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Mosquitoes and Potatoes: How Local Climatic Conditions Impede Development

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Abstract
The historical diffusion of the potato in the Old World serves as an example of the contribution of technological innovations to socio-economic growth and development (Nunn and Qian in Q J Econ 126(2):593–650, 2011). Climate-related diseases, on the other hand, might offset some of these benefits. Here we examine the long-term impact of malaria on the potato-driven growth of the population and urbanization in the Old World during the 18th and 19th centuries. We exploit local variations in environmental suitability both for potato and for malaria transmission to estimate and compare the impact of potato cultivation on population and urbanization in highly endemic to non-endemic areas at a high level of spatial disaggregation. We show that local climate conditions ideal for malaria transmission counteracted the potential benefits of introducing the potato to the Old World, which are conversely found to be strong and positive in non-endemic regions. These results highlight the interplay between technological change, public health, and development outcomes.

Keywords Technological innovation · Population · Public health · Urbanization · Malaria · Development

1 Introduction

The global population and urbanization rate more than doubled between 1700 and 1900. Figure 1 shows the spatial distribution of the population growth rate and the share of the population living in urban areas across these two centuries. Historians and economists have identified several determinants of such a rapid transformation, ranging from the industrial revolution (Bairoch and Goertz 1986; Mays et al. 2008), the discovery of new drugs that reduced mortality (Cutler et al. 2006), to the introduction of new staple crops which increased agricultural productivity (Bustos et al. 2016).

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One notable example is the extent to which such a dramatic increase in population and urbanization can be attributed to the introduction of potatoes from the New World to the Old World (Nunn and Qian 2011).[1] Because the potato provides more calories and nutrients per hectare of dedicated land compared to other staple crops, its role in increasing population and social development cannot be underestimated (Lutaladio and Castaldi 2009). As a result, the introduction of the potato to the Old World serves as an important example of the effects of agricultural innovations on socio-economic development (McNeill 1999; Salaman and Burton 1985). Figures 1 and 2 suggest a clear spatial correlation between the suitability for cultivating potatoes and the population and urbanization growth observed in the Old World after the potato introduction.

Although the adoption of new crops can generate positive social impacts, climate conditions favorable to the diffusion of diseases may counteract such positive productivity gains (Croppenstedt and Muller 2000; Loureiro 2009). Therefore, assessing the interaction between technological innovation and climate-influenced health conditions is pivotal for historians as well as for social scientists and environmental economists focusing on the link between climate and historical development (Acemoglu and Johnson 2007; Gooch 2017; Acemoglu et al. 2020). In the case of potatoes, Figs. 1, 2 and 3 reveal that areas suitable for cultivating the potato experienced different growth rates in population and urbanization share due to the difference in their health-affecting climate conditions. To the best of our knowledge, such a link between climate-influenced health conditions and socio-economic development through their impact on agricultural productivity has not yet been established in the literature.

In this paper, we investigate the possible adverse effects that the presence of warmer and more humid climate conditions, suitable for the transmission of vector-borne diseases, might have had on the development of areas suitable for cultivating potatoes. Figure 4 shows the conceptual framework of our study: starting from a period before 1700, farmers in areas suitable for malaria transmission (Panel B) were experiencing lower initial population growth and urbanization compared to their counterparts in the areas not suitable for malaria transmission (Panel A). Between 1700 and 1900 and after the introduction of the potato, non-endemic areas enjoyed a significant increase in population and urbanization, while the effect on endemic areas was insignificant. Finally, the introduction of anti-malaria measures in 1900 put both areas on a similar trajectory of population growth and urbanization.

While the diffusion of the potato in the Old World contributed the increase in population, mainly due to lowering mortality rates, to the best of our knowledge, Nunn and Qian (2011) is the only paper assessing the empirical effects of the potato suitability on the urbanization rate as well as the population growth of the Old World countries.

A key challenge in empirical quantification of the socio-economic impact of the diffusion of the potato and malaria transmission is to address the possible reverse causality. That is, on the one hand, the cultivation of the potato might have contributed to an increase in urbanization and population growth. On the other hand, the increased population and the subsequent demand for high-calorie low-price food might have accelerated the diffusion of the potato. A similar issue can be raised in the case of malaria diffusion. While malaria negatively affects the population and urbanization growth, higher urbanization and living standards reduce the transmission of vector-borne diseases.

[1] The Old World comprises all countries in Europe, Africa, Asia, and Oceania with the exclusion of the Americas.

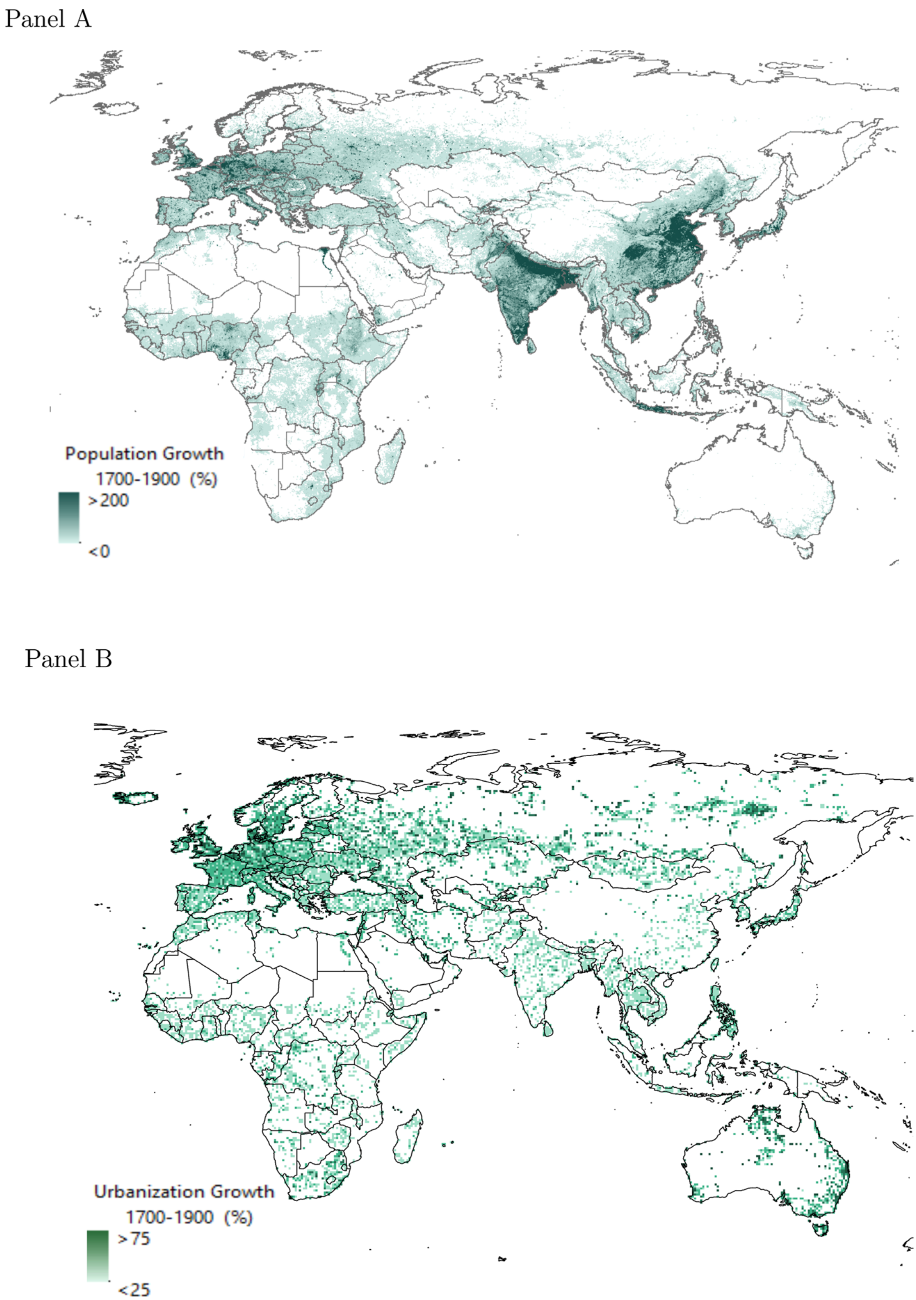


Fig. 1 Spatial distribution of population growth (Panel **A**) and urban population change (Panel **B**) between 1700 and 1900 Source: HYDE database (Klein Goldewijk et al. 2011)

To address the concerns over possible reverse causality and other endogeneity problems, we utilise two exogenous indexes, which only depend on spatial variation of climate

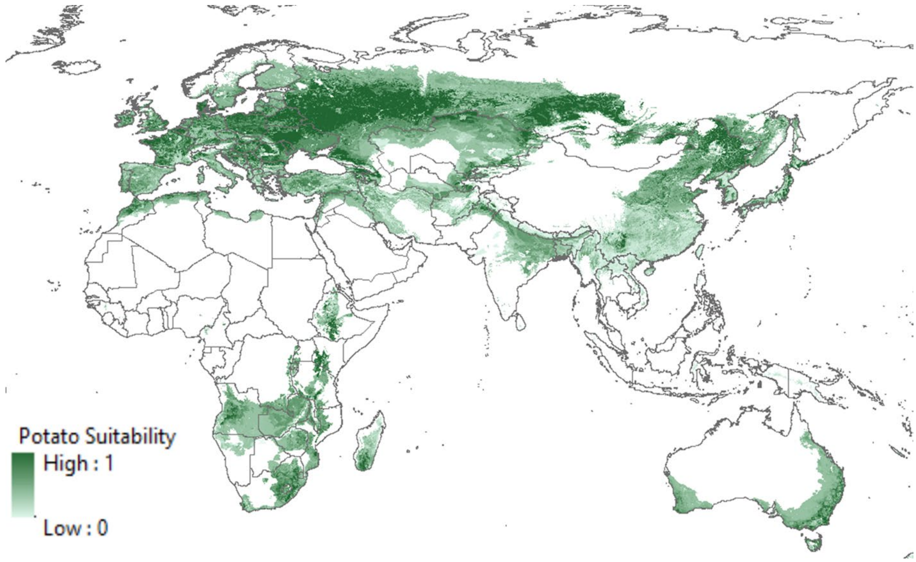


Fig. 2 Spatial distribution of the Potato Suitability Index. Source: IIASA/FAO (2012)

