In fact, in the 19th century, transmission was very common along travel routes as well as during funeral wakes when mourners touched the body and the clothes of the dead. This is possible because the cholera bacterium can remain alive during six to seven weeks on dry clothes which were contaminated when they were damp and sweaty.

Furthermore, the recurrent seasonal pattern has also been shown to differ across various areas of the world. For instance, in the 320 km-long Cheaseapeake Bay on the US east coast, it has been observed that warmer summer temperatures entail a resurgence of the cholera and that the bacterium is more prevalent in the north of the Bay (where temperatures are slightly lower than in the south) because of the difference in the salinity and

[7] The analysis is restricted to mainland France and excludes Corsica where no death from cholera was recorded in 1832 and 1849, and where there were only 220 cholera deaths out of 236,251 inhabitants in 1854 (0.09% of the population). Moreover, three new departments (Alpes-Maritimes, Haute-Savoie and Savoie) were added to France in 1860. Since they were not part of France during the 1832, 1849 and 1854 pandemics, they are excluded from the analysis.

humidity levels (Colwell, 2004; St.Laurent et al., 2021). As we discuss in the next section, this is a similar pattern to the incidence of cholera in $19^{th}$ c. France, whereby cholera was more prevalent in the north than in the south during the summer.

### 2.1.2 Cholera in 19th century France

To build the main explanatory variable on the intensity of cholera outbreaks in 1832, 1849 and 1854, the study uses the official statistics provided by the French government on the share of cholera deaths within the population of each department (France, 1862). As can be seen in Fig. 1, the three cholera pandemics mainly affected the north of France and the Atlantic Coast. The south of France was only hit harshly in 1854.[8] Only 11 departments located in the hinterland south-west of the French territory were spared in the three cholera outbreaks (Cantal, Corrèze, Creuse, Dordogne, Gers, Landes, Lot, Lozère, Hautes-Pyrénées, Vienne and Haute-Vienne).

Here two remarks are important. First it must be noted that before 1855, the transmission mode of the cholera had not been conclusively established. At a time where basic knowledge about microbes was just being discovered, some scientists were mistakenly arguing that there were airborne "miasmas"which explained the diffusion of the disease. As such, avoiding polluted water sources, as well as proper hygiene and social distancing, did not play a role in the behavior of individuals: since no-one knew how the disease spread, it was not even clear that running away from areas affected by the cholera could offer any protection.[9] Second, the disease was a problem for the central State, the local governmental authorities, the Church as well as the local associations. However there was no health policy which any government or organization could implement to stop the disease.

As can be seen in Table 1, the distribution of cholera deaths within the population of each department is skewed: the 25th percentile is equal to 0, the median 0.057%, the 75th percentile 0.30% and the 99th percentile 2.84%. This reflects the fact that the disease reached most departments at least once in either 1832, 1849 and 1854, but only a few were hit harshly. Nonetheless, 20 departments lost more than 1% of their population in at least one of the three outbreaks.

Tables B.1 and B.2 provide additional descriptive statistics and tests regarding the share of cholera deaths in the population. Table B.1 distinguishes between the gender and age of the victims during the 1854 pandemic while Table B.2 focuses on the share of victims by distinguishing departments by their mean and median population in each of the three pandemics.

The tests of means reported in both Tables B.1 and B.2 are never significant, thereby alleviating concerns that some sections of the population would be more (or less) likely to die from exposure to the cholera. In particular, the tests in Table B.1 suggest that our results cannot be driven by the gender and/or age of the cholera victims within the population of the departments hit by the cholera while those in Table B.2 indicate that they cannot be driven by the size of the departmental population and hence by the propensity of the

[8] Anecdotal evidence suggests that each time, the cholera came by boat from England. It only spread to the south-east of France in 1854 because of the French soldiers who embarked from the southern harbors of Toulon and Marseille to fight the war in Crimea.

[9] The French population soon came to refer to the cholera as the "blue fear"(peur bleue) because of the blue coloration that the faces of sick individuals would take just before dying. The expression "peur bleue"is still commonly used in French and refers to something which is terrifying.

victims to inhabit urban or rural departments. The results are not surprising and in line with the discussion in the previous sub-section that person-to-person transmission was a major cause of the spread of the cholera in the 19th century, and was as common as contamination through polluted water. It is therefore not surprising that the prevalence of the cholera is not related to population density and social status.

It is worth noting that there were additional cholera outbreaks in 19th century France, i.e., in 1884 and 1892. However, they occurred after 1855, when the transmission mode of the cholera had been finally established by Snow (1855). As a result, it is preferable to restrict the main analysis to the pre-1855 cholera outbreaks: this avoids endogeneity concerns that specific areas might become more efficient than others in preventing the spread of the disease once the mode of contagion was known. In this respect, we show in Table B.3 that the spread of cholera before 1855 was not correlated with its spread in 1884 and 1892 whose consequences were more limited because local authorities then understood and could prevent the diffusion of the disease. Table B.4 further shows that the 1832, 1849 and 1854 cholera pandemics were not correlated with the various causes of deaths in each department in 1855. Moreover, Table B.5 shows that the cholera pandemics in 1832, 1849 and 1854 are not correlated with the spread of illnesses before the 19th century insofar as there is no correlation with the number of towns hit by the spread of the plague in the 18th c. in each department.

### 2.2 Summer temperature in 19th century France

As established by modern research (e.g., Glass & Black, 1992), the Vibrio Cholerae Bacterium quickly spreads in humid environments where temperatures are above 15 degrees Celsius. This implies two predictions for the diffusion of cholera in France. First, cholera mainly spreads during the summer because this is the season when temperatures in France are above 15 degrees Celsius for a long time period. Second, cholera is more likely to spread in the North than in the South of France because relative humidity is always higher in northern areas where temperatures are always relatively lower. While this second point might seem slightly counter-intuitive to the reader because humans feel humidity more accurately (and hence experience more discomfort) at higher levels of temperature, it is actually the case that relatively lower temperatures entail more relative humidity because they enable for less water evaporation (Wallace & Hobbs, 1977; Lutgens & Tarbuck, 2015). In the case of France, the regression results in Table C.1 use modern weather data from 42 weather stations in 2018 and establish that lower temperatures are indeed associated with higher relative humidity, accounting for weather station fixed effects as well as month-, day- and hour- fixed effects.[10]

Given the properties of the Vibrio Cholerae Bacterium and the historical context, our identification strategy predicts that (1) temperatures in the summer of 1832, 1849 and 1854, and not in any other season or in any other year, are significantly correlated with the spread of cholera because this is the only time period where temperatures remain above

[10] The negative correlation between temperature and relative humidity is not specific to France. For instance, (2019, Table 1) report that in China, where temperatures in the North are lower than in the South, there is a negative correlation between mean temperature and relative humidity throughout the year that is only significant at the 5% level during the summer. For the sake of the argument, it should also be noted that the Sahara desert is located to the South of the Mediterranean sea and that this desertic area is dryer than the coastal Mediterranean areas of North Africa.

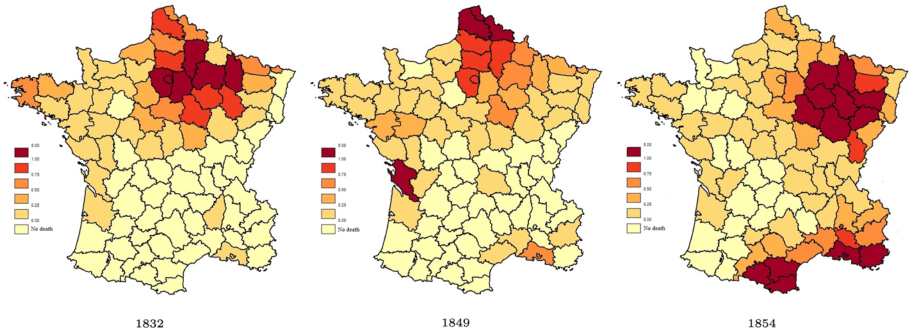


**Fig. 1** Share of cholera deaths out of departmental population, 1832, 1849 and 1854. *Note* The source of the map layer is Daudin et al. (2019).

**Table 1** The distribution of the percentage of cholera deaths in the population across French departments in 1832, 1849 and 1854

| | Mean | $25^{th}$ | $50^{th}$ | $75^{th}$ | $90^{th}$ | $99^{th}$ |
|---|---|---|---|---|---|---|
| 1832 | 0.26 | 0 | 0.01 | 0.26 | 0.86 | 2.35 |
| 1849 | 0.20 | 0 | 0.02 | 0.22 | 0.88 | 1.70 |
| 1854 | 0.46 | 0.009 | 0.16 | 0.61 | 1.36 | 4.20 |
| All Years Combined | 0.31 | 0 | 0.06 | 0.30 | 0.90 | 2.84 |

This table reports descriptive statistics for the percentage of cholera deaths in the population across the 85 French departments in 1832, 1849 and 1854. The total French population amounted to 32,443,430 inhabitants in 1832, 36,910,360 in 1849 and 35,782,708 in 1854.

15 degrees Celsius and that (2) summer temperature levels in 1832, 1849 and 1854 would be negatively correlated with the spread of cholera because northern French departments experienced relatively lower temperatures, and hence more relative humidity, than southern departments. Anecdotal evidence on the monthly spread of cholera in 1854 seems to support this prediction: Fig. 2 shows that the disease spread from the north of the country and claimed the highest number of victims in July, August and September.[11]

Our study relies on the historical weather data of Luterbacher et al. (2004), Luterbacher et al. (2006) and Pauling et al. (2006). These data were reconstructed using various sources such as lake sediments and tree rings as well as historical records for every season over the 1500–1900 period at a resolution of 0.5 by 0.5 decimal degrees. There are therefore concerns about measurement error and the interpolation of climatic data over departments, i.e., two cells per department on average. Still Luterbacher et al. (2004), Luterbacher et al. (2006) and Pauling et al. (2006) show that the quality of the data improve over time, especially from the end of the $18^{th}$ c. onward. Figure 3 maps those data for the summers of

[11] More generally, it must be that acknowledged that water bodies could have increased the transmission of the cholera. However, since the empirical strategy which we discuss in Sect. 3 uses department fixed effects, it is unlikely that water bodies can systematically explain variations in the spread of the cholera in 1832, 1849 and 1854.

1832, 1849 and 1854 and shows that temperature levels were relatively lower in the north than in the south of France during each of those summers.

It is worth noting that summer temperatures in 1832, 1849 and 1854 were rather mild. As the descriptive statistics in Table B.6 indicate, the average summer temperatures in 1832, 1849 and 1854 were around 17C, ranging from 13.3C to 21.7C. In other words, as we show in the robustness checks in the Appendix and in particular in Table D.4, summer temperature levels, but not summer temperature shocks, explain the local spread of cholera.