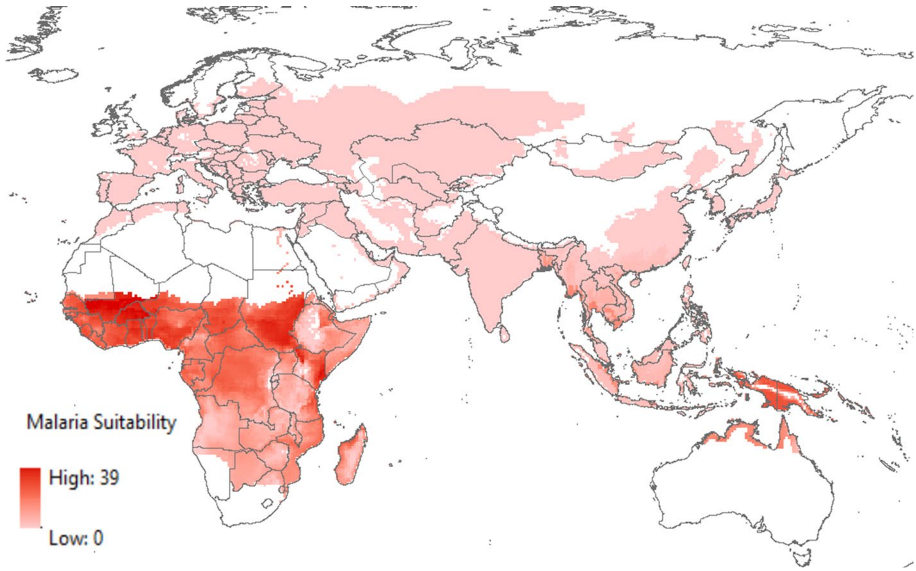


Fig. 3 Spatial distribution of the Malaria Stability Index. Source: Kiszewski et al. (2004)

and are not affected by socioeconomic conditions.

We investigate the hypothesis shown in Panel A of Fig. 4, under which the areas suitable for potato cultivation experienced a larger increase in population and urbanization after the introduction of potatoes in 1700 compared to areas not suitable for the cultivation of the staple crop. To evaluate this hypothesis, we assemble a novel grid-cell dataset of climate,

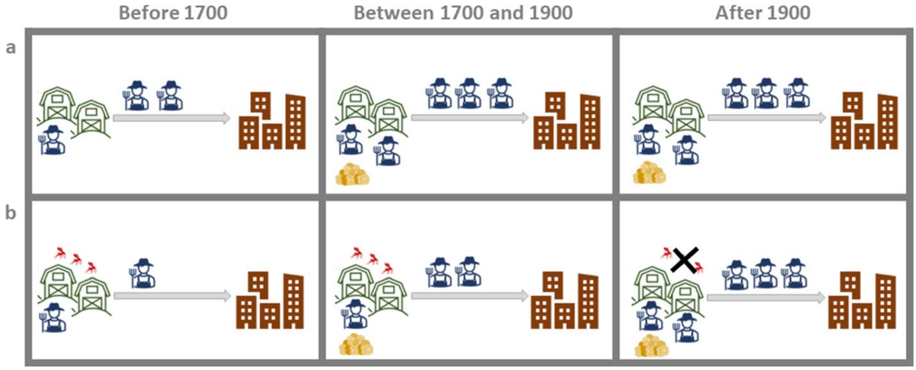


Fig. 4 Conceptual Framework

population, and urbanization data covering more than 30,000 grid cells of the Old World (at 0.5 x 0.5 degrees of resolution) from 1100 to 1900. We use a cross-sectional, exogenous index to measure the suitability of any given area for potato cultivation, the Potato Suitability Index (PSI), which represents the soil conditions required for sustained growth of the potato based on regional weather and land conditions (IIASA/FAO, 2012). Higher values of this index indicate that the soil is more suitable for potato cultivation.[2]

Second and after confirming Nunn and Qian (2011)'s results at a more spatially-disaggregated level, we investigate our hypothesis in Panel B of Fig. 4, which shows that between 1700 and 1900, the positive impact of the potato on the Old World's population and urbanization was hampered by climate-induced health conditions caused by the presence of malaria. To evaluate this hypothesis, we consider an index that measures the suitability of any given area for the reproduction of the mosquitoes larvae responsible for transmitting malaria and its associated vector-borne disease, the Malaria Stability Index (MSI), which is a global indicator of malaria transmission based on regionally dominant vector mosquitoes, temperature, and precipitation data (Kiszewski et al. 2004). We also use additional suitability indexes for other crops (IIASA/FAO, 2012) along with relevant geographical factors which may have influenced population and urbanization growth since 1700 (Nunn and Puga 2012). Figures 2 and 3 plot the spatial heterogeneity of PSI and MSI, respectively.

We match PSI and MSI with a validated panel dataset of historical population and urbanization data (HYDE) developed by Klein Goldewijk et al. (2011).[3] This dataset collects population and urbanization data from existing historical archives at the most local level available. This allows us to compare the relative impact of potato suitability on population and urbanization in areas with high potato suitability and low malaria stability with areas equally suitable for cultivating potatoes but with higher malaria stability.

We find statistical evidence to support our hypothesis in Panel B of Fig. 4 that areas equally suitable for the cultivation of the potato experienced differential population growth

[2] In one of our robustness exercises, we exclude the medieval warm period occurring between the 1200s and the 1400s (Hughes and Diaz 1994). With this check, we are able to exclude that the previous warm period might confound the identification of the treatment effect.

[3] Section A of the Appendix contains a detailed description and summary statistics of the data used in our analysis.

and urbanization due to different climatic conditions, which made the transmission of vector-borne diseases more or less likely.

Of course, there is a wide range of other factors, such as the adoption of new agricultural technologies and practices, that might have affected urbanization and population growth from 1700 to 1900 beyond the possible impact of the potato suitability. To address this issue and validate our estimates, we exploit three sources of variation in our estimation strategy.

The first one is the time variation related to the introduction of potatoes as a field crop in the Old World. As in Nunn and Qian (2011), the introduction of the potato from the New World to the Old World occurred towards the end of the seventeenth and beginning of the eighteenth century, constituting an exogenous agricultural shock. The second source of variation is cross-sectional and related to exogenous geo-climatic conditions suitable for the cultivation of potatoes. Conditional on the availability of potatoes, areas suitable for potato cultivation experienced an increase in their food production. Finally, the third source of variation is also cross-sectional but related to exogenous geo-climatic conditions suitable for malaria transmission. Areas suitable for potato cultivation but not suitable for stable malaria transmission experienced an increase in their population and urbanization rates, significantly more than areas suitable for potato cultivation but, at the same time, also suitable for malaria transmission.

Our empirical strategy follows Nunn and Qian (2011) and is a difference-in-differences (DiD) setup that relies on the interaction of the three sources of variations. We compare population and urbanization levels before and after potatoes were adopted in the Old World, in areas suitable for potato cultivation but not suitable for malaria transmission, to areas equally suitable for potato cultivation but with higher suitability for malaria transmission.

A crucial assumption of our procedure is that no other exogenous shock correlated with potato suitability had occurred during the period that potatoes were being adopted (i.e. from 1700 to 1900). This is an important identification concern that we address in several ways. First, in contrast to previous studies in which the comparison is made at the country level (Nunn and Qian 2011), our data allow us to exploit higher spatial heterogeneity. The inclusion of grid cells and time-fixed effects substantially reduces concerns over other shocks affecting more potato-suitable areas differently from less potato-suitable ones within a range of neighboring cells belonging to the same country.

Moreover, we include country-specific time trends and control for grid-varying factors that might bias our estimates, such as the suitability for cultivating other staple crops, as well as three geographic characteristics that are correlated with potato suitability: terrain ruggedness, elevation, and the presence of a tropical climate.[4]

Another important assumption of our estimation procedure is about the date on which the potato was adopted in the Old World. We choose 1700 based on the historical evidence, which suggests that the adoption of the potato began in a few locations in the late seventeenth century and spread significantly by the early eighteenth century (Nunn and Qian 2011).

However, there exists historical evidence that Spain and Portugal adopted the potato earlier than the rest of the Old World countries (Glendinning 1983). As a result, the difference-in-difference estimates might be biased between early and late-treated countries. We address this potential issue in two ways: first, we restrict the sample to Spain and Portugal

[4] The control for the additional geographic characteristics is done following Nunn and Qian (2011).

as they were the first countries to import and cultivate potatoes. Results of this robustness check confirm both the positive effects of the potato on population growth and urbanization and the role of malaria in counteracting those positive impacts. Second, we perform an additional check excluding European countries from the sample. This restriction is done since Western European countries achieved larger growth rates in population and urbanization after 1700 compared to countries in other continents.[5]

Finally, although Nunn and Qian (2011) show no considerable climatic variations prior to 1900, we perform an additional check by changing the starting point of our empirical exercise from 1100 to 1500. Results of this exercise confirm that changes in climatic conditions did not affect the impact of the diffusion of the cultivation of the potato in more or less malaria-endemic areas of the Old World.

The findings of our study contribute to understanding the relationship between technological progress and climate-related health conditions. Our procedure combines local climatic conditions with historical data on population and urbanization rates at a disaggregated level. We show that the introduction of the potato to the Old World had a positive but geographically unequal impact on the socio-economic development of rural communities: areas equally suitable for potato cultivation but with different prevalence of malaria benefited differently from the diffusion of the new staple crop.

The remainder of the paper is organized as follows. Section 2 provides background information about the relationship between agricultural innovation and population growth and urbanization and the role played by climate-related health conditions. Section 3 describes the data used in our study. Section 4 describes the empirical strategy examining the effects of the introduction of the potato to the Old World in areas characterized by different malaria stability and presents the baseline results from the analysis. Section 5 presents the robustness checks. Finally, Sect. 6 concludes and provides some additional insights into the findings.

2 Background and Conceptual Framework

In the following section, we provide information on the geographical and institutional context relevant to our study. First, we discuss the historical link between agricultural innovations and economic development. We then proceed with a brief overview of the historical diffusion of the potato in the Old World as an example of a revolutionary agricultural product. Third, we focus on the link between infectious diseases and agricultural productivity. Finally, we present a conceptual framework of the interplay between the geographical distribution of the suitability for potato cultivation and for malaria transmission. This interplay is then exploited with a rigorous empirical analysis in Sect. 4.

2.1 Historical Agricultural Innovations and Economic Development

Throughout human history, the introduction of new crops (e.g., maize or potato) or agricultural innovations (e.g., availability of tractors or the use of fertilizers) has boosted agricultural productivity and driven socio-economic development.

[5] Results reported in Table 11 in the Appendix reinforce the main findings.

The economic literature has, in particular, focused on the mechanisms underlying productivity growth in agriculture and the consequent socio-economic growth. For example, the introduction of crop genetic improvements and enhanced fertilizers in the twentieth century led to what is known as the "Green Revolution" in Latin American and Asian countries and contributed to large increases in crop production (Gollin et al. 2021; Evenson and Gollin 2003). In particular, as McArthur and McCord (2017) have shown, fertilizers have had a key role in boosting yields and GDP per capita as a result (Emerick 2018). Bustos et al. (2016) used the introduction of genetically engineered soy in Brazil as an agricultural productivity shock to provide empirical evidence for the structural transformation effects of agrarian technical change. They showed that when agricultural innovation is strongly labor-saving, as in the case of genetically engineered soy, it can foster industrialization.[6]

From a historical perspective, the introduction and the consequent diffusion of potatoes from the New World to the Old World contributed to one-quarter of the growth in the Old World's population and urbanization between 1700 and 1900 (Nunn and Qian 2011; Cook 2014). There exist historical evidence that the cultivation of the potato in the Old World followed the colonization of the Americas. Before that, potatoes were cultivated only in modern-day Colombia, Ecuador, Peru, Bolivia, Chile, and Northern Argentina (Glendinning 1983; McNeill 1999). The first evidence of potatoes being consumed in Europe is from Spain. In 1573 Spanish conquistadors conquered Peru and brought potatoes back with them to Europe.

However, despite the benefits of potatoes, it took more than a few decades for the potato to gradually spread to the rest of Europe and become a staple crop. Not long after its arrival in Europe, the potato was spread across the rest of the Old World and China by colonial powers.[7] As a result, the diffusion of the potato as a new staple crop had a significant role in population growth and urbanization trends in the Old World (Nunn and Qian 2011).

These improvements were achieved mainly through two channels. The first channel is the *nutrition effect* through which the introduction of a new and more nutrient crop resulted in a healthier and more productive population. The second channel is the *productivity effect*, where increased agricultural productivity allowed more workers to migrate from rural areas to cities and work in industry (Galor and Weil 2000). Hence, countries with larger areas suitable for growing potatoes experienced higher population and urbanization growth between 1700 and 1900, as depicted in Panel A of Fig. 4.

Even if potatoes were not the only staple crop introduced from the New World to the Old World, they resulted in the highest socio-economic benefits (Nunn and Qian 2011). Grennes (2007) and Nunn and Qian (2010) focused on other New World crops, which were also introduced along with potatoes to the Old World after the colonization of the

[6] See also Chen and Kung (2016) and Nunn and Qian (2011), which focused on the impact of maize and potato on socio-economic development. Olmstead and Rhode (2001) and Emerick (2018), on the other hand, focused on the role played by tractors and fertilizers.

[7] Jia (2014) focuses on the effects of the introduction of sweet potatoes on peasant uprisings in China. The potato was brought to China from the Americas as part of the Columbian Exchange around the seventeenth century. He finds that its diffusion significantly lowered the number of peasants' uprisings due to periods of droughts. In fact, before the introduction of sweet potatoes in China, there was a significant negative relationship between precipitations (which represent a positive income shock for peasants) and peasant uprisings. After the diffusion of the sweet potato, which was more resistant to droughts, the uprisings significantly declined in areas more suitable for the cultivation of the newly introduced staple crop.

Americas. These include maize, cassava, tomatoes, chili and bell peppers, cacao, and sunflowers.[8] However, none of these crops matches the potato in terms of calories and other nutrients. For instance, maize and cassava were two other high-caloric crops introduced in the Old World.

However, maize produces significantly fewer calories per acre of land, and cassava has a substantially lower amount of protein. On the other hand, an acre of land dedicated to the cultivation of the potato can generate 10,900 kgs of yield, while oats, barley, and wheat produce 690, 820, and 650 kgs, respectively (Nunn and Qian 2011). As a result, potato cultivation requires less land to produce the same amount of calories as other crops. For instance, only 0.5 acres of dedicated land for potato cultivation is required to produce 42 megajoules (or approximately 10,000 calories) per day for one year. In contrast, 1.6, 1.4, and 1.7 acres of land would be needed for growing oats, barley, and wheat to generate the same amount of calories (Young 1771).

2.2 Infectious Diseases and Agricultural Productivity

In contrast to the positive impacts of new crops and technological innovations on population growth, deteriorating health conditions due to infectious disease outbreaks such as malaria infection have negatively affected economic productivity (Gooch 2017; Cutler et al. 2010; Bleakley 2009). Therefore, as Panel B in Fig. 4 demonstrates, any potential gain from introducing new crops can be offset by the emergence of infectious disease threats that undermine the health and availability of farmers and their productivity (Hansen and Lønstrup 2015; Percoco 2013). On the contrary, public health interventions can improve the well-being of the farmers and make a positive impact on their productivity (Wouterse and Badiane 2019).

Such macroeconomic effects of health conditions have been documented in other studies too. For instance, using mortality rate data from the most widespread and deadly diseases during the 1940–1980 period, it was shown that the reduction in mortality rates increased the population levels, but the same does not hold for income per capita (Acemoglu and Johnson 2007). In particular, the improvements in health conditions have a positive impact on the population levels in the short run. However, because the land is fixed in the short period, the effects on income per capita might be slightly adverse.

In the case of malaria, numerous studies have lighted its role as one of the primary infectious diseases throughout the sixteenth to the twentieth century (Bruce-Chwatt 1988; Poser et al. 1999). However, it was not until the early years of the 1900s when technological advancements and the discovery of new drugs and modern chemical components made it possible to prevent malaria transmission effectively (Acemoglu and Johnson 2007; Cutler et al. 2010; Bleakley 2010; Gooch 2017). One early example of effective control policies was recorded during the construction of the Panama Canal in the 1910s. Prior to the construction of the Panama Canal, malaria was a major cause of death and illness among workers in the area. According to the Centers for Disease Control and Prevention (CDC), in 1906, over 26,000 employees were working on the Canal. Of these, over 21,000 (i.e., more than 80%) were hospitalized for malaria at some point during their work. Thanks to

[8] It is necessary to highlight that for sweet potatoes, which show similar nutritional properties to those of the potato, there is historical evidence of their introduction, and consequently, their diffusion in Europe and China already in 1000 (Nunn and Qian 2011).

the discovery of the malaria transmission mechanism and the subsequent eradication measures, by 1912, while there were more than 50,000 workers at the Canal, the hospitalization number had dropped to approximately 5600 (Waldo 1907; Sibert and Stevens 1915).

Furthermore, widespread eradication programs in the early 1900s have also contributed to the increased agricultural productivity in the United States (Malpede 2022).

3 Data

We use four main datasets that provide geographical and temporal information at different levels of aggregation for a variety of agriculture, climate, population, and urbanization variables. The agricultural data which allow for the construction of the Potato Suitability Index (PSI) come from the IIASA/FAO (2012) database (Fischer et al. 2012).[9]

Kiszewski et al. (2004) provided the Malaria Stability Index (MSI). The population and urbanization data for each geographic area come from Klein Goldewijk et al. (2010). Finally, data for additional grid-specific controls such as terrain ruggedness and suitability for growing other crops come from various data sets and recent studies (Nunn and Puga 2012; Fischer et al. 2012). Table 7 summarizes the data inputs used for the empirical analysis.

3.1 Potato Suitability Data

The PSI is constructed based on grid-cell level data on rain-fed potato suitability from the Food and Agriculture Organization (FAO)'s Global Agro-Ecological Zones (GAEZ) 2012 database. It captures the potential suitability for cultivating potatoes based on regional weather and land conditions. The PSI is available at a spatial resolution of 0.5° latitude by 0.5° longitude, which is approximately 56 kms by 56 kms (measured at the equator). It ranges from 0 to 1, with one being totally suitable for potato cultivation.

The construction of FAO's GAEZ database occurred in various stages that we summarize in Appendix A. The result of this articulated procedure is, for each crop, a simple spatial raster file with global coverage containing information on the suitability for cultivating a specific crop such as potato. It is important to note that these suitability calculations do not consider actual crop yield data and, therefore, are not affected by socioeconomic variables such as supply and demand for specific crops.

FAO provides a discrete version of this database that reports the proportion of each grid's land classified under five mutually exclusive categories describing how suitable the environment is for growing each crop. The categories are based on the calculated percentage of the maximum yield that can be attained in each grid cell. The five categories and their corresponding yields are: i. very suitable land (0.8–1), ii. suitable land (0.6–0.8), iii. moderately suitable land (0.4–0.6), iv. marginally suitable land (0.2–0.4), and v. unsuitable land (0–0.4).[10]

The PSI is not based on only one variety of potatoes. Rather, it is calculated considering four different varieties that span a heterogenous range of climatic environments. This

[9] The PSI is also used to study the economic effects of long-term climate change (Waldinger 2022).

[10] To approximate historical conditions as closely as possible, we use variables constructed under the assumption that cultivation occurs under rain-fed conditions and medium input intensity.

addresses the concern that new potato varieties might have been developed in areas that experienced higher urbanization and population growth.

In addition, historical evidence suggests that new varieties of potato were developed only after the potato blights between 1845 and 1846 Nunn and Qian (2011). Moreover, Salaman and Burton (1985) reports that there is no evidence that the focus on new varieties occurred in areas with a rapid increase in population.[11]

That said, the possibility of the development of new varieties of potatoes still exists. To address this issue, we follow Nunn and Qian (2011) and perform a test in which we first compute the proportion of potato-suitable area out of the total area at the country level and then use this as our main regressor. The results of this robustness check are presented in Section 5.3 and corroborate the findings shown in the baseline equation.