### 2.3 Measures of technology adoption and human capital

#### 2.3.1 Technology adoption, wages and production in agriculture and industry

This study relies on the governmental surveys of agriculture carried out in 1852 and 1862 (France, Ministère de l'agriculture du commerce et des travaux publics, 1852, 1862).[12] They provide department-level information on the number of agricultural day laborers and their wages, as well as agricultural tools and cereal production (millet, oats, rye and wheat). It is worth noting that, in line with the historical evidence (e.g., Agulhon et al., 2003), the descriptive statistics in Table A.1 show that there were more mechanized ploughs than day laborers: the average number of mechanized ploughs per day laborer in our sample is 2.80, with a standard deviation of 3.17. This is because the majority of landowners in 19th century France were small farmers who were themselves engaging in agricultural work and who would only hire day laborers during the harvest season.[13]

Furthermore, the empirical analysis takes advantage of the data on the French mining industry in the successive volumes of the *Statistique des Mines*: this official governmental publication provides information on the types of machines, the production of coal and peat, as well as the number and wages of workers working inside the mines. While the department-level data in the *Statistique des Mines* are restricted to one industrial sector, they are available every year from the late 1830s onwards and pertain to an industry which had used steam engines since the 18th c. (Woronoff, 1994). These data thus enable a refined analysis of the short- and long-run effects of labor scarcity on technology adoption.

In addition, the study uses the governmental surveys of the French industries which were carried out in 1839–47 and 1860–65 at the arrondissement level. For firms in the textile sector, which was the other leading industrial sector in 19th century France, they provide information on water-powered, wind-powered and steam-powered machines as well as on wages and workers. A drawback of these surveys is their lack of consistency which prevents us from using them in a panel data setting: the 1839–47 survey reports data on the number of machines while the 1860–65 reports data on the horse power of machines.

A potential concern for our analysis is that the prices of tools in agriculture and industry would be different, thereby driving mechanization in one sector at the expense of the other. Anecdotal evidence (Désert, 1984, p. 206) suggests that both industrial and agricultural

[12] Some of the data in the agricultural surveys might not be entirely accurate, as is usually the case in surveys carried out in the 19*th* century. Still, nothing suggests that the data were purposefully misreported. See Désert (1984) for a discussion on the reliability of these surveys.

[13] It is beyond the scope of the article to discuss why there were few large landowners and many small farmers in 19th century France. French historiography still debates whether 18th c. France was already characterized by the presence of small landowners or whether the policies of the 1789 French revolutionaries led to the dismemberment of many large land estates (see, e.g., Bodinier & Teyssier, 2000).

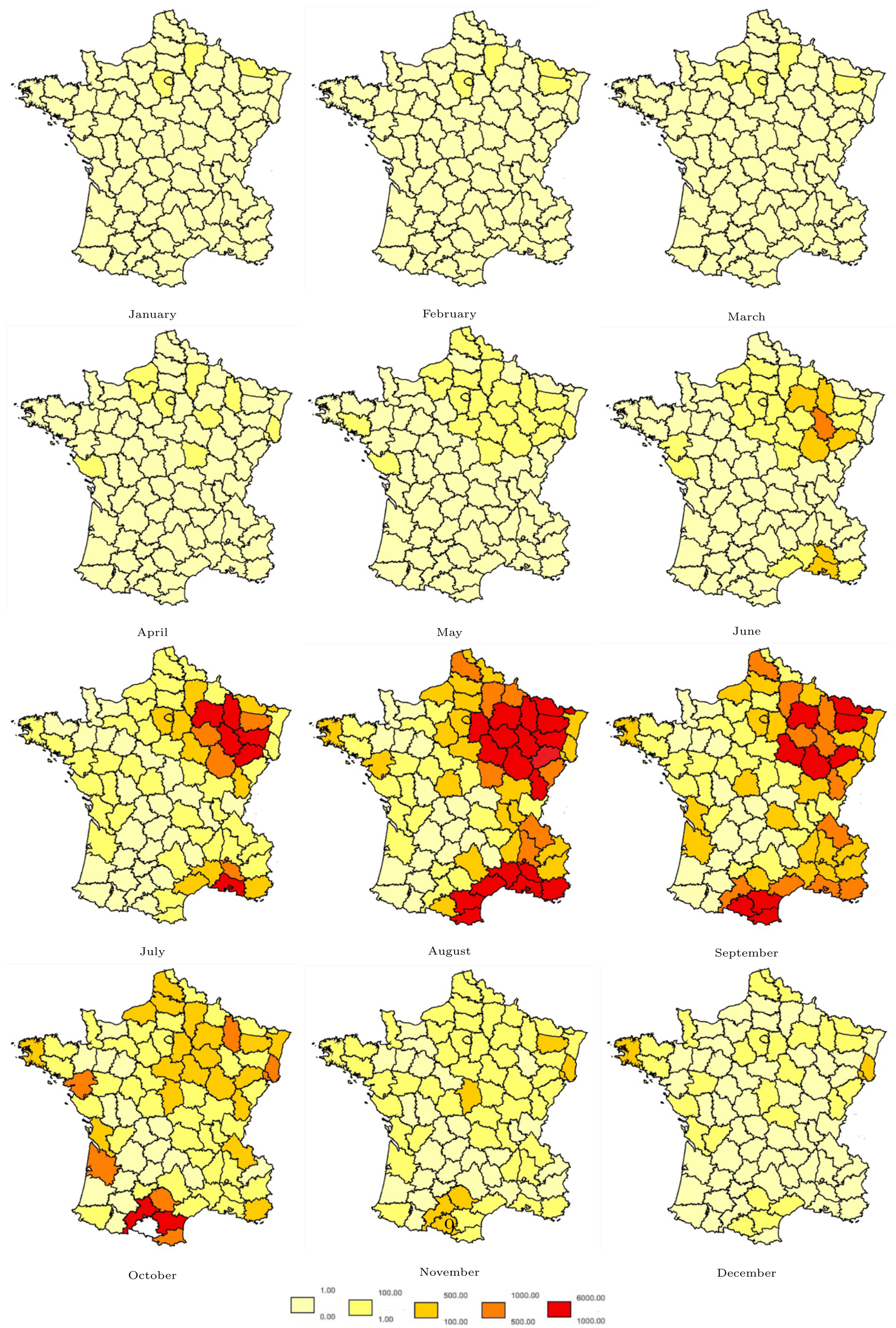


**Fig. 2** Cholera deaths: January–December 1854

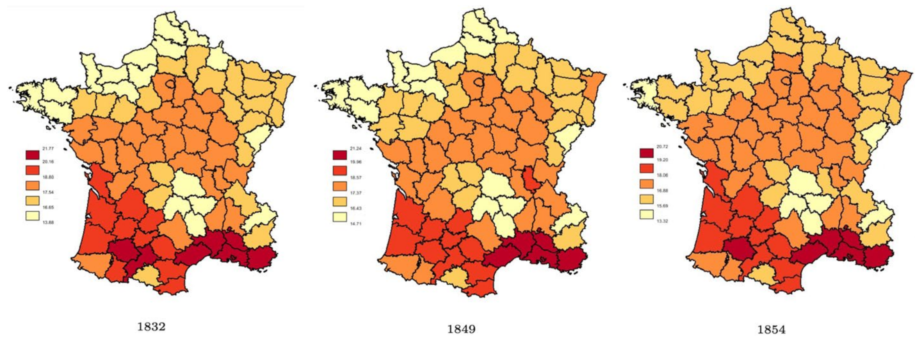


**Fig. 3** Summer temperature, 1832, 1849 and 1854

tools were expensive during our sample period and were either bought by a rich entrepreneur and/or landlord, or by a cooperative of small farmers.[14] In any case, to assuage concerns regarding the prices of machinery in agriculture and industry, we run in Table B.7 a test of means on the prices and tariffs levied on imports of steam-powered engines, other industrial machines as well as scythes (a basic agricultural tool) over the 1827–1856 period. The p-values of the tests show no difference between the value of those imported goods, suggesting that price differences could not have constrained French producers to invest in agriculture or in industry.

### 2.3.2 Technological innovation

To test the hypothesis that labor scarcity spurred technological innovation, this study takes advantage of the data on patents from the French Institute for Intellectual Property (Institut National de la Propriété Intellectuelle) which was established in 1791. Since the patent documents provide the purpose of the invention as well as the location of the inventor, it is possible to determine whether local labor scarcity triggered more innovation. Furthermore, the patents are listed in 20 categories shown in Table 2, thus enabling us to examine which sectors of the French economy spearheaded innovation in the wake of the cholera pandemics.[15] As an illustration, Fig. 4 shows two density plots over the 5-year bin following each pandemic for all patents and for hydraulic agricultural patents. It shows that there was innovation is all departments, but there was more innovation in some departements.

### 2.3.3 Human capital: literacy and schooling

The empirical analysis explores potential channels which could have fostered technology adoption in the aftermath of each cholera outbreak. Human capital could be such a

[14] For instance, in the 1830s–1850s, French-made water pumps used in factories in the Seine department cost between 400 and 2400 francs while in the Normandie region, threshing machines cost between 500 to 1600 francs (Brocchi, 1834; Désert, 1984; Dupré, 1993). For the sake of comparison, the average daily wage of an agricultural day laborer in our sample is 1.81 francs.

[15] The categories at used at face value beause it is probably best not to try to reconstruct and impose some modern categories on the patents filled out by inventors in mid-19th century France. Table A.4 provides the original names of each category for the French-speaking reader.

channel, especially in light of recent studies which highlight the complementarity between education and technological change during the 19th century (e.g., Katz & Margo, 2014; Atack et al., 2019; Franck & Galor, 2022).

For this purpose, the empirical analysis uses individual data from the *Enquête des 3000 familles* (Survey of the 3000 Families, Bourdieu et al. (2014)). This survey follows during the 19th century men and women from families whose last name starts by the three letters TRA. It provides information on their ability to sign their wedding licenses, as opposed to mark it with a cross, as well as on their birth year and birth department.[16] It also provides this same information for their spouses (whose last name does not start with these three letters).[17] Furthermore, in additional tests, we use the data of the *Enquête des 3000 familles* to assess the impact of the cholera on the age at marriage and on inheritance value.

Moreover, the empirical analysis relies on governmental data on the departmental shares of literate individuals among the French army conscripts, i.e., 20-year old men reporting for military service in the area where their father lived (France - Ministère de la Guerre, 1839–1937). These yearly data are not subject to selection bias because every Frenchman had to report for military service, although changes in conscription rules meant that every man did not eventually serve during the 19th century (Crépin, 2009).

The empirical analysis also uses various measures of formal education at the department level from the *Statistique Générale de la France*. These data pertain to primary school attendance as well as to spending on primary schooling by the three tiers of the French government (communes, departments and the central State). They also provide information on courses for male and female adults and apprentices, as well as public spending on these courses for men (the data on public spending for the courses for women are not available in the time frame of our study). These courses for adults and apprentices can be thought of as the 19th century equivalent of workers' retraining classes insofar as they sought to provide basic technical knowledge and literacy skills (Marchand, 2005).

### 2.4 Characteristics of departments

The empirical analysis controls for the characteristics of departments that may be correlated with the adoption of new technology. These time-varying characteristics might actually be viewed as "bad controls"in the terminology of Angrist and Pischke (2008) as they could be correlated with the spread of cholera and the adoption of new technology.

First, we use Bazot (2014)'s data on the GDP per capita of each department. These data are reconstructed from official documents and provide a measure of local income. Specifically, we employ Bazot (2014)'s GDP estimates for 1850 and 1860 to respectively account for the effects of the 1849 and 1854 pandemics.

Second, we control for the possibility that summer rainfall shocks might have contributed to the diffusion of the cholera since this disease spreads in humid environments. For this purpose, we use the historical weather data of Luterbacher et al. (2004), Luterbacher et al. (2006) and Pauling et al. (2006) to define a measure of seasonal rainfall shocks $R_{s,d,t}$ in season $s$ in department $d$ in year $t$ such that $R_{s,d,t} \equiv (\mu_{s,d,t} - \mu_{s,d})/\sigma_{s,d}$

16 Arguably, signing a wedding license provides a lower bound on literacy. It does not fully assess the ability to read and write.

17 There might be concerns with respect to this dataset and its representativeness of the whole French population in the 19th century. However Abramitzky et al. (2011) show that it is representative of nuptiality patterns while Daudin et al. (2019) find it to map accurately the patterns of internal migration.

**Table 2** Categories of patents

| | | | |
|---|---|---|---|
| 1 | Agriculture, milling, bakery, viticulture | 2 | Agricultural hydraulics, watercourses, irrigations, artesian wells |
| 3 | Railways, steam engines, engines | 4 | Textile materials |
| 5 | Machines and tools | 6 | Navigation |
| 7 | Constructions, carpentry | 8 | Metallurgy, mining |
| 9 | Hardware, plumbing, locksmith, cutlery | 10 | Bodywork, carpentry, saddler, harness, brushwork |
| 11 | Artillery | 12 | Precision instruments, watchmaking, physics, surgery |
| 13 | Ceramic, brickyard, glass works | 14 | Chemical products and food substances |
| 15 | Lighting and heating | 16 | Clothing |
| 17 | Fine arts, music, engraving, painting, lithography, typography | 18 | Paper, Binding, Parisian Articles and Stationery |
| 19 | Leather and skins | 20 | Miscellaneous items |

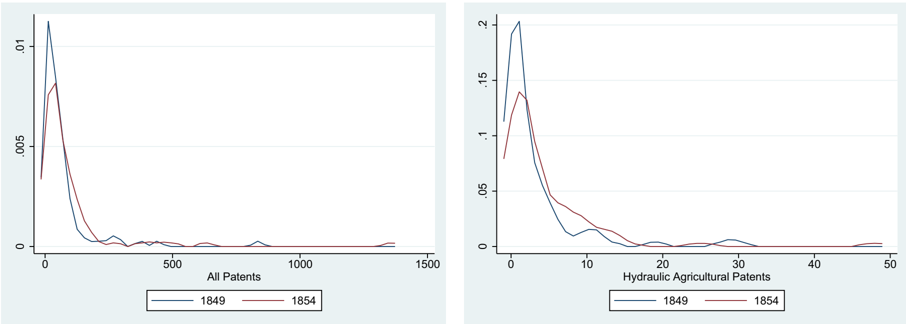


**Fig. 4** All patents and hydraulic patents in the five years after the 1849 and 1854 Cholera Pandemics. *Note* This figure shows density plots for all patents and hydraulic agricultural patents in the five years following the 1849 and 1854 cholera pandemics. Since the Seine department concentrates half of the patents, it is not shown in the graph, although it is included in all the regressions

where the average rainfall $\mu_{s,d,t}$ is standardized by mean $\mu_{s,d}$ and standard deviation $\sigma_{s,d}$ of rainfall in each department. This one-sided deviation of rainfall as a control allows for the possibility that high levels of rainfall can have an effect on the adoption of technology as well as a significant effect on the share of cholera deaths. In what follows, both $\mu_{s,d}$ and $\sigma_{s,d}$ are computed over the 25-year period before each pandemic but additional regressions available upon request show that our results are also robust to using 10-, 15- and 20-year periods before each pandemic.

Finally, as discussed in detail below, the empirical strategy relies on a panel data approach with fixed effects that account for the time-invariant characteristics of the administrative areas. It is however possible that some time-invariant characteristics might have a different impact over time, especially if they are correlated with technology adoption. For this purpose, our empirical analysis includes interaction variables between year-fixed effects and specific geographic variables whose impact might have changed over time. These are the administrative areas' share of carboniferous area (Fernihough & O'Rourke, 2021), their land suitability (Ramankutty et al., 2002) as well as dummies indicating their location on the border with a foreign country and on the seashore.

## 3 Empirical strategy

The empirical analysis examines whether areas which lost a large share of their population during cholera outbreaks, and where consequently, labor scarcity became more acute, experienced greater adoption of labor-saving technology in the agricultural and industrial sectors. A priori, it is unclear whether production factors in agriculture and industry are complementary or substitute. It is also unclear what the dominant effect of labor scarcity on wages and production is in a general equilibrium framework. On the one hand, labor scarcity increases wages, and so does the adoption of machines which increases the productivity of workers. On the other hand, the adoption of machines could also lower wages. Furthermore, if production factors are complementary, labor scarcity would decrease production. However if production factors are substitute, then technology adoption is a cost-cutting measure: producers may choose to increase production, but may also produce the same quantity at a lower cost, or may even decrease production if demand has declined.

### 3.1 Empirical model

The empirical specification can be presented in two stages and estimated with 2SLS. The second stage can be written as

$$Y_{it} = \alpha_i + \alpha_t + \beta_1 C_{it} + \beta_2 \boldsymbol{X'_{it}} + u_{it}, \tag{1}$$

where $Y_{it}$ is one of our measures of technology adoption and innovation in administrative area $i$ in year $t$, $C_{it}$ is the share of deaths caused by the cholera pandemics within the population of administrative area $i$ in year $t$, $\boldsymbol{X'_{it}}$ is a vector of geographical and economic characteristics of administrative area $i$ in year $t$, $\alpha_i$ and $\alpha_t$ are administrative-area- and year-fixed effects while $u_{it}$ is an i.i.d. error term for administrative area $i$ in year $t$.[18]

In the first stage, $C_{it}$ is instrumented by $T_{it}$, which represents summer temperature levels in administrative area $i$ in year $t$

$$C_{it} = \gamma_i + \gamma_t + \delta_1 T_{it} + \delta_2 \boldsymbol{X'_{it}} + v_{it}, \tag{2}$$

where $\boldsymbol{X'_i}$ is the same vector of geographical and economic characteristics of administrative area $i$ in year $t$ used in Eq. 1, $\gamma_i$ and $\gamma_t$ are administrative area- and year-fixed effects while $v_{it}$ is an i.i.d. error term for administrative area $i$ in year $t$.

[18] In the empirical analysis, we use the log share of cholera deaths. Since some departments were spared from the pandemics, using the variables in log implies that 1 is added to the value x of the share of cholera deaths. Namely, all values are computed as log(1+x).

## 3.2 Summer temperatures and cholera deaths in the population: first-stage regression results and tests for pre-trends

### 3.2.1 First-stage regression results

In line with the historical evidence on the spread of cholera in 19th century France, where the disease mainly hit northern departments during the summers of 1832, 1849 and 1854, Table 3 shows that the summer temperature instrument has a negative and significant effect on the share of cholera deaths in the population (the complete specifications with the control variables are shown in Table D.1). In all the specifications using robust clustered standard errors at the department level, this negative effect is significant at the 1% level. To ensure the robustness of our results, we also compute the standard errors with the maximum likelihood estimation strategy of Acemoglu et al. (2020) that corrects for measurement error and geographic correlation in rainfall measurement. These standard errors are reported in curly brackets in Table 3: they confirm the significant and negative effect of summer temperature on the share of cholera deaths in the population.

The estimate in Column 1 of Table 3 suggests that a 1% decrease in summer temperature levels increased the share of cholera deaths in the population by 11.8%. Hence, for a department experiencing a decrease in temperature from the 75th percentile of summer temperature (18.10 degrees Celsius) to the 50th percentile (i.e., 17.38 degree Celsius), this 4.03% decrease in temperature would entail 0.6% more in the share of cholera deaths in the population, i.e., a decline equal to one standard deviation. Thus, in line with the historical evidence, these computations suggest that the successive cholera pandemics entailed a substantial loss of population.

### 3.2.2 Falsification tests and robustness checks for pre-trends

To enhance the credibility of our identification strategy, we present several falsification tests and robustness checks for pre-trends. They show that neither summer temperatures nor cholera deaths are correlated with potentially omitted variables pertaining to the pre-existing characteristics of the departments that could drive their vulnerability to the cholera epidemics and their subsequent adoption of technology.

Note that we already discussed the following robustness checks in Sect. 2: (i) Tables B.1 and B.2 show that all population groups (distinguished by age or gender, urban or rural) were equally affected by the cholera; (ii) Tables B.3 and B.4 show that the numbers of victims in the 1832, 1849 and 1854 cholera pandemics were not correlated with the numbers of victims from various causes of death in each department in 1855 or with the numbers of victims in the minor cholera outbreaks in 1884 and 1892 (which occurred after the transmission mode of the disease was understood); (iii) Table B.5 shows that the diffusion of cholera pandemics in 1832, 1849 and 1854 is not correlated with the number of towns hit in each department by the spread of the plague in the $18^{th}$ century and (iv) Table B.7 shows that there are no significant differences in the prices of imported machinery in agriculture and industry that could potentially drive the results.