3.2 Malaria Stability Data

The MSI captures the potential stability of malaria transmission based on regionally dominant vector mosquitoes, temperature, and precipitation data set (Kiszewski et al. 2004). In other words, the MSI indicates the presence of climate conditions correlated with the reproduction of mosquito larvae which are the natural vector of malaria. Similar to the PSI, the MSI is available at a spatial resolution of 0.5° latitude by 0.5° longitude, which is approximately fifty-six kilometers by fifty-six kilometers (measured at the equator). It ranges from 0 to 39, with 39 being extremely suitable for stable malaria transmission throughout the year.

The MSI represents the climatic suitability for the reproduction of mosquito larvae, and it, therefore, is a proxy of the stability for the diffusion of the malaria disease (Kiszewski et al. 2004). As for the PSI, the MSI is time-invariant and only depends on exogenous climatic factors (i.e., humidity, average temperature, and precipitation levels) along with the biological characteristics of two particular species of mosquitoes (i.e., Plasmodium falciparum and Plasmodium vivax) which are the responsible for transmitting the malaria disease to humans. Those biological factors are, for instance, reproductive rates and life span. Specifically, the construction of the MSI involved four steps, which we summarize in Appendix A.

Although the MSI is a continuous variable, we consider different categories of Malaria Stability according to the scientific literature (Kiszewski et al. 2004): i. no endemic areas ($MSI < 0.06$); ii. low endemic areas ($0.06 < MSI < 1$); iii. moderately endemic areas ($1 < MSI < 5$); iv. highly endemic areas ($5 < MSI < 10$); vi. very highly endemic areas ($MSI > 10$). We use this classification to assess the impact of potato suitability on population and urbanization in areas with different endemic conditions.

Figure 8 in the Appendix plots the spatial distribution of the two main variables of interest, namely the Potato Suitability Index (PSI) and the Malaria Stability Index (MSI), respectively. Moreover, in Fig. 9, we show a slight correlation between suitability for potato cultivation and stability of malaria (i.e., in the order of 0.48). In particular, some areas that are highly suitable for potato cultivation exhibit high stability of malaria as well.[12]

[11] Further details on the varieties of potatoes, which appeared since 1850, are provided in Nunn and Qian (2011).

[12] Areas highly suitable for potato cultivation have a Potato Suitability Index > 0.8 as defined by FAO.

3.3 Population and Urbanization Data

Grid-cell level data on historical population and urbanization rates are retrieved from the History Database of the Global Environment (HYDE) (Klein Goldewijk et al. 2011). HYDE is an internally consistent combination of updated historical population (gridded) estimates and land use for the past 12,000 years. HYDE is developed by the PBL Netherlands Environmental Assessment Agency and is used by the World Climate Research Program Coupled Model Intercomparison Project (CMIP6). This is a very disaggregated dataset with a spatial resolution of 5 arc minute pixels (about 10 kms at the equator) covering the whole world from 10,000 BC to 2017 AD. We use century data on population and urbanization from 1100 to 1900 (Table 1).

HYDE population and urbanization data offer four particular advantages that are unique among available historical data. First, they provide highly disaggregated historical population and urbanization data. Second, no other database on population and urbanization for endemic areas is available before 1900. Therefore, HYDE allows us to go back as far as 1100. Third, HYDE also contains information on the proportion of land dedicated to the cultivation of crops. Forth and most importantly, the backward-projection procedure used by Klein Goldewijk et al. (2011) to construct the historical grid-level population and urbanization data does not change across centuries, thus avoiding any artificial break in the data. The major implication is that it allows for an internally consistent dataset, even if it goes long back in time. For these reasons, HYDE's population database has been extensively used both in the scientific literature (Ellis et al. 2021; Andermann et al. 2020; Mottl et al. 2021; Morrison et al. 2021), and recently in the economic literature as well (Gooch 2017; Okoye 2021).

The process of estimating population and urbanization at very disaggregated units is explained in the documentation of the History Database of the Global Environment (HYDE) (Klein Goldewijk et al. 2011) and involves a series of steps described in Section A of the Appendix. We extract data on population and urbanization from the HYDE dataset and map it on a global regular grid shapefile with a resolution of 0.5° latitude and 0.5° longitude, using Geographic Information System (GIS) libraries in the R software.

Table 1 Table of data inputs for the econometric identification

Variable	Source	Unit	Resolution	Mean	Min	Max
Malaria stability	(Kiszewski et al. 2004)	Index	0.5°	2.546	0	39
Potato suitability	IIASA/FAO (2012)	Index	0.08°	0.187	0	1
Maize suitability	IIASA/FAO (2012)	Index	0.08°	0.128	0	1
Cassava suitability	IIASA/FAO (2012)	Index	0.08°	0.058	0	1
Barley suitability	IIASA/FAO (2012)	Index	0.08°	0.137	0	1
Wheat suitability	IIASA/FAO (2012)	Index	0.08°	0.143	0	1
Ln(Population)	HYDE 3.2	Count	0.08°	6.802	−30.634	15.109
Urban population share	HYDE 3.2	Share	0.08°	0.031	0	1
Ln(Terrain ruggedness)	(Nunn and Puga 2012)	Index	0.08°	−0.239	−3.310	1.908
Ln(Distance from the equator)	(Nunn and Puga 2012)	Kilometers	0.5°	3.336	−0.62	4.174
Ln(Distance from the coast)	(Nunn and Puga 2012)	Kilometers	0.5°	6.321	1.500	7.699
Ln(Elevation)	(Nunn and Puga 2012)	Meters	0.5°	6.247	2.322	7.998
Country shapefiles	(Hijmans et al. 2010)	Polygon	-	-	-	-

A spatial join is performed between the regular grid and the Global Administrative Unit Layer shapefiles to create a country attribute in the regular grid shapefile matching the underlying country name. Figure 10, in the Appendix, shows the urbanization and population growth rates in potato-suitable areas versus non-potato-suitable areas from 1200 to 1900. Limitations of this data and the appropriate workarounds are further discussed in Section A of the Appendix.

3.4 Additional Control Variables

To control for additional agricultural grid-specific characteristics, which might bias the results, we also consider the suitability for growing other crops (i.e., maize, cassava, barley, and wheat) retrieved from the GAEZ 2012 database of the IIASA/FAO. In particular, we use rain-fed crop suitability to avoid measurement error from changes over time in irrigation intensity and technologies.

We also include additional time-invariant geographical characteristics which might have affected population and urbanization growth in the Old World after 1700, such as terrain ruggedness, elevation, the presence of a tropical climate, the distance to the equator and to the nearest coast (Nunn and Qian 2011). To allow for time-varying effects of these variables, each variable is interacted with time period indicator variables as in Waldinger (2022).

We first use the QGIS software to adjust the spatial resolution of the HYDE database to that of the Potato Suitability Index and Malaria Stability Index and second to match the spatial data (Section A of the Appendix). We intersect the final dataset with current national boundaries using the Global Administrative Unit Layer shapefiles (Hijmans et al. 2010) to include country-by-time fixed effects.[13] We also control for country-specific characteristics, such as the proportion of cropland or total country area, the ratio of tropical area, the distance from the equator, and the nearest coast (Nunn and Qian 2011).

4 Empirical Strategy and Main Results

4.1 Empirical Strategy

We use a difference-in-differences strategy where the reference group is composed of grids not suitable for the cultivation of the potato (i.e., $PSI < 0.4$).

We consider two treatment groups. The first treatment group comprises grids suitable for growing potatoes but not suitable for malaria transmission (i.e., $PSI > 0.4$ and $MSI < 0.06$).[14] The second treatment group, instead, is composed of grids both suitable for growing potatoes and suitable for malaria transmission (i.e., $PSI > 0.4$ and $MSI > 0.06$).

In particular, we first estimate the impact of growing potatoes on Old World urbanization and population considering the whole sample of grids. Second, we estimate the impact

[13] Current national boundaries are artificially stretched back in time so that country trends take into account some common trends of grids that in the future will belong to the same country.

[14] We use the definition of non-endemic areas provided by Kiszewski et al. (2004) as areas with $MSI < 0.06$. Areas with $MSI > 0.06$ show some degree of Malaria Stability.

of potato diffusion by restricting the sample to only non-malaria-endemic areas; and finally, we restrict the sample to malaria-endemic areas only. This restriction of the sample to non-malaria endemic areas and to endemic areas allows us to understand if the agricultural boost brought by the diffusion of the potato led to different effects on population and urbanization growth rates in areas with lower or higher stability of malaria transmission. In Sect. 4.3, we also compute the effects of the diffusion of the potato in the Old World on different classes of Malaria Stability (i.e., non-endemic if $MSI < 0.06$, low endemic if $0.06 < MSI < 1$, moderately endemic if $1 < MSI < 5$, and highly endemic if $5 < MSI < 10$ against the reference category $10 < MSI < 39$).

To compute the effects of the introduction of the potato we first estimate the following equation:

$$\mathrm{y}_{i,c,t} = \alpha + \beta_1(\text{Potato})_i \cdot I_t^{Post} + \beta_2(\text{Potato})_i + \sum_{t=1000}^{1900} \gamma \mathbf{X'}_i \cdot I_t + \mathbf{W}_c^{'} + \omega_i + \delta_t + \sigma_{ctrend} + \epsilon_{i,c,t} \tag{1}$$

where index i indicates the grids in country c and t indexes time periods considered in the analysis (i.e., 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1750, 1800, 1850, and 1900). The dependent variable is represented as $y_{i,c,t}$, which is either the natural log of population or city population share for each grid i in the country c at time t. Variable $(\text{Potato})_i$ is an indicator variable that takes a value of zero if the grid is not suitable for the cultivation of the potato (i.e., $PSI < 0.4$) and a value of one if the grid is suitable for the cultivation of the potato (i.e., $PSI > 0.4$). This variable is then interacted with another indicator variable I_t^{Post} which takes a value of zero for years from 1000 to 1600, which are part of the pre-potato introduction period (Nunn and Qian 2011); and a value of one for the post-introduction period ranging from 1700 to 1900.

Vector $\mathbf{X}_i^{'}$ controls for additional time-invariant grid-specific characteristics which might have affected urbanization and population between 1700 and 1900 (i.e., the suitability for growing other crops such as maize, cassava, barley, and wheat). Vector $\mathbf{W}_c^{'}$ controls for country-specific characteristics, such as terrain ruggedness, elevation, the presence of a tropical climate, the distance to the equator and to the nearest coast (Nunn and Qian 2011).