**Table 3** Summer temperature levels and share of cholera deaths in the population

| | (1) | (2) | (3) |
|---|---|---|---|
| First stage: the instrumented variable is Share of Cholera Deaths in Population | | | |
| Summer temperature | −0.118*** | −0.141*** | −0.140*** |
| | [0.0271] | [0.0303] | [0.0308] |
| | {0.044}*** | {0.058}** | {0.061}** |
| Mean dep.var | 0.0031 | 0.0031 | 0.0031 |
| 1st stage F-stat | 19.012 | 21.652 | 20.788 |
| Moran I | −0.008 | −0.008 | −0.008 |
| Moran I $p$-value | 0.212 | 0.209 | 0.210 |
| Department and year fixed effects | Yes | Yes | Yes |
| Deviation from summer rainfall | No | Yes | Yes |
| Geographic controls * year fixed effects | No | Yes | Yes |
| GDP per capita | No | No | Yes |
| Clusters | 85 | 85 | 85 |
| Observations | 255 | 255 | 255 |

This table reports the first stage estimates relating summer temperature levels to the share of cholera deaths in the population in 1832, 1849 and 1854. Geographic controls for departments, which are interacted with year-fixed effects, include their land suitability, their share of carboniferous area and dummies for border and maritime departments. Constant not reported. All variables are in logarithm. Robust standard errors clustered at the department level are reported in brackets. Robust standard errors clustered at the departement level using the Maximum Likelihood approach of Acemoglu et al. (2020) are reported in curly brackets. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

In what follows, we summarize the additional falsification tests which we carry out in support of our identification strategy. In the Appendix, we present the data sources and report the regression results.

*Cholera, temperatures and rainfall*. Because weather data are correlated over time, a potential concern regarding the identification strategy is that the significant effect of summer temperature levels on cholera deaths in the year of each pandemic can be attributed to the general effect of summer temperatures in other years, and is correlated with temperatures in other seasons and with rainfall. Reassuringly, the share of cholera deaths is not correlated with summer temperatures in the years just before or after the cholera outbreaks in Table D.2. Moreover, in the years of cholera outbreaks, the share of cholera deaths in the population is not correlated with temperatures in spring, fall and winter in Table D.3,[19] with summer temperature shocks in Table D.4 and with rainfall in spring, fall and winter in Table D.5.[20] In Table D.5 however, summer rainfall is significantly correlated with the

[19] As can be seen in Table D.3, there are specifications where temperatures in other seasons are sometimes significantly, but not systematically, correlated with the spread of the cholera. In other words, they may not indicate a significant impact on the spread of the cholera so much as a temporal correlation with summer temperatures. Thus these regressions suggest that it is best to use summer temperature as the sole instrument, which is significant throughout, instead of cherry-picking the data and use different seasonal temperatures in different regressions.

[20] The results in Table D.4 provide support for the validity of the exclusion restriction: different temperatures explain the differential impact of the pandemics across the French departments, but they were not outliers and therefore were unlikely to impact other variables, most notably agricultural yields. In Sect. 4

spread of the cholera in the first stage regressions, although its effect is quantitatively small. Since summer rainfall is not systematically significant in many 2nd stage and reduced form regressions, it seems that its limited impact is captured by summer temperature.

Furthermore, Table D.6 shows that there is a statistically significant relationship between summer temperatures in 1832, 1849 and 1854 in log and level, and the share of cholera deaths in 1832, 1849 and 1854, but not between the latter and squared summer temperatures in level (which gives equal weight to abnormal rainfall and droughts) in those years. Finally Table D.7 shows that there is a statistically significant relationship between summer temperatures in 1832, 1849 and 1854 in log and level, and the share of cholera deaths in 1832, 1849 and 1854, but not a systematically significant relationship between the latter and seasonal rainfall, even when the interaction variables between summer temperatures and seasonal rainfall are included.

*Pre-pandemic trade and industry*. A potential concern regarding the exogeneity of the relationship between summer temperature and cholera deaths pertains to trade and industry. In particular, it is possible that the transport of goods within France, and the associated circulation of people, would be correlated with weather conditions and would have an impact on the spread of the pandemic. Reassuringly, both Tables D.8 and D.9 show that there is no relationship between internal trade and temperature as well as between internal trade and the spread of cholera.

In addition, Table D.10 shows that summer temperature and technology adoption in industry were not correlated before the first cholera pandemic in 1832. Namely, in 1789, 1811 and 1815, summer temperatures had no significant impact on the numbers of iron forges and mechanical mills in the cotton industry.

*Entry points and diffusion hubs* It is possible that the local share of cholera deaths could be correlated with the initial point of entry of the disease or with a specific hub of diffusion such as a major city. Unfortunately, no-one knows with absolute certainty what the disease's points of entry were. Each time, the cholera most likely came from England. At best, it can be said that the first cases of cholera were noticed in the Manche department in 1832, in the Aisne department in 1849 and in the Nord department in 1854. The Manche and Nord departments are located on the English Channel but the Aisne department is a landlocked area, making it even less likely to determine the point of entry in 1849 (Bourdelais & Raulot, 1987; France - Ministère de l'agriculture, 1862). Table D.11 tests the hypothesis that the intensity of the cholera pandemics would be correlated with London or with potential points of entry and diffusion hubs such as Paris, harbors like Rouen and Marseille, or Fresnes-sur-Escaut, the mining village in the Nord department where the first steam engine was used for industrial purposes in France in the 18th century. The results show that the distance between each of these hubs and the main administrative center of each department has no impact on the significant effect of summer temperature on the local share of cholera deaths in 1832, 1849 and 1854.

*Pre-pandemic characteristics of the population*. Table D.12 shows that the first stage relationship is not influenced by omitted variables linking summer temperatures and the number of deaths in each department over time. Furthermore, Tables D.13 and D.14 show that summer temperatures and cholera deaths were not correlated with the number and

Footnote 20 (continued)

below, we provide evidence for the lack of a persistent impact of the pandemics on agricultural yields and land rents.

density of inhabitants as well as with the age structure of each department prior to the 1832, 1849 and 1854 cholera pandemics.[21]

*Pre-pandemic human capital and wealth*. It could be conjectured that the share of cholera deaths in the population was correlated with the relative presence of poor/rich individuals or of educated/uneducated individuals. While there is no historical evidence suggesting that the cholera victims were characterized by specific social statuses or income levels, Tables D.15, D.16, D.17 are meant to assuage concerns regarding a possible link between cholera deaths, education and wealth.

Thus, in line with the historical evidence, Table D.15 shows that the cholera claimed victims among different occupational groups, whether rich (e.g., shipowners), poor (e.g., tenant farmers) or educated (e.g., clergymen, professors & teachers).[22] Furthermore, Table D.16 shows that there is no significant relationship between the share of cholera deaths in the population, the probability that the dead left an inheritance as well as the value of the inheritance. Finally, Table D.17 shows that the cholera pandemics were not correlated with human capital as proxied by the likelihood that individuals born one to 20 years before each pandemic could sign their wedding license (as opposed to mark it with a cross).

## 4 Results: Short-term effects on technology adoption and innovation

This section explores the effect of the cholera pandemics on technology adoption and innovation in agriculture and industry. The regression results in Tables 4, 5, 6 and 7 suggest that the cholera epidemics had short-term and quantitatively small effects on technology adoption and innovation (Appendix E reports the regression results with the full set of controls). These effects were conducive to technology adoption in agriculture but not in the industrial sector. In addition, the results suggest that the cholera epidemics entailed labor reallocation from the agricultural to the industrial sectors. They also indicate that the negative effects of labor scarcity lasted longer in the textile sector than in the industrial sector. The results are robust to the inclusion of control variables, including GDP per capita, thereby making it unlikely that they are driven by short-term negative income effects.

In our results, our IV estimates for the effect of the cholera epidemics on technology adoption are two to three times larger than the OLS coefficients. A possible interpretation of these findings is that our regressions suffer from errors in variables and attenuation bias: while there is no evidence that the local civil servants who collected data on the number of cholera deaths sought to minimize or inflate the impact of the epidemics, some might have collected data more diligently than others. Another explanation is that our IV estimates reflect the expectations of individuals regarding the consequences of the cholera

[21] The regression in Column 1 of Table D.13 has one fewer observation than the other regressions (254 instead of 255) because the Tarn-et-Garonne department was only created in 1808. Its future territory was split between neighbouring departments (mostly Lot and Haute-Garonne). We chose not to adjust the GDP per capita for these departments for this falsification test because it is unclear how we would account for the exact income differences between the various areas of Lot and Haute-Garonne.

[22] The size of the coefficients in Table D.15 is not the same for all occupations. However, it is probably best not to provide an interpretation for the size of the coefficients. It is possible to speculate that textile workers were more negatively affected than blacksmiths or professors because their sector entailed more trade and interaction. However, the coefficient regressions also suggest that transport workers and members of the clergy were less affected by the cholera in 1854 than textile workers, even though they also interacted with many sections of the population.

**Table 4** The effects of the cholera in 1849 and 1854 on the Number and horse power of machines per worker in the mining industry one year after each pandemic

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| | OLS | OLS | OLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS |
| | Average number of steam-powered machines per Worker Year t+1 | | | | | Average horse power of steam-powered machines per Worker Year t+1 | | | | |
| Share of cholera deaths in population | −24.33*** | −30.79*** | −28.51*** | −75.52** | −64.49** | −32.98** | −37.52** | −34.61** | −104.7** | −91.55** |
| | [8.538] | [9.632] | [8.720] | [31.71] | [28.28] | [13.66] | [15.18] | [14.38] | [46.60] | [43.80] |
| Department and year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Deviation from summer rainfall | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| Geographic controls | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| GDP per capita | No | No | Yes | No | Yes | No | No | Yes | No | Yes |
| Within R2 | 0.174 | 0.228 | 0.255 | | | 0.123 | 0.137 | 0.155 | | |
| Mean dep.var | 38.709 | 38.709 | 38.709 | 38.709 | 38.709 | 401.809 | 401.809 | 401.809 | 401.809 | 401.809 |
| Clusters | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| Observations | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 |
| | First stage: the instrumented variable is share of cholera deaths in population | | | | | | | | | |
| Summer Temperature | | | | −0.180*** | −0.179*** | | | | −0.180*** | −0.179*** |
| | | | | [0.0471] | [0.0485] | | | | [0.0471] | [0.0485] |
| 1st stage F-stat | | | | 14.602 | 13.577 | | | | 14.602 | 13.577 |
| | Reduced form: the dependent variable is | | | | | | | | | |
| | Average number of steam-powered machines Per Worker Year t+1 | | | | | Average horse power of steam-powered machines Per Worker Year t+1 | | | | |
| Summer Temperature | | | | 13.60** | 11.53** | | | | 18.86** | 16.37** |
| | | | | [5.977] | [5.357] | | | | [8.808] | [8.172] |