Furthermore, since potatoes can be successfully cultivated on the rugged terrain at high altitudes and are less suitable to be cultivated in tropical areas (Nunn and Qian 2011; Nunn and Puga 2012), we control for the natural log of a country's average elevation, the natural log of its ruggedness, and the natural log of a country's land that is defined as being tropical. Each variable is interacted with time period indicator variables to allow for time-varying effects of these variables.

This equation also includes grid fixed effects ω_i, time fixed effects δ_t, along with country-specific linear trends σ_{ctrend}. Moreover, to ensure that the effect of introducing the potato in the Old World is not confounded by other changes in the suitability of crops over the same time period, we include the grid-specific agricultural suitability index (Galor and Özak 2015). Standard errors are clustered at the grid-cell level.

The coefficient of interest in Eq. 1 is β_1, which is the estimated impact of potato suitability on either population or urbanization. It measures the additional growth in population or urbanization experienced by grid cells that are suitable for potato cultivation after potatoes were introduced in 1700 (relative to earlier decades). A positive value of this coefficient indicates that countries with a geographic environment more suitable for growing potatoes had witnessed a more significant increase in population after 1700 compared to the period before 1700 compared to areas not suitable for growing potatoes. If malaria effectively counteracted the positive effects of potato on the population and the urbanization rates in the Old World countries, we would expect to find a positive effect of the PSI in non-endemic grids and a negative (or not significant) effect in endemic grids.

Results of the baseline Eq. 1 confirm the positive demographic impact of the adoption of the potato after its diffusion in the Old World. We estimate the coefficient of the potato suitability interaction term, Potato $\cdot I_t^{Post}$ (first row in Table 2). According to the estimates in column (1), grid cells that were suitable for potato cultivation (i.e., those with $PSI > 0.4$) experienced a 1.9 percentage point increase in urban population share compared to non-suitable grid cells.

In addition, the estimated coefficient of the total population in column (4) suggests that the population in areas suitable for potato cultivation increased by 9.1 percentage points relative to areas not suitable for growing potatoes. However, not all people living in potato-suitable areas could benefit from the positive effects generated by the cultivation of the potato. Columns (2) and (5) in Table 2 show that only *non-endemic* ($MSI < 0.06$) areas have benefited from the positive impacts of the diffusion of the potato. The non-endemic potato-suitable areas increased their urbanization share by two percentage points, and their population rose by 9.09 percentage points relative to non-suitable locations. On the other hand, the suitability for cultivating potatoes had no statistically significant impact on endemic areas ($MSI > 0.06$) as the estimated coefficients in columns (3) and (6) suggest.[15]

Drawing from the results shown in Table 2, we draw the following conclusions: First, the relationship between the suitability of growing potatoes on the urbanization and population growth of the Old World is positive, meaning that higher suitability of potato is associated with higher population and urbanization growth; Second, the relationship between malaria stability and our socio-economic variables is negative, implying that higher values of malaria stability are associated with lower population and urbanization growth of the Old-World; Third: as the stability of malaria increases, the impact of potato cultivation on the socio-economic growth of the Old World declines.

4.2 Flexible Estimates

A crucial assumption of the empirical strategy in Eq. 1 is the cutoff date of 1700 for the introduction of the potato to the Old World. The historical evidence suggests that the adoption of the potato began in the late seventeenth century and spread significantly by the early eighteenth century (Nunn and Qian 2011; Salaman and Burton 1985; McNeill 1999). Here, we estimate a fully flexible estimating equation that takes the following form:

$$y_{i,c,t} = \alpha + \sum_{j=1100}^{1900} \beta_j (\text{Potato})_i \times \text{I}_t^j + \alpha_j (\text{Potato})_i + \boldsymbol{\gamma}\, \mathbf{X}_i^{'} + \mathbf{W}_c^{'} + \omega_i + \delta_t + \sigma_{ctrend} + \epsilon_{i,c,t} \tag{2}$$

where all variables are defined as in Eq. (1). The main difference is that here, we interact $(\text{Potato})_i$ with each time-period indicator (i.e., I_t^j) rather than a single post-adoption indicator to allow for time-varying effects of the diffusion of potato cultivation on urbanization and population. The estimated vectors of β_js reveal the relationship between potato suitability and population and urbanization of grid i in each time period. If, for example, the introduction of potatoes increased urbanization of grid cell i after year t, then we would

[15] Table 9 in the Appendix reports the coefficients of all variables included in Eq. 1.

Table 2 The impact of potato suitability on urbanization and population: Old World, Pre Malaria Eradication, Gridded analysis

	Dependent variable					
	Urbanization share			Log population		
	(1)	(2)	(3)	(4)	(5)	(6)
Potato × I^{Post}	0.019***			0.092***		
	(0.003)			(0.009)		
Potato × I^{Post} (No endemic areas)		0.020***			0.087***	
		(0.002)			(0.009)	
Potato × I^{Post} (Endemic areas)			0.009			0.039
			(0.006)			(0.041)
Country × Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Grid FE	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	457,356	330,325	127,031	457,356	330,325	127,031
Grid-cells	42,264	30,712	11,552	42,264	30,712	11,552

Observations are at the grid-year level. Regressions in columns (1) and (4) use a baseline sample of 42,264 Old-World grid cells. Regressions in columns (2) and (5) use a restricted sample of 30,712 Old-World grid cells with non-endemic climate conditions (i.e., $MSI < 0.06$). Regressions in columns (3) and (6) use a restricted sample of 11,552 Old-World grid cells with endemic climate conditions (i.e., $MSI > 0.06$). Countries in North and South America are excluded. The periods are 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1750, 1800, 1850, and 1900. The dependent variable is either the natural log of the total population of the grid measured in persons (log population) or the share of the population living in urban areas (urbanization share). Potato takes value of 0 if the grid is not suitable for growing potato (i.e., $PSI < 0.4$) and value of 1 if the grid is suitable for growing potato (i.e., $PSI > 0.4$). This is interacted with an indicator for each period of the sample. All regressions include year-fixed effects and grid-specific fixed effects. Each control variable listed is interacted with a full set of time-period fixed effects. Coefficients are reported with standard errors clustered at the grid level in parentheses

expect the estimated β_j coefficients to be significant only for the years after t but non-significant for the years before. Moreover, we expect the coefficients of interest to be positive in magnitude only for non-endemic areas, while no or little effects should be found in more endemic areas. Estimates of Eq. (2) are reported in Fig. 5. This figure indicates that the choice of the year 1700 as the starting point for the mass introduction of the potato to the Old World can be indeed supported by considering the negligible impact of potato suitability on population growth and urbanization in non-endemic areas prior to 1700 in contrast to its increasing positive impact in these areas in the subsequent years.[16]

An important additional finding from Fig. 5 is the negative and statistically significant impact of potato suitability on urbanization in highly endemic areas. This result may seem

[16] In addition, in Section C of the Appendix, we present the results of the analysis considering different cutoff values for the definition of potato-suitable areas. Finally, in section D of the Appendix, we estimate a dynamic model in which we include a spatial matrix that exploits variations in the Potato Suitability Index occurring in grids located within 0.5° latitude x 0.5° longitude.

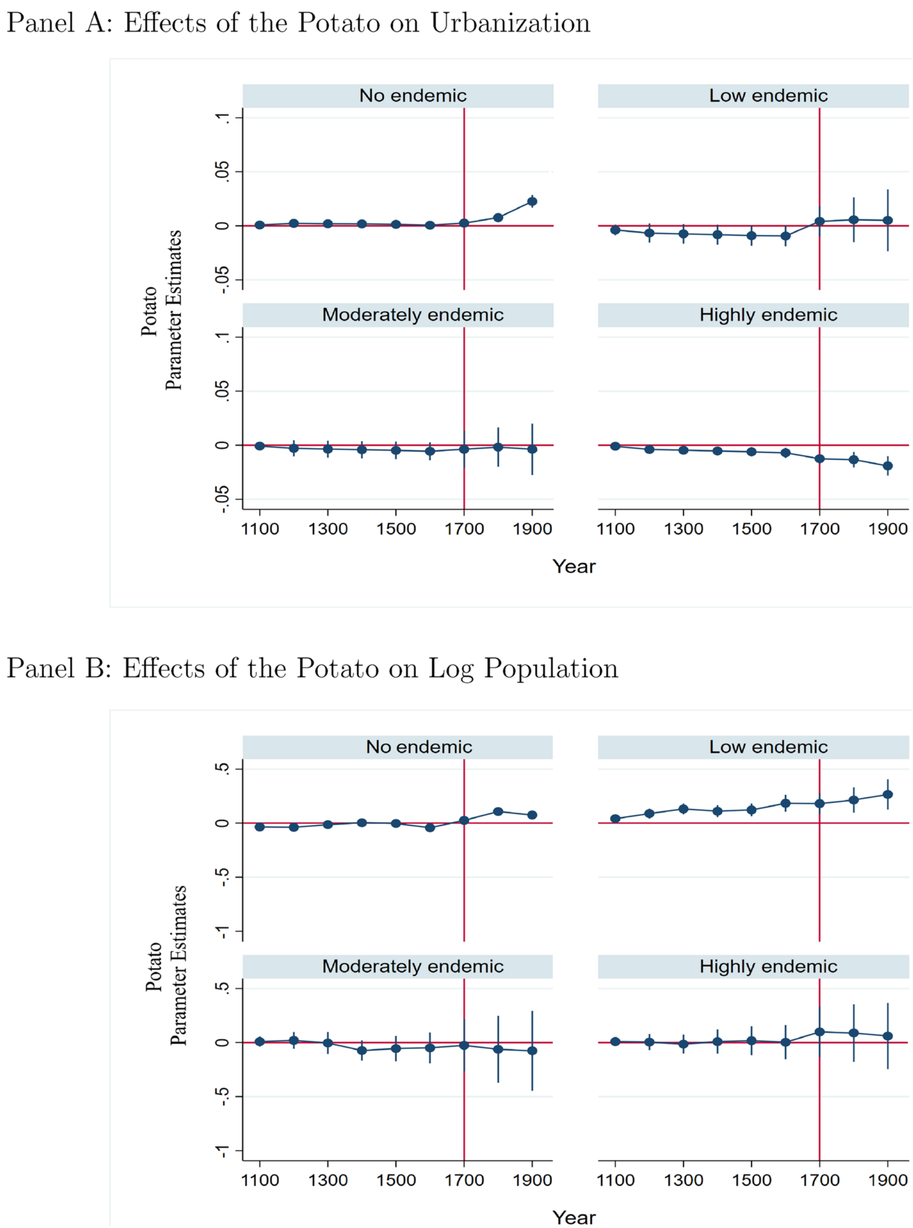


Fig. 5 Flexible estimates of the relationship between potato-suitable areas and urbanization (Panel A) and population (Panel B) across different malaria stability classes. Blue vertical lines show the 95% confidence intervals and the vertical red lines indicate the year 1700 when the potato was introduced to the Old World

counter-intuitive, considering the generally positive effects of potato diffusion on socioeconomic growth in the Old World.

However, Table 8 provides a possible explanation by showing summary statistics of the PSI for each malaria stability class. According to the table, there is no correlation between the suitability of potatoes and the occurrence of malaria. However, regions with a high incidence of vector-borne diseases (with an MSI greater than 5) are usually more suitable for growing potatoes. For instance, places with a low or non-existent occurrence of malaria have an average potato suitability of approximately 0.19. In contrast, areas with an extremely high prevalence of vector-borne diseases have an average potato suitability index of 0.21. This suggests that areas with a high incidence of vector-borne diseases are about 10% more suitable for growing potatoes than non-endemic regions.

Second, farmers living in highly endemic areas who attempted to cultivate potatoes could easily fall victim to the vector-borne disease, leading to their deaths. As a result, the higher suitability of potatoes in extremely endemic areas negatively affected urbanization due to the threat it posed to farmers' lives.

In this regard, Hong (2011) found that during the period 1850–1860, malaria was responsible for up to 166 deaths per 100,000 people living in the most endemic areas of the US. This was more substantial among farmers who required physical strength and frequent outdoor work than among other occupational groups. Concerning the African continent, during the 1800s, family members were the primary source of labor supply in farming. Indeed, when farmers were affected by the vector-borne disease, they were temporarily replaced by other family members (children and grandchildren). If multiple members of a farm family suffered from malaria during planting and harvest seasons, it would have a significant impact on the success of the farm and be the cause of vast migratory waves from endemic areas to less endemic ones (Packard 2001). This explains why, in highly endemic areas of the Old World, the urbanization share decreased after the cultivation of the potato.

To demonstrate this reasoning, we estimate model 2 excluding extremely endemic areas (i.e., $MSI > 20$). Those areas cover less than 2% of the total Old-World area (796 grids out of a total of 42,264 grids). The results of this restriction are shown in Fig. 11, showing that the negative impact of potato cultivation in highly endemic areas disappears when excluding areas with a $MSI > 20$, that is where mortality caused by malaria was extremely high.

4.3 Impact of Potato Suitability per Class of Malaria Stability

Equation (1) builds on the assumption that the effects of potato diffusion on urbanization and population are linear across different levels of Malaria Stability. We can relax this assumption and allow for non-linearity of the effects in the following regression model:

$$y_{i,c,t} = \alpha + \sum_{b} \beta_b (\text{Potato})_i \cdot I_t^{Post} + \sum_{b} \alpha_b (\text{Potato})_i + \boldsymbol{\gamma}\, \mathbf{X}_i^{'} + \mathbf{W}_c^{'} + \delta_t + \sigma_{ctrend} + \epsilon_{i,c,t} \quad (3)$$

where we combine four estimations of Eq. (1) across different classes of malaria-suitable areas (indexed by b in the equation above) in one model: the first class includes all non-endemic areas with $0 < MSI < 0.06$, the second class comprises the low-endemic areas with $0.06 < MSI < 1$, the third class comprises moderately-endemic areas with $1 < MSI < 5$, and finally the fourth class comprises high-endemic areas with $5 < MSI < 10$. Those values are compared with the reference category $10 < MSI < 39$, which identifies areas with very high Malaria Stability. The specification controls for the same fixed effects, trends, and individual-level controls as the baseline specification in Eq. (1).

If our specification is correct, we expect the positive effects of the introduction of the potato on the population and urbanization to be higher in non-endemic areas and decline as the climatic suitability of malaria increases. The results of Eq. (3) are reported in Fig. 6. They confirm that the effect of the potato on population growth and urbanization is primarily positive in non-endemic areas. On the contrary, these results indicate that for locations with a $MSI > 1$, we see little effects on urbanization and no significant effects on the population, with the estimates approaching zero for higher endemicity levels. These results confirm that the positive impact of the diffusion of the potato on urbanization and population only occurred in non-endemic areas.[17]

As for the previous section, we estimate model 3 excluding extremely endemic areas (i.e., $MSI > 20$). The results of this restriction are shown in Fig. 12. Once again, it shows that the negative impact of potato cultivation in highly endemic areas disappears.

4.4 Interaction of PSI and MSI

Here we evaluate the interaction of the Potato Suitability Index and the Malaria Stability Index in endemic areas as well as non-endemic ones. This specification allows us to better comprehend if the presence of climate conditions suitable for malaria transmission counteracted the positive effects of the diffusion of the potato.

$$\begin{aligned} y_{i,c,t} = {} & \beta_1\, \mathrm{PSI}_i \times \mathrm{MSI}_i \cdot I_t^{Post} + \beta_2\, \mathrm{PSI}_i \cdot I_t^{Post} + \beta_3 \mathrm{MSI}_i \cdot I_t^{Post} \\ & + \sum_{t=1000}^{1900} \Omega \mathbf{X}'_{i,c} \cdot I_t + \sum_{t=1000}^{1900} \delta I_t + \sum_p \gamma_p I_t^p + \epsilon_{i,c,t} \end{aligned} \tag{4}$$

The variable $\mathrm{PSI}_i \times \mathrm{MSI}_i$ is the interaction of the suitability index for potato cultivation (PSI) and the stability of malaria index (MSI) for each grid i. Our variable of interest $\mathrm{PSI}_i \times \mathrm{MSI}_i$ shows the impact of potato suitability in non-endemic grids versus endemic grids.

Again, the variable I_t^{Post} is a post-adoption dummy variable which takes value 1 for years after the exogenous adoption of potato in the Old World (i.e., 1700, 1750, 1800, 1850, and 1900) while value 0 for years ex-ante the exogenous introduction of the potato in the Old World (i.e., 1000, 1100, 1200, 1300, 1400, 1500 and 1600). Equation 4 also includes grid fixed effects $\sum_p \gamma_p I_t^p$, where p indicates the set of Old World grids; time period indicators $\sum_{t=1000}^{1900} \delta I_t$ and country-specific fixed effects which allow for a comparison of each grid within the same country.

As before $\mathbf{X}_{i,s}$ represents vectors of time-invariant grid-specific controls included in the regression. As grid-level controls, we use a set of relevant geographical and historical characteristics which might have affected population and urbanization: i.e., total cropland area per grid, ruggedness level, and total areas of other crops, i.e., maize, silage, sweet potato, and cassava.

Table 3 shows the results of this model. Columns (1) and (4) show that the impact of potato suitability on urbanization and population in no endemic areas is positive. In

[17] In section C of the Appendix, we also check for different cutoff values of potato suitability. We define a grid to be suitable for growing potatoes if it has a $PSI > 0.5$, or $PSI > 0.3$, or $PSI > 0.2$, or $PSI > 0.1$.

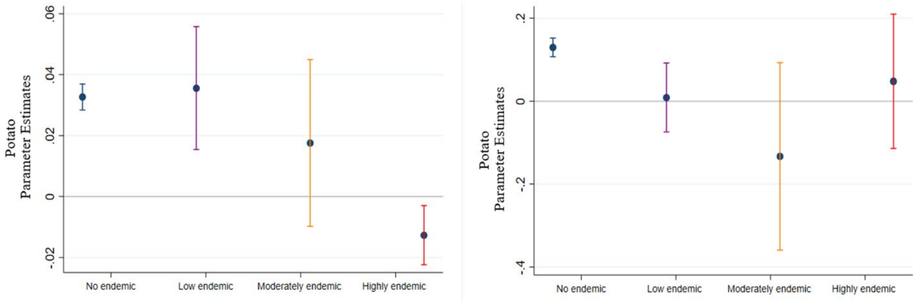


Fig. 6 Effects of the diffusion of the potato on urbanization (left) and population (right) growth rates after 1700 across different malaria stability classes

contrast, columns (2) and (5) indicate that, in endemic areas, the impact of potato cultivation on the socio-economic growth of the Old World disappears. Overall, the impact of the diffusion of the new staple crop if positive and significant as shown in columns (3) and (6). Using the continuous version of the PSI and the MSI, Table 3 confirms the baseline results shown in Table 2.

5 Addressing Potential Concerns

In this section, we address some of the potential concerns about our empirical method, including the possibility that the baseline estimates might have been driven (a) by the greater impact of potato on the population and urbanization of countries that adopted the potato early on (notably Spain and Portugal) and (b) by changes in climatic conditions throughout the period of the analysis. Finally, we check the validity of our estimates at the country level.

5.1 Early Importers of the Potato

In this section, we consider that not all Old World countries discovered and adopted the potato at the same time. As a result, our baseline estimates might be partly driven by the Old World countries that cultivated potatoes before everyone else.

Spain and Portugal were the first countries to import and cultivate potato (Glendinning 1983). To address this potential bias, we restrict the sample to Spain and Portugal only. The results of this restriction are shown in Table 4 and once again confirm our baseline findings that the positive effects of potato suitability on the population and urbanization growth only occurred in no-endemic areas, while no significant effect can be found in more endemic areas.

In addition, we run the same regression excluding Spain and Portugal. This would address the concern that the results shown in Table 4 are driven by the early importer countries. Results of this additional check are reported in Table 10 in the Appendix and show that the estimates remain robust to the exclusion of Spain and Portugal.