**Table 4** (continued)

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| | OLS | OLS | OLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS |
| | Average number of steam generators | | | | | Average number of boilers | | | | |
| | Per Worker Year t+1 | | | | | Per Worker Year t+1 | | | | |
| Share of Cholera Deaths in Population | −21.29** | −27.51*** | −24.89*** | −86.21** | −74.20** | −13.64 | −20.14* | −20.51* | −90.47** | −99.37** |
| | [8.887] | [10.31] | [9.427] | [34.05] | [30.86] | [10.50] | [10.35] | [10.36] | [38.90] | [41.65] |
| Department and year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Deviation from summer rainfall | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| Geographic controls | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| GDP per capita | No | No | Yes | No | Yes | No | No | Yes | No | Yes |
| Within R2 | 0.131 | 0.182 | 0.215 | | | 0.211 | 0.329 | 0.330 | | |
| Mean dep.var | 40.091 | 40.091 | 40.091 | 40.091 | 40.091 | 45.667 | 45.667 | 45.667 | 45.667 | 45.667 |
| Clusters | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| Observations | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 |
| | First stage: the instrumented variable is share of cholera deaths in population | | | | | | | | | |
| Summer temperature | | | | −0.180*** | −0.179*** | | | | −0.180*** | −0.179*** |
| | | | | [0.0471] | [0.0485] | | | | [0.0471] | [0.0485] |
| 1st stage F-stat | | | | 14.602 | 13.577 | | | | 14.602 | 13.577 |
| | Reduced form: the dependent variable is | | | | | | | | | |
| | Average Number of Steam Generators per Worker Year t+1 | | | | | Average number of boilers per worker year t+1 | | | | |
| Summer temperature | | | | 15.53** | 13.26** | | | | 16.30** | 17.76** |
| | | | | [6.325] | [5.718] | | | | [7.479] | [7.237] |

This table presents OLS and IV regressions relating the share of cholera deaths in each department to the number and horse power of steam-powered machines per worker as well as to the number of boilers and steam generators per worker in the mining sector in the year after each cholera outbreak. Geographic controls for departments, which are interacted with year-fixed effects, include their land suitability, their share of carboniferous area and dummies for border and maritime departments. Constant not reported. Robust standard errors clustered at the department level. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

**Table 5** The effects of the cholera in 1849 and 1854 on employment, wages and production in the wake of each pandemic

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| | OLS | OLS | OLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS |
| | Average Number of Workers Year t+1 | | | | | Average Wage per Worker Year t+1 | | | | |
| Share of cholera deaths in population | 3.960 | 9.768 | 8.128 | 38.65 | 30.41 | −24.46 | −11.48 | −12.78 | 99.52 | 101.0 |
| | [7.685] | [9.736] | [8.917] | [33.55] | [31.01] | [22.63] | [22.71] | [22.23] | [93.35] | [92.91] |
| Department and year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Deviation from summer rainfall | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No |
| Geographic controls | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No |
| GDP per capita | No | No | Yes | No | Yes | No | Yes | No | Yes | No |
| Within R2 | 0.064 | 0.326 | 0.341 | | | 0.009 | 0.130 | 0.131 | | |
| Mean dep.var | 176.404 | 176.404 | 176.404 | 176.404 | 176.404 | 66.535 | 66.535 | 66.535 | 66.535 | 66.535 |
| Clusters | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| Observations | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 |
| | First stage: the instrumented variable is share of cholera deaths in population | | | | | | | | | |
| Summer temperature | | | | −0.180*** | −0.179*** | | | | −0.180*** | −0.179*** |
| | | | | [0.0471] | [0.0485] | | | | [0.0471] | [0.0485] |
| 1st stage F-stat | | | | 14.602 | 13.577 | | | | 14.602 | 13.577 |
| | Reduced form: the dependent variable is | | | | | | | | | |
| | Average number of workers year t+1 | | | | | Average wage per worker year t+1 | | | | |
| Summer Temperature | | | | −6.961 | −5.436 | | | | −17.93 | −18.06 |
| | | | | [6.389] | [5.804] | | | | [16.01] | [15.70] |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| | OLS | OLS | OLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS |
| | Average Value of Extracted Coal (t+2)-(t+3) | | | | | Average Value of Extracted Peat (t+2)-(t+3) | | | | |
| Share of Cholera Deaths in Population | −2.765 | −2.409 | 3.615 | −2.625 | 2.732 | −9.316** | −11.37** | −10.98** | −25.95** | −24.71* |
| | [2.242] | [1.832] | [6.429] | [1.867] | [6.724] | [4.672] | [5.090] | [5.254] | [12.06] | [13.79] |
| Department- and year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Deviation from summer rainfall | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |

**Table 5** (continued)

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| | OLS | OLS | OLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS |
| | Average Value of Extracted Coal (t+2)-(t+3) | | | | | Average Value of Extracted Peat (t+2)-(t+3) | | | | |
| Geographic controls | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| GDP per capita | No | No | Yes | Yes | No | No | No | Yes | No | Yes |
| Within R2 | 0.091 | 0.157 | 0.162 | | | 0.367 | 0.464 | 0.467 | | |
| Mean dep.var | 0.527 | 0.527 | 0.527 | 0.527 | 0.527 | 0.234 | 0.234 | 0.234 | 0.234 | 0.234 |
| Clusters | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| Observations | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 |
| | First stage: the instrumented variable is share of cholera deaths in population | | | | | | | | | |
| Summer temperature | | | −0.180*** | | −0.179*** | | | | −0.180*** | −0.179*** |
| | | | [0.0471] | | [0.0485] | | | | [0.0471] | [0.0485] |
| 1st stage F-stat | | | 14.602 | | 13.577 | | | | 14.602 | 13.577 |
| | Reduced form: the dependent variable is | | | | | | | | | |
| | Average value of extracted coal (t+2)-(t+3) | | | | | Average value of extracted peat (t+2)-(t+3) | | | | |
| Summer temperature | | | −0.651 | | −0.488 | | | | 4.675** | 4.417 |
| | | | [1.157] | | [1.213] | | | | [2.330] | [2.660] |

This table presents OLS and IV regressions relating the share of cholera deaths in each department to the number and wage of workers in the mining sector in the year after each cholera outbreak and to the values of extracted coal and peat two and three years after each cholera outbreak. Geographic controls for departments, which are interacted with year-fixed effects, include their land suitability, their share of carboniferous area and dummies for border and maritime departments. Constant not reported. Robust standard errors clustered at the department level. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

**Table 6** The effects of the cholera in 1849 and 1854 on the number of mechanized ploughs and animal-powered threshing machines per day laborer and on the number and wage of agricultural day laborers in 1852 and 1862

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| | OLS | OLS | OLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS |
| | Mechanized ploughs per day laborer | | | | | Animal-powered threshing machines per day laborer | | | | |
| Share of cholera deaths in population | 67.29** | 55.09* | 58.35* | 323.6*** | 369.9*** | 18.90* | 18.32** | 18.58** | 2.708 | 3.002 |
| | [28.36] | [29.67] | [29.65] | [117.4] | [135.1] | [9.529] | [8.501] | [8.516] | [7.922] | [7.940] |
| Department- and year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Deviation from summer rainfall | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| Geographic controls | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| GDP per capita | No | No | Yes | No | Yes | No | No | Yes | No | Yes |
| Within R2 | 0.615 | 0.672 | 0.674 | | | 0.354 | 0.488 | 0.49 | | |
| Mean depvar | 2.80 | 2.81 | 2.82 | 2.83 | 2.84 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Clusters | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| Observations | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 |
| | First stage: the instrumented variable is share of cholera deaths in population | | | | | | | | | |
| Summer temperature | | | | −0.180*** | −0.179*** | | | | −0.180*** | −0.179*** |
| | | | | [0.0471] | [0.0485] | | | | [0.0471] | [0.0485] |
| 1st stage F-stat | | | | 14.602 | 13.577 | | | | 14.602 | 13.577 |
| | Reduced form: the dependent variable is | | | | | | | | | |
| | Mechanized ploughs per day laborer | | | | | Animal-powered threshing machines per day laborer | | | | |
| Summer temperature | | | | −58.29*** | −66.12*** | | | | −0.488 | −0.537 |
| | | | | [16.49] | [18.28] | | | | [1.531] | [1.549] |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| | OLS | OLS | OLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS |
| | Number of day laborers | | | | | Average wage of day laborers | | | | |
| Share of cholera deaths in population | −15.56*** | −12.39** | −11.32** | −43.19*** | −38.86*** | 0.0072 | 0.0051 | 0.0039 | 0.0353** | 0.0304* |
| | [5.449] | [5.467] | [5.452] | [14.68] | [14.63] | [0.005] | [0.006] | [0.006] | [0.018] | [0.018] |
| Department- and year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

**Table 6** (continued)

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| | OLS | OLS | OLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS |
| | Number of day laborers | | | | | Average wage of day laborers | | | | |
| Deviation from summer rainfall | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| Geographic controls | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| GDP per capita | No | No | Yes | No | Yes | No | No | Yes | No | Yes |
| Within R2 | 0.924 | 0.934 | 0.936 | | | 0.464 | 0.576 | 0.593 | | |
| Mean dep.var | 26661.65 | 26661.65 | 26661.65 | 26661.65 | 26661.65 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Clusters | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| Observations | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 |
| | First stage: the instrumented variable is share of cholera deaths in population | | | | | | | | | |
| Summer temperature | | | | −0.180*** | −0.179*** | | | | −0.180*** | −0.179*** |
| | | | | [0.0471] | [0.0485] | | | | [0.0471] | [0.0485] |
| 1st stage F-stat | | | | 14.602 | 13.577 | | | | 14.602 | 13.577 |
| | Reduced form: the dependent variable is | | | | | | | | | |
| | Number of day laborers | | | | | Average wage of day laborers | | | | |
| Summer temperature | | | | 7.780*** | 6.947*** | | | | −0.00637** | −0.00543* |
| | | | | [2.428] | [2.596] | | | | [0.00315] | [0.00324] |

This table presents OLS and IV regressions relating the share of cholera deaths in each department to the number of mechanized ploughs and animal-powered threshing machines per day laborer. Geographic controls for departments, which are interacted with year-fixed effects, include their land suitability, their share of carboniferous area and dummies for border and maritime departments. Constant not reported. Robust standard errors clustered at the department level. ***$p < 0.01$,** $p < 0.05$,* $p < 0.1$

**Table 7** The effects of cholera in 1849 and 1854 on the number of patents and the share of agricultural hydraulic patents in the five years following each pandemic