Table 3 The impact of potato suitability on urbanization and population: Interaction PSI x MSI

	Dependent variable					
	Urbanization share			Log population		
	No endemic	Endemic	All	No endemic	Endemic	All
PSI × Post	0.020***	0.008	0.020***	0.090***	0.032	0.091***
	(0.002)	(0.008)	(0.002)	(0.010)	(0.051)	(0.009)
MSI × I^{Post}		0.000	0.000		0.002	0.002
		(0.000)	(0.000)		(0.002)	(0.002)
PSI x MSI x I^{Post}		−0.001	−0.001		0.005	0.001
		(0.001)	(0.001)		(0.008)	(0.007)
Country × Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Grid FE	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	330,325	127,031	457,356	330,325	127,031	457,356
Grid-cells	30,712	11,552	42,264	30,712	11,552	42,264

Observations are at the grid-year level. Regressions in columns (1) and (4) use a restricted sample of 11,552 Old-World grid cells with endemic climate conditions (i.e., $MSI > 0.06$). Regressions in columns (2) and (5) use a restricted sample of 30,712 Old-World grid cells with non-endemic climate conditions (i.e., $MSI < 0.06$). Regressions in columns (3) and (6) use a baseline sample of 42,264 Old-World grid cells. Countries in North and South America are excluded. The periods are 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1750, 1800, 1850, and 1900. The dependent variable is either the natural log of the total population of the grid measured in persons (log population) or the share of the population living in urban areas (urbanization share). All regressions include year-fixed effects and grid-specific fixed effects. Each control variable listed is interacted with a full set of time-period fixed effects. Coefficients are reported with standard errors clustered at the grid level in parentheses

5.2 Restriction of the time period between 1500 and 1900

Our estimation strategy assumes constant geo-climatic conditions over the period between 1100 and 1900; however, we know that the weather changed considerably during the middle-age period.[18]

To alleviate concerns about changes in climate that may have affected the impact of potato cultivation on endemic areas, we perform our empirical exercise by considering only the years after 1500. Results of this further restriction in Table 5 show a positive effect of potato suitability on urbanization share in endemic grids as well (although less significant). This can partially be due to low endemic areas (see Fig. 7). Here, the estimated β_j coefficients are not significantly different from zero for the years 1500, 1600, and 1700 (i.e., before potatoes were adopted). However, they are positive and larger in magnitude for the years after 1700 until 1900.

[18] Notably the medieval warm period which occurred between the 1300s and the 1400s (Hughes and Diaz 1994).

Table 4 The impact of potato suitability on urbanization and population in endemic vs non-endemic areas (Spain and Portugal, only): Old World, Gridded Analysis

	Dependent variable					
	Urbanization share			Log population		
	(1)	(2)	(3)	(4)	(5)	(6)
Potato × × I^{Post}	0.048***			0.054***		
	(0.004)			(0.006)		
Potato × I^{Post} (No Mal. areas)		0.096***			0.109***	
		(0.005)			(0.009)	
Potato × I^{Post} (Mal. areas)			0.001			−0.035
			(0.039)			(0.108)
Country × Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Grid FE	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3762	2145	1617	3762	2145	1617
Grid-cells	342	195	147	342	195	147

Observations are at the grid-year level. Regressions in columns (1) and (4) use a baseline sample of 342 grid cells for Spain and Portugal. Regressions in columns (2) and (5) use a restricted sample of 195 grid cells for Spain and Portugal with non-endemic climate conditions (i.e., $MSI < 0.06$). Regressions in columns (3) and (6) use a restricted sample of 147 grid cells for Spain and Portugal with endemic climate conditions (i.e., $MSI > 0.06$). Countries in North and South America are excluded. The periods are 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1750, 1800, 1850, and 1900. The dependent variable is either the natural log of the total population of the grid measured in persons (log population) or the share of the population living in urban areas (urbanization share). Potato takes value of 0 if the grid is not suitable for growing potato (i.e., $PSI < 0.4$) and value of 1 if the grid is suitable for growing potato (i.e., $PSI > 0.4$). This is interacted with an indicator for each period of the sample. All regressions include year-fixed effects and grid-specific fixed effects. Each control variable listed is interacted with a full set of time-period fixed effects. Coefficients are reported with standard errors clustered at the grid level in parentheses

5.3 Country-Level Analysis

For country-level modeling, data is extracted with the following procedure. First, the Potato Suitability Index layer is downloaded from FAO Global Agro-Ecological Zones database. Second, the Malaria Stability Index is retrieved from Kiszewski et al. (2004). The two files are imported in Google Earth Engine (Gorelick et al. 2017), where we compute the proportion of country area suitable for the cultivation of the potato (i.e., $PSI > 0.4$). Having calculated the proportion of the area suitable for growing potatoes for each of the Old World countries, we then compute the area with climate conditions more or less suitable for the transmission of malaria (i.e., $MSI > 1$).

Using this procedure, for each country, we obtain the proportion of the land suitable for growing potatoes and not malaria endemic on the one hand and the proportion of the land suitable for growing potatoes and malaria endemic on the other hand. The Global Administrative Unit Layer is used as the reference shapefile for national borders (Hijmans et al. 2010).

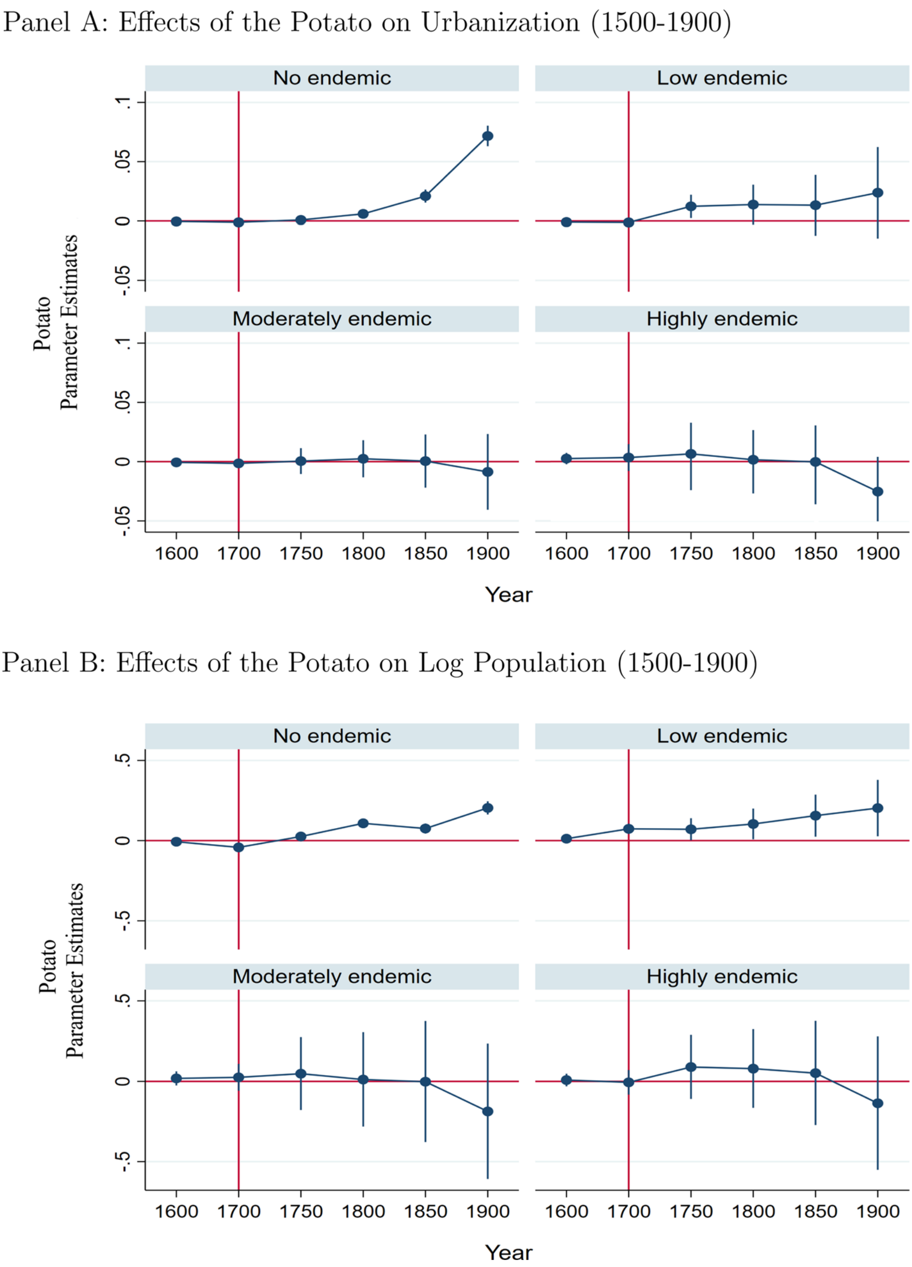


Fig. 7 Flexible estimates of the relationship between potato-suitable areas and urbanization (Panel **A**) and population (Panel **B**). The period of analysis starts in 1500. Blue vertical lines show the 95% confidence intervals, and the vertical red lines indicate the year 1700 when the potato was introduced to the Old World

Table 5 The impact of potato suitability on urbanization and population in endemic vs non-endemic areas (1500–1900): Old World, Gridded Analysis

	Dependent variable					
	Urbanization share			Log population		
	(1)	(2)	(3)	(4)	(5)	(6)
Potato × I^{Post}	0.019***			0.078***		
	(0.002)			(0.009)		
Potato × I^{Post} (No Mal. areas)		0.020***			0.076***	
		(0.002)			(0.009)	
Potato × I^{Post} (Mal. areas)			0.011*			0.052
			(0.005)			(0.042)
Country × Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Grid FE	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	291,442	210,595	80,847	291,442	210,595	80,847
Grid-cells	42,264	30,712	11,552	42,264	30,712	11,552

Observations are at the grid-year level. Regressions in columns (1) and (4) use a baseline sample of 42,264 Old-World grid cells. Regressions in columns (2) and (5) use a restricted sample of 30,712 Old-World grid cells with non-endemic climate conditions (i.e., $MSI < 0.06$). Regressions in columns (3) and (6) use a restricted sample of 11,552 Old-World grid cells with endemic climate conditions (i.e., $MSI > 0.06$). Countries in North and South America are excluded. The periods are 1500, 1600, 1700, 1750, 1800, 1850, and 1900. The dependent variable is either the natural log of the total population of the grid measured in persons (log population) or the share of the population living in urban areas (urbanization share). Potato takes the value of 0 if the grid is not suitable for growing potato (i.e., $PSI < 0.4$) and the value of 1 if the grid is suitable for growing potato (i.e., $PSI > 0.4$). This is interacted with an indicator for each period of the sample. All regressions include year-fixed effects and grid-specific fixed effects. Each control variable listed is interacted with a full set of time-period fixed effects. Full details of each control variable are provided in the text and Data Appendix. Coefficients are reported with standard errors clustered at the grid level in parentheses

$$\begin{aligned} y_{i,t} = {} & \beta_1 \ln(Potato\ Area)_i \cdot I_t^{Post} + \beta_2 \ln(Potato\ NoMal\ Area)_i \cdot I_t^{Post} \\ & + \beta_3 \ln(Potato\ Mal\ Area)_i \cdot I_t^{Post} + \sum_{j=1000}^{1900} \Omega_j \mathbf{X}'_i I_t^j + \sum_{j=1000}^{1900} \delta I_t^j \\ & + \sum_{c=1}^{130} \gamma_c I_i^c + \epsilon_{i,t} \end{aligned} \tag{5}$$

where index i represents each Old World country. A total of 130 countries were considered in the analysis, indexed with c. Index t represents time periods that are part of the analysis (i.e. 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1750, 1800, 1850, and 1900). Years from 1000 to 1600 are part of the pre-potato introduction period as in Nunn and Qian (2011). Since potatoes became widely diffused in the Old World soon after 1700, 1700 is considered the start of the post-introduction period, which ranges from 1700 until 1900.[19] The dependent variable is represented as $y_{i,t}$, which is the natural log of population and city population share for each Old World country i at time t.