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| | OLS | OLS | OLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS |
| | Total number of patents | | | | | Number of agricultural hydraulic patents | | | | |
| | Year t+1 to t+5 | | | | | | | | | |
| Share of cholera deaths in population | −10.55 | −12.90* | −12.17* | −15.39 | −10.78 | 7.075 | 2.323 | 3.909 | 63.85*** | 80.02*** |
| | [6.463] | [6.751] | [6.716] | [16.03] | [16.47] | [11.89] | [13.38] | [13.20] | [22.92] | [24.77] |
| Department- and year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Deviation from summer rainfall | No | No | No | Yes | Yes | No | No | No | Yes | Yes |
| Geographic controls | No | No | No | Yes | Yes | No | No | No | Yes | Yes |
| GDP per capita | No | No | No | No | Yes | No | No | No | No | Yes |
| Within R2 | 0.275 | 0.307 | 0.313 | | | 0.119 | 0.185 | 0.206 | | |
| Mean dep.var | 172.329 | 172.329 | 172.329 | 172.330 | 172.331 | 7.018 | 7.018 | 7.018 | 7.019 | 7.020 |
| Moran I | −0.013 | −0.013 | −0.012 | −0.013 | −0.012 | −0.014 | −0.013 | −0.013 | −0.013 | −0.013 |
| Moran I *p*-value | 0.187 | 0.194 | 0.196 | 0.194 | 0.196 | 0.133 | 0.170 | 0.178 | 0.178 | 0.178 |
| Clusters | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| Observations | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 | 170 |
| | First stage: the instrumented variable is share of cholera deaths in population | | | | | | | | | |
| Summer temperature | | | | −0.180*** | −0.179*** | | | | −0.180*** | −0.179*** |
| | | | | [0.0471] | [0.0485] | | | | [0.0471] | [0.0485] |
| 1st stage F-stat | | | | 14.602 | 13.577 | | | | 14.602 | 13.577 |
| | Reduced form: the dependent variable is | | | | | | | | | |
| | Total number of patents | | | | | Number of agricultural hydraulic patents | | | | |
| | Year t+1 to t+5 | | | | | | | | | |
| Summer temperature | | | | 2.772 | 1.926 | | | | −11.50** | −14.31*** |
| | | | | [3.024] | [3.082] | | | | [4.495] | [4.281] |

This table presents OLS and IV regressions relating the share of cholera deaths in each department to the number of patents and the share of agricultural hydraulic patents in the decade after each outbreak. Geographic controls for departments, which are interacted with year-fixed effects, include their land suitability, their share of carboniferous area and dummies for border and maritime departments. Constant not reported. Robust standard errors clustered at the department level. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

epidemics. These expectations, which might be viewed as self-fulfilling, explain the different effects of labor scarcity on technology adoption in agriculture and in industry. Finally, another interpretation is that the OLS estimates, unlike the IV estimates, underestimate the actual impact of the cholera epidemics on technology adoption.

In addition, three series of robustness checks support our main regression results. First, while our main regression results focus on the number of machines and tools per worker, Tables F.1-F.3 show the robustness of their sign and significance when the dependent variables are only the number of machines and tools. Second, we show that our main regression results are robust to accounting for spatial autocorrelation in two ways. In line with Kelly (2019), we compute the Moran I test and its p-value over the residuals of each regression and are unable to reject the null hypothesis of no spatial autocorrelation at the 1%-level (these statistics are reported with the full specifications in Tables E.4-E.18 and Tables I.1-I.7). We also show in Tables G.1-G.6 that our main regression results are robust to using a weighting matrix based on the great-circle distance between the department's administrative centers (Colella et al., 2020). Third, we show in Tables H.1-H.2 that they are also robust to accounting for heterogeneous treatment effects using the two-way fixed effects estimators of de Chaisemartin and D'Haultfoeuille (2020).[23]

### 4.1 Technology adoption, wages and production in industry

*In the mining industry* The effects of the 1849 and 1854 cholera pandemics on the mining industry suggest that labor and capital are complementary factors of production. The upper part of Table 4 shows that the cholera had a negative and significant effect on the average number and horse power of steam-powered machines per worker inside mines in the year that followed each outbreak. Similarly, the lower part of Table 4 indicates that the cholera had a significant negative impact on the average numbers of steam generators and boilers per worker inside mines one year after each outbreak.

However the negative and significant effects of labor scarcity on technology adoption are quantitatively small. The IV regression results in Table 4 suggest that a department at the median of the distribution of the share of cholera deaths in the population (0.057%) would have had 3.68 fewer steam-powered machines (0.11 of the sample mean), 5.22 fewer horse power in steam-powered machines (0.01 of the sample mean), 4.23 fewer steam generators per worker (0.10 of the sample mean) and 5.66 fewer boilers per worker (0.19 of the sample mean). Furthermore, additional regressions available upon request show that these negative and significant effects of cholera on technology adoption in the mining sector do not persist in subsequent years. These limited quantitative effects may explain why we find no significant effect on wages and the number of workers in the year after each outbreak in the upper part of Table 5.

Moreover, using the average production of peat and coal over the years t+2 and t+3 after the pandemic, the lower part of Table 5 shows that the cholera had no effect on the

[23] In additional regressions available upon request, we examine the potential existence of the pandemics' non-linear effects on the main outcomes. The results are overall qualitatively robust, suggesting that there were no strong non-linearities, except for those pertaining to innovation. This is not surprising insofar as the Seine department, were Paris is located, was a leading innovation center in France, but was also heavily hit by the cholera epidemics.

production of coal but led the mining industry to reduce the production of peat.[24] This is most likely because peat is cheaper than coal as the combustion of the former produces less energy than that of the latter. In other words, the complementarity of production factors led producers to make a rational decision and reduce the production of the least valuable good.

*In the textile industry* Tables E.8 and E.9 report the effects of the 1832 and 1854 cholera pandemics on the textile industry in 1839–47 and 1860–65 at the arrondissement level. As we noted above, these data cannot be used in a panel data framework, thereby leading us to run Equations (1) and (2) without fixed effects.

In line with the results in Tables 4 and 5, Tables E.8 and E.9 show that the pandemics had a negative and significant but quantitatively limited on the number and horse-power of water-, wind- and steam-powered machines in the textile industry that persisted six to 10 years after the outbreak. For instance, the OLS regression in Column (5) in Table E.9 shows that an area at the median distribution of the share of cholera deaths (0.057%) would have 1.84% fewer horse power of steam engines in 1860–65. In addition, in Table E.9, the 1854 cholera epidemic is shown to have a negative and significant effect on the total number of workers in the 2SLS regression in Column (8) as well as a negative impact on the wages of male, female and child workers in the OLS regressions in Columns (9), (11) and (13). These effects are however quantitatively small: in an area experiencing the median share of cholera deaths in the population (0.057%), the wages of men, women and children would only decline by 0.24%, 0.27% and 0.55% respectively.

Overall, the negative effects of labor scarcity on technology adoption in the mining and textile industries were quantitatively limited, although they persisted slightly longer in the textile industry.[25] In other words, our analysis suggests that areas that were hit the harshest by the cholera epidemics only momentarily stopped replacing old machines with new ones. This result thus contrasts with that of Abramitzky et al. (2023) on the effects of the 1920 U.S. quotas where the negative effect of labor scarcity on technology adoption in mining persisted over time. Before venturing a mechanism, we examine the effect of labor scarcity on technology adoption, wages and production in agriculture.

### 4.2 Technology adoption, wages and production in agriculture

The effects of the 1849 and 1854 cholera pandemics on the agricultural sector in 1852 and 1862 suggest that labor and capital are substitute factors of production. Columns (1)-(5) in the upper part of Table 6 show that the share of cholera deaths in the population had a significant and positive but quantitatively limited impact on the number of mechanized ploughs per day laborer. The IV estimate in Column (5) in the upper part of Table 6 suggests that departments at the 50th percentile of the distribution of the share of cholera deaths in the population (0.057%) would have experienced an increase of 0.21 in the number of mechanized ploughs per day laborer (0.075 of the sample mean). In addition,

[24] The different timing between the negative effects of cholera on the adoption of technology (year t+1) and on production (years t+2 and t+3) likely stems from the previous existence of stocks of coal and peat and/or a delayed negative demand shock.

[25] Additional results confirm that the cholera pandemics did not have any long-term effects: Tables E.5 and E.6 show that the share of cholera deaths did not have any impact on the shares of the industrial workforce and of professionals (e.g., doctors, lawyers, etc...) 40 years after each cholera outbreak while Table E.7 shows that it did not have an effect on GDP per capita 150 years afterwards.

Columns (6)-(10) in the upper part of Table 6 show that the cholera epidemics had a positive effect on animal-powered threshing machines per day laborer, even though that result is only significant in the OLS regressions. Table E.12 furthermore shows that they had no significant effect on the adoption of steam-powered threshing machines, which were then the most technology advanced agricultural tools available to French farmers.

The pandemics also had a significant but quantitatively limited effect on employment and wages in agriculture. Columns (1)–(5) in the lower part of Table 6 indicate that the cholera had a significant and negative impact on the number of agricultural day laborers (Table E.10 shows the full regressions) while Columns (6)–(10) in the lower part of Table 6 show the positive effect of labor scarcity on wages, although that effect is only significant in the IV regressions. Namely, Column (10) in the lower part of Table 6 suggests that agricultural day laborers in a department experiencing a median loss in population (0.057%) would benefit from a 0.17% wage increase. As such, these results are in line with those of Clemens et al. (2018) and San (2023) that the adoption of labor-saving technologies offset the anticipated increase in wages.

Furthermore, Tables E.13, E.14, and E.15, show that the effects of the cholera on land rents were limited. Labor scarcity had a slightly positive and significant effect on the rents of meadows of “first and second class”(i.e., highest and medium quality), but no such impact on the rents of meadows of “third class”(i.e., lowest quality) as well as no significant effect on the rents of arable land and vineyards, irrespective of quality.

Finally, Tables E.16 and E.17 show that the cholera pandemics had a slightly negative and significant effect on the production of wheat and rye but none on the production of millet, oats and corn. This negative impact of labor scarcity on wheat and rye may reflect lower demand for these crops or may suggest that the investments for a capital-intensive crop like wheat were not sufficient to prevent a decline in production.[26] In addition, it might have been conjectured that the cholera pandemics would have driven out less efficient farmers but the results suggest that the pandemics and their associated toll on economic activity did not cause any major change in land concentration that could have directly increased mechanization in agriculture.

Overall, our results establish that labor scarcity had a positive, limited and significant effect on the adoption of agricultural tools in the short-run, suggesting that production factors in agriculture are substitute. The adopted tools were not however the most advanced ones, which were steam-powered, but rather mechanized ploughs and animal-powered threshing machines. The most straightforward explanation is that acquiring steam-powered engines was not profitable enough for most farmers, all the more so as coal was scarcer in France than in England and Germany (Cameron & Neal, 2015). However, faced with labor scarcity and higher wages, it can be hypothesized that French landowners would try to cut production costs, notably by looking for more efficient irrigation tools and fostering innovation in agricultural hydraulic technologies. This is what we explore in the next section.

### 4.3 Innovation

In this section, Table 7 assesses the impact of the cholera pandemics in 1832, 1849 and 1854 on innovation in the ten years after each pandemic. Columns 1–5 in Table 7 show that the cholera pandemics did not entail a rise in the total number of patents in the following

[26] Wheat is a capital-intensive crop, unlike labor-intensive crops like corn and hay (Lafortune et al., 2015)

five years. However, Columns 6–10 in Table 7 indicate that there was an increase in the number of agricultural hydraulic patents, even if this effect was only significant in the IV regressions. Additional results available upon request show that the cholera had no systematically significant effect on the other patent categories, and in particular on patents in the industrial sector.

The IV estimate in Column 10 of Table 7 suggests that departments at the median of the distribution of the share of cholera deaths in the population (0.057%) would have experienced a significant, albeit limited, increase of 4.56% in the number of agricultural hydraulic patents.

In this respect, anecdotal evidence suggest that landowners did not themselves develop new agricultural hydraulic technology for which their human capital would not be suited. Instead, local entrepreneurs seized the opportunity offered by labor scarcity in the agricultural sector looking for labor-saving technology. For instance, patent 32,365 for a "garniture de piston roulante"(rolling filling for piston) was classified in 1857 as part of the agricultural hydraulic patents (category 2) and was owned by a plumber. It could indeed be expected that a plumber with some knowledge of hydraulics would seize the opportunity created by local labor scarcity to design a patent for agricultural hydraulics that s/he would sell to landowners.[27]

Overall, in line with our analysis above regarding technology adoption in agriculture, we find that labor scarcity was conducive to innovation in agricultural irrigation, although its impact was quantitatively limited.

## 5 Results: mid-run effects on human capital formation

In this section, we focus on the mid-run effects of the cholera pandemics that could also at the same time rationalize their short-term effects on technology adoption and innovation which we highlighted in the previous section: we argue that labor scarcity provided incentives to invest in literacy as it increased the expected returns to human capital. Because of the complementarity between education and technology (Katz & Margo, 2014; Atack et al., 2019; Franck & Galor, 2022), this increase in literate workers canceled out the negative effect of population losses on technology adoption in industry. In addition, labor scarcity made menial jobs in agriculture less appealing to literate workers, thereby leading to more technology adoption and innovation in agriculture to cut production costs as cheap labor was harder to find. If this conjecture is correct, areas hit by the cholera epidemics would have experienced increases in (i) literacy and in (ii) child and adult education as well as in public spending on education.

### 5.1 Literacy

Table 8 captures the relationship between the cholera pandemics and literacy at the individual level: it focuses on the ability of brides and grooms born in each department between one to 20 years after each cholera outbreak to sign their wedding license, as opposed to

[27] The plumber, by the name of Chamard, obtained a 15-year patent in 1857 for this "garniture de piston roulante". He lived in Neuilly-sur-Seine, a town in the suburbs of Paris, that was then located in the Seine department.

mark it with a cross (Table I.1 displays the regression results with the full set of controls). While the regressions in Columns 1 to 6 use the whole sample, those in Columns 7 to 12 employ the subsample of individuals who worked in agriculture.[28]

The regression results suggest that the cholera pandemics had a positive and significant effect at the 1% level on the literacy of brides and grooms. The IV estimate in Column 6 of Table 8 suggests that individuals in departments at the median (0.057%) of the distribution of the share of cholera deaths in the population would have experienced an increase of 1.60% in their ability to sign a wedding license one to 20 years later (relative to sample mean of 80%). The results on the agricultural subsample confirm those on the whole sample, thereby suggesting that labor scarcity provided incentives to invest in human capital formation.

The positive and significant but quantitatively limited effects of labor scarcity on literacy are confirmed by Table I.2 that focuses on the departmental share of literate army conscripts (i.e., 20-year old men who could read and write) born during the year of each pandemic, as well as 20 and 35 years later. The IV estimates in Columns 5 and 10 of Table I.2 show that departments at the median (0.057%) of the distribution of the share of cholera deaths in the population would have experienced a quantitatively small but significant increase in their share of literate conscripts by 0.86% 20 years later (relative to sample mean of 77%) and by 0.66% 40 years later (relative to a sample mean of 88%). Furthermore, Columns 11–15 of Table I.2 show that the cholera did not have a significant impact on the literacy of conscripts born 35 years after each outbreak. This lack of significance can be explained by the fact that those army conscripts were born in 1867, 1884 and 1899, i.e., two of these three cohorts were born after the adoption of the 1881–1882 laws on free and mandatory schooling until age 13 for boys and girls. These policies thus offset the long-term positive effect of the cholera pandemics on literacy.

Overall, in line with our main analysis, the results in this section suggest that labor scarcity had a positive and significant effect on literacy. This effect was persistent but quantitatively small. As such, it was probably sufficient to compensate for the negative effect of the population loss on technology adoption, but not sufficiently large for the increase in literacy and skilled workers to give an edge in technology adoption and innovation to areas heavily hit by the cholera epidemics.

### 5.2 Child and adult education and public spending on education

While the previous section establishes the positive effect of the epidemics on literacy, it raises the question as to whether labor scarcity provided adults incentives to invest in their human capital but also gave parents incentives to invest in their children's human capital, notably through higher school attendance rates and greater public spending.

Table 9 assesses the effect of the cholera on the number of participants in courses for male adults and apprentices in 1837, 1850 and 1863 and female apprentices in 1850 and 1863 while Table 10 analyzes the effect of the pandemics on the number of available courses for men and women as well as public spending on courses for men (data on spending for courses for women are not available). They show that the pandemics increased the

[28] The validity of the regressions on the agricultural subsample should be taken with caution since there is no information on the occupations of 1457 out of the 11953 individuals in the sample (12%), some of whom might have worked in the agricultural sector.

**Table 8** The effects of the cholera in 1832, 1849 & 1854 on the signatures of wedding licenses by spouses born one to 20 years after each cholera pandemic

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | OLS | OLS | OLS | 2SLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS | 2SLS |
| | Signature of wedding license for | | | | | | | | | | | |
| | All individuals | | | | | | Individuals working in agriculture | | | | | |
| | Born 1 to 20 years after each epidemic | | | | | | | | | | | |
| Share of cholera deaths in population | 6.754*** | 5.983*** | 5.554*** | 27.89*** | 25.69*** | 28.13*** | 5.991* | 4.962 | 3.454 | 39.37*** | 42.48** | 40.72** |
| | [1.324] | [1.379] | [1.685] | [4.940] | [5.950] | [6.729] | [3.329] | [3.462] | [4.002] | [14.40] | [17.21] | [16.12] |
| Male | −0.00912 | −0.00906 | −0.00905 | −0.00932 | −0.00905 | −0.00915 | −0.0126 | −0.0129 | −0.0130 | −0.0114 | −0.0117 | −0.0117 |
| | [0.00694] | [0.00693] | [0.00693] | [0.00698] | [0.00696] | [0.00697] | [0.0145] | [0.0145] | [0.0145] | [0.0144] | [0.0143] | [0.0143] |
| Department- and year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Deviation from summer rainfall | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes |
| Geographic controls | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes |
| GDP per capita | No | No | Yes | No | No | Yes | No | No | Yes | No | No | Yes |
| Mean dep.var | 0.797 | 0.797 | 0.797 | 0.797 | 0.797 | 0.797 | 0.731 | 0.731 | 0.731 | 0.731 | 0.731 | 0.731 |
| Moran I | −0.0002 | −0.0002 | −0.0002 | −0.0002 | −0.0002 | −0.0002 | 0.002 | 0.002 | 0.002 | −0.001 | −0.001 | −0.001 |
| Moran I *p*-value | 0.246 | 0.246 | 0.246 | 0.246 | 0.246 | 0.246 | 1.000 | 1.000 | 1.000 | 0.242 | 0.243 | 0.243 |
| Clusters | 3085 | 3085 | 3085 | 3085 | 3085 | 3085 | 1744 | 1744 | 1744 | 1744 | 1744 | 1744 |
| Observations | 11,953 | 11,953 | 11,953 | 11,953 | 11,953 | 11,953 | 3,224 | 3,224 | 3,224 | 3,224 | 3,224 | 3,224 |
| | First stage: the instrumented variable is Share of Cholera Deaths in Population | | | | | | | | | | | |
| Summer temperature | | | | −0.0825*** | −0.0708*** | −0.0628*** | | | | −0.0510*** | −0.0443*** | −0.0472*** |
| | | | | [0.00571] | [0.00545] | [0.00460] | | | | [0.00531] | [0.00516] | [0.00497] |
| 1st stage F-stat | | | | 208.975 | 168.945 | 186.706 | | | | 92.480 | 73.729 | 89.878 |
| | Reduced form: the dependent variable is Signature of wedding license for | | | | | | | | | | | |

**Table 8** (continued)

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | OLS | OLS | OLS | 2SLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS | 2SLS |
| | Signature of wedding license for | | | | | | | | | | | |
| | All individuals | | | | | | Individuals working in agriculture | | | | | |
| | Born 1 to 20 years after each epidemic | | | | | | | | | | | |
| | All individuals | | | | | | Individuals working in agriculture | | | | | |
| | Born 1 to 20 years after each epidemic | | | | | | | | | | | |
| Summer temperature | | | | −2.301*** | −1.818*** | −1.766*** | | | | −2.009*** | −1.883** | −1.920*** |
| | | | | [0.400] | [0.414] | [0.416] | | | | [0.725] | [0.745] | [0.741] |

\This table presents OLS and IV regressions relating the share of cholera deaths to the ability of brides and grooms born one to 20 years after each outbreak to sign their wedding license. Geographic controls for departments, which are interacted with year-fixed effects, include their land suitability, their share of carboniferous area and dummies for border and maritime departments. Constant not reported. Robust standard errors clustered at the year-department level. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

number of participants in courses for male adults and apprentices as well as public spending on these courses. However, labor scarcity neither had a significant effect on the number of courses for female adults and apprentices nor on the number of participants in these courses. A potential explanation for this result is that agricultural mechanization mainly reduced the demand for male labor, thereby leading men to *immediately* invest more in human capital and seek work in industry where literacy skills were necessary (e.g. Franck & Galor, 2022).

Table I.5 shows that the impact of the cholera pandemics in 1832, 1849 and 1854 on the primary school attendance rate of boys and girls out of the population age 5–15 in 1837, 1851 and 1856 is positive but not significant in all the specifications. Moreover, Tables I.6 and I.7 assess the effect of the cholera on public spending by the three tiers of the French government (i.e., the central state, the departments and the communes) on primary schooling.[29] Whether we consider total education spending or education spending per inhabitant, the results suggest that the pandemic had a negative impact on the departments' spending but none on that of the communes and of the central state, and overall, no effect on total public spending on primary schooling.

Those results should be put in the general context of 19th century French education. There were of course primary schools in France before the first cholera pandemic in 1832 (Mayeur, 2003). Moreover, after the 28 June 1833 law (known as the "Loi Guizot" after the then Minister of Education), all communes had to host a primary school in their jurisdiction. That school could be privately or publicly funded, and run by a secular teacher paid by municipality or by the local priest (or nun). Thus, we may not find any significant impact of the cholera on school spending because state intervention in education was already taking place in France at the time, independently of the pandemics.

As such, in line with our analysis that views labor and technology as complementary factors of production in industry and substitute in agriculture, labor scarcity entailed a rise in human capital in the aftermath of the cholera pandemics. This increase did not stem from the rising importance of state-funded primary schooling. Instead it resulted from private investments made by parents in their own human capital as well as that of their children.

### 5.3 Alternative explanations

Other than the increase in human capital, factors such as migration, urbanization, fertility, age at marriage, religiosity or local financial intermediation, could provide alternative explanations for our main results.

In this section, we briefly present the tests which we carry out to assess the importance of such factors and provide more detailed explanations, including the data sources, in the Appendix. Reassuringly, our tests show that these factors were not correlated with the spread of cholera or with summer temperatures in 1832, 1849 and 1854.

*Migration and urbanization.* 19th century France was characterized by a high rate of internal migration (Daudin et al., 2019) but no historical evidence connects migration and urbanization to the cholera epidemics. If anything, the potential effects of labor scarcity on migration and urbanization are not straightforward. Labor scarcity entails higher wages and may attract immigrants but the adoption of new technology may lower wages and hence

[29] Because of data limitations, Tables I.6 and I.7 only focus on the impact of the 1854 cholera pandemic.

**Table 9** Cholera in 1832, 1849 and 1854: number of participants in courses for male and female adults and apprentices

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| | OLS | OLS | OLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS |
| | Number of participants in courses for | | | | | | | | | |
| | Male adults and apprentices 1837–1850-1863 | | | | | Female adults and apprentices 1850–1863 | | | | |
| Share of cholera deaths in population | 26.49 | 19.20 | 21.42 | 126.0** | 130.6** | 29.80 | 34.15 | 32.28 | −3.720 | −19.63 |
| | [23.36] | [24.45] | [24.46] | [57.31] | [59.70] | [27.62] | [29.86] | [28.32] | [88.75] | [89.00] |
| Department- and year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Deviation from summer rainfall | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| Geographic controls | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| GDP per capita | No | No | Yes | No | Yes | No | No | Yes | No | Yes |
| Within R2 | 0.404 | 0.430 | 0.438 | | | 0.023 | 0.057 | 0.059 | | |
| Clusters | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| Observations | 255 | 255 | 255 | 255 | 255 | 170 | 170 | 170 | 170 | 170 |
| | First stage: the instrumented variable is Share of Cholera Deaths in Population | | | | | | | | | |
| Summer temperature | | | | −0.141*** | −0.140*** | | | | −0.180*** | −0.179*** |
| | | | | [0.0303] | [0.0308] | | | | [0.0471] | [0.0485] |
| 1st stage F-stat | | | | 21.652 | 20.788 | | | | 14.602 | 13.577 |
| | Reduced form: the dependent variable is | | | | | | | | | |
| | Number of participants in courses for | | | | | | | | | |
| | Male adults and apprentices 1837–1850-1863 | | | | | Female adults and apprentices 1850–1863 | | | | |
| Summer Temperature | | | | −17.75** | −18.32** | | | | 0.670 | 3.509 |
| | | | | [7.848] | [7.826] | | | | [16.31] | [15.97] |

This table presents OLS and IV regressions relating the share of cholera deaths in each department to the number of participants in courses for male and female adults and apprentices. Geographic controls for departments, which are interacted with year-fixed effects, include their land suitability, their share of carboniferous area and dummies for border and maritime departments. Constant not reported. Robust standard errors clustered at the department level. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

**Table 10** The effects of the cholera in 1832, 1849 and 1854 on Spending on courses for male adults and apprentices and the number of courses for male and female adults and apprentices in 1837, 1850 sand 1863

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | OLS | OLS | OLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS |
| | Spending on courses for | | | | | Number of courses for | | | | | Number of courses for | | | | |
| | Male adults and apprentices | | | | | Male adults and apprentices | | | | | Female adults and apprentices | | | | |
| | 1837–1850–1863 | | | | | 1837–1850–1863 | | | | | 1850–1863 | | | | |
| Share of cholera deaths in population | 57.53*** | 53.71** | 54.65** | 148.6 | 150.9 | 0.765 | −5.898 | −5.073 | 42.42 | 44.19 | 9.979 | 13.94 | 13.12 | 7.052 | 0.957 |
| | [20.98] | [22.16] | [21.69] | [98.38] | [98.31] | [15.05] | [15.24] | [15.29] | [40.81] | [41.06] | [11.81] | [12.02] | [11.27] | [29.05] | [30.16] |
| Department- and year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Deviation from summer rainfall | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| Geographic controls | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| GDP per capita | No | No | Yes | No | Yes | No | No | Yes | No | Yes | No | No | Yes | No | Yes |
| Within R2 | 0.607 | 0.615 | 0.616 | | | 0.416 | 0.438 | 0.441 | | | 0.009 | 0.054 | 0.058 | | |
| Mean dep. var | 41.2 | 41.2 | 41.2 | 41.2 | 41.2 | 6669.5 | 6669.5 | 6669.5 | 6669.5 | 6669.5 | 2.04 | 2.04 | 2.04 | 2.04 | 2.04 |
| Moran I − 0.008 | −0.008 | −0.008 | −0.008 | −0.008 | −0.007 | −0.007 | −0.007 | −0.007 | −0.007 | −0.012 | −0.012 | −0.012 | −0.012 | −0.0122 | −0.012 |
| Moran I *p*-value | 0.239 | 0.236 | 0.235 | 0.237 | 0.237 | 0.259 | 0.257 | 0.257 | 0.253 | 0.255 | 0.207 | 0.210 | 0.209 | 0.210 | 0.209 |

**Table 10** (continued)

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | OLS | OLS | OLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS | OLS | OLS | OLS | 2SLS | 2SLS |
| | Spending on courses for | | | | | Number of courses for | | | | | Number of courses for | | | | |
| | Male adults and apprentices | | | | | Male adults and apprentices | | | | | Female adults and apprentices | | | | |
| | 1837–1850–1863 | | | | | 1837–1850–1863 | | | | | 1850–1863 | | | | |
| Clusters | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| Observations | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 170 | 170 | 170 | 170 | 170 |
| | First stage: the instrumented variable is Share of Cholera Deaths in Population | | | | | | | | | | | | | | |
| Summer temperature | | | | −0.141*** | −0.140*** | | | | −0.141*** | −0.140*** | | | | −0.180*** | −0.179*** |
| | | | | [0.0303] | [0.0308] | | | | [0.0303] | [0.0308] | | | | [0.0471] | [0.0485] |
| 1st stage F-stat | | | | 21.652 | 20.788 | | | | 21.652 | 20.788 | | | | 14.602 | 13.577 |
| | Reduced form: the dependent variable is | | | | | | | | | | | | | | |
| | Spending on courses for | | | | | Number of courses for | | | | | Number of courses for | | | | |
| | Male adults and apprentices | | | | | Male adults and apprentices | | | | | Female adults and apprentices | | | | |
| | 1837–1850–1863 | | | | | 1837–1850–1863 | | | | | 1850–1863 | | | | |
| Summer temperature | | | | −20.94 | −21.16 | | | | −5.976 | −6.198 | | | | −1.270 | −0.171 |
| | | | | [14.69] | [14.60] | | | | [5.988] | [5.957] | | | | [5.454] | [5.553] |

This table presents OLS and IV regressions relating the share of cholera deaths in each department to spending on courses for male adults and apprentices and the number of courses for male and female adults and apprentices. Geographic controls for departments, which are interacted with year-fixed effects, include their land suitability, their share of carboniferous area and dummies for border and maritime departments. Constant not reported. Robust standard errors clustered at the department level. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

trigger emigration (e.g., Fadinger & Mayr, 2014). It may also be the case that individuals would leave areas hit by the cholera to escape death and would not come back. Tables J.1 and J.2 show that migration and urbanization were not correlated with the spread of cholera and cannot therefore drive our main results (it nonetheless bears pointing out that both Tables do not rule out that migration and urbanization could have played a role in technology adoption and innovation).

*Religiosity*. To account for research highlighting the link between natural disasters (such as pandemics) and religiosity (e.g., Bentzen, 2019), we explore whether the cholera outbreaks could be correlated with changes in religiosity and potentially with a deeper cultural shift that could delay or accelerate technology adoption and innovation. Table J.3 shows that the pandemics had a positive and significant but quantitatively small effect on the share of seminarians in the population, and no significant impact on the share of religious community members in the population. Overall, these results suggest that religiosity was not affected by the cholera pandemics and cannot therefore explain their impact on technology adoption.

*Fertility and nuptiality*. Mortality shocks triggered by pandemics could have an impact on optimal fertility behavior (Boucekkine et al., 2009; Siuda & Sunde, 2021). However, given that the fertility decline in France had begun in the late 18th century (e.g., Galor, 2011; Daudin et al., 2019; Blanc & Wacziarg, 2020), it is not clear whether the spread of cholera could have an impact on fertility rates and on the age at marriage. Tables J.4 and J.5 show that indeed, the cholera epidemics had no systematic significant effect on fertility and nuptiality patterns, thereby suggesting that those channels did not affect our results.

*Local financial intermediation*. Because of the relationship between financial intermediation, economic growth and innovation (e.g., Gorodnichenko & Schnitzer, 2013; Gennaioli et al., 2014), we examine whether labor scarcity fostered technological adoption through the presence of local banks. Table J.6 reports the impact of the cholera pandemics on the amount of deposits per capita in the savings banks of each department averaged over the five-year period which followed each pandemic. The effect is insignificant in all the specifications. These results thus suggest that local financial development was not correlated with the cholera outbreaks and cannot therefore drive our results pertaining to technology adoption and innovation.

## 6 Conclusion

This paper examines the impact of labor scarcity entailed by the cholera epidemics in 1832, 1849 and 1854 in France on subsequent technology adoption and innovation. The results show that in the short-run, labor scarcity had a positive and significant impact on technology adoption and innovation in agriculture while it had a negative impact on technology adoption in industry. This negative impact lasted longer in the textile industry than in the mining sector.

As labor scarcity increased the expected returns to human capital, individuals invested more in their own literacy: this increase in the share of literate individuals in the population canceled out the negative effect of the population loss on technology adoption. Moreover, menial agricultural work became less appealing to literate workers, thereby leading to more technology adoption and innovation in agriculture.

There are three main implications of this study. First, it suggests that in the 19th century, labor and technology were substitute factors of production in agriculture but complementary in industry. Second, it provides some support for the notion that agricultural mechanization in 19th century France was partly fostered by labor scarcity. Third, it provides a moderate view on the effects of repeated pandemics on economic growth. Notwithstanding the human losses, the economic consequences of pandemics in societies that escaped the Malthusian trap appear quantitatively limited in the short-run and disappear in the mid- to long-run.

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