The variable $Potato\ Area_i$ is the land area suitable for potato cultivation in country i. As in Nunn and Qian (2011) β_1 shows the estimated impact of potato-suitable areas on population and city population share after its adoption in the Old World. A positive and statistically significant value of β_1 is interpreted as an additional increase in population and urbanization of Old World countries with higher potato-suitable land between 1700 and 1900 compared to countries with less amount of potato-suitable land.

Besides computing the impact of the total size of the area suitable for potato cultivation on population growth and urbanization in each country, this procedure allows us to separate the impact of the size of the country area suitable for potato cultivation *but not* malaria-endemic from the impact of the size of the country area suitable for potato *and* malaria-endemic. To this regard, the variable $Potato\ NoMal\ Area_i$ is the land area suitable for potato cultivation but not malaria-endemic in country i.

The coefficient of our interest is β_2, which is the estimated impact of the adoption of the potato in non-malaria-endemic and potato-suitable land rather than on mere potato-suitable land. On the other hand, the variable $Potato\ Mal\ Area_i$ is the land area suitable for potato cultivation and, at the same time, suitable for stable transmission of malaria in country i. We expect β_2 to be positive and greater in magnitude than respectively β_1 and β_3. In particular, we would expect that $\beta_2 > \beta_1 > \beta_3$. For concreteness, such a situation would mean that the cultivation of the potato after its introduction in 1700 had a greater impact on population growth and urbanization in countries that, besides having a geographic environment more suitable for growing potatoes, were not as malaria-endemic. Moreover, a small coefficient β_3 would mean that the adoption of potatoes had a small impact on those countries that had a large amount of potato-suitable and malaria-endemic land areas.

Variable I_t^{Post} is a post-treatment dummy variable which takes value 1 for years after 1700 (i.e. 1700, 1750, 1800, 1850, and 1900) while value 0 for years before the exogenous introduction of the potato in the Old World (i.e. 1000, 1100, 1200, 1300, 1400, 1500 and 1600). This specification also includes country fixed effects $\sum_{c=1}^{130} \gamma_c I_t^c$, where c indicates the set of Old World countries constituted by a total of 130 countries and time period fixed effects $\sum_{t=1000}^{1900} \delta I_t$.

European countries have, on average, experienced higher growth in population and urbanization between 1700 and 1900 for reasons related to socio-economic and technological progress, which are beyond the cultivation of potatoes. However, European countries were also naturally more suitable for growing potatoes. It would be, therefore, necessary to estimate the effects of introducing the cultivation of potatoes within continent variation only.[20] Hence, to allow for a comparison of each country within the same continent, we add to Eq. 5 continent fixed effects interacted with time-period fixed effects.

The introduction of $Continent \times\ Year\ FE$ to Eq. 5 changes the interpretation of our coefficients of interest β_1, β_2 and β_3, which are now identified from within-continent variation only. $\sum_{j=1000}^{1900} \Omega_j \mathbf{X}'_i I_t^j$ represents country-specific characteristics interacted with time

[19] In the original paper, Nunn and Qian (2011) further test 1700 as the only valid cut-off date by performing the empirical analysis using alternative cut-offs.

[20] In other words, we do not want to compare a European country such as Italy with an African country, but comparing a European country with another European country makes the estimation strategy more robust and allows us to take into account all the other factors that may have caused European divergence.

period indicators to take into account other country-specific characteristics aside from the cultivation of potato that might have affected population and urbanization growth between 1700 and 1900. As country-level controls, we use the set of relevant geographical and historical country-specific characteristics which might have affected population and urbanization between 1000 and 1900 used in Nunn and Qian (2011), namely, country elevation, total cropland area, ruggedness, tropical area, distance from the equator and the nearest coast, an indicator variable taking value one if a country is an exporter of potatoes along with total areas of other crops, i.e., maize, silage, sweet potato, and cassava.

Table 6 shows the estimates from the Eq. 5 with the inclusion of all country-level geographical-specific control variables. All columns include country and time-period fixed effects along with all control variables used in the analysis, i.e., controls for land suitable for Old World staple crops interacted with time-period fixed effects and controls for ruggedness, elevation, and tropics, each interacted with the time-period fixed effects. Results shown in Table 6 confirm that climate conditions particularly favorable for the transmission of malaria counteracted the positive benefits of the cultivation of the new crop.

This is illustrated by the estimated coefficient of the potato suitability interaction term, $\ln(\textit{Potato Area}_i) \cdot I_t^{Post}$, which displays the average increase in population and urbanization levels respectively arising from the wide diffusion of potato in the Old World after 1700. According to the estimates in columns (1) and (4), a 1 percent increase in the amount of land suitable for the cultivation of the potato had a positive, although not significant, impact on urbanization, while population increased by 0.4 percentage points after 1700. This result is, with no surprise, very similar to what was shown in Nunn and Qian (2011).[21] However, the following two rows of Table 6 show that the positive impact of the introduction of the potato in the Old World was clustered in non-malaria endemic areas only. In contrast, the diffusion of the potato did not have any positive effect on malaria-endemic locations.

6 Conclusions

Introducing new crops and farming technologies can boost agricultural productivity, improve food security, and enhance other development outcomes. However, the diffusion of vector-borne diseases might counteract the positive effects generated by technological innovations.

In this paper, we used the historical diffusion of the potato to the Old World between 1700 and 1900 to examine how the presence of malaria counteracted the positive socio-economic effects caused by the diffusion of the newly discovered staple crop.

Our results indicate that the presence of malaria reduced, and in some cases offset, the increase in population and urbanization caused by the introduction of the potato, highlighting the interplay between environmental conditions, human health, and economic development.

Our findings also highlight the dangers of the emergence of infectious diseases due to climate change. Indeed, the rapid increase in temperatures during the last decades is

[21] The slight differences are due to the fact that Nunn and Qian (2011) use a version of the Potato Suitability Index dated 2002 while the version used to perform the following analysis is the most recent available, dated 2012.

Table 6 The impact of potato suitable area on population and urbanization. Country-level Analysis

	Dependent variable					
	Urbanization share			Log population		
	(1)	(2)	(3)	(4)	(5)	(6)
ln Potato area × I^{Post}	0.010			0.004***		
	(0.013)			(0.001)		
ln No Mal potato area × I^{Post}		0.019			0.004***	
		(0.015)			(0.001)	
ln Mal potato area × I^{Post}			−0.001			−0.000
			(0.017)			(0.001)
Continent × Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1528	1528	1528	1528	1528	1528
Adjusted R^2	0.665	0.665	0.612	0.456	0.456	0.447

Observations are at the country-year level. The sample consists of 1,528 observations for Old World countries. Regressions in columns (2) and (5) show the relationship between non-malaria endemic, potato suitable country-land (i.e., $MSI < 0.06$ and $PSI > 0.4$) and population and urbanization after 1700. Regressions in columns (3) and (6) show the relationship between endemic, potato-suitable country-land (i.e., $MSI > 0.06$ and $PSI > 0.4$) and population and urbanization after 1700. Countries in North and South America are excluded. The periods are 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1750, 1800, 1850, and 1900. The dependent variable is either the natural log of the total population of the grid measured in persons (log population) or the share of the population living in urban areas (urbanization share). All regressions include year-fixed effects and continent-specific fixed effects. Each control variable is interacted with a full set of time-period fixed effects. Coefficients are reported with standard errors clustered at the country level in parentheses

putting at risk areas of the world that, to this day, were never affected by vector-borne diseased (Rossati 2017). At the same time, climate change also affected crop yields in particularly fragile areas of the world (Sub-Saharan Africa and South-East Asia).

Overall, this study provides a new foundation for assessing global and local impacts of environmental-related health threats on the potential benefits of technological innovations.

Appendix

A. Data and Summary Statistics

See Tables 7 and 8.

Table 7 Descriptive statistics by continent

Variable	Obs	Mean	SD	Min	Max
Panel A: Europe					
Malaria stability	150,881	0.005	0.023	0	0.360
Potato suitability	150,881	0.187	0.221	0	0.937
Maize suitability	150,881	0.078	0.165	0	0.993
Cassava suitability	150,881	8.530	0.009	0	0.048
Barley suitability	150,881	0.229	0.259	0	0.999
Wheat suitability	150,881	0.237	0.267	0	0.999
Ln(Population)	150,881	5.741	3.440	−30.634	15.109
Urban population share	150,881	0.044	0.133	0	1
Ln(Terrain ruggedness)	150,881	−0.118	0.505	−3.310	1.560
Ln(Distance from the equator)	150,881	4.070	0.118	3.678	4.174
Ln(Distance from the coast)	150,881	6.771	1.221	3.003	7.518
Ln(Elevation)	150,881	5.840	0.423	2.322	7.189
Panel B: Asia					
Malaria stability	160,815	0.654	2.399	0	23.889
Potato suitability	160,815	0.085	0.133	0	0.816
Maize suitability	160,815	0.113	0.159	0	0.991
Cassava suitability	160,815	0.053	0.108	0	0.744
Barley suitability	160,815	0.115	0.158	0	0.964
Wheat suitability	160,815	0.119	0.163	0	0.964
Ln(Population)	160,815	8.200	2.351	−4.488	14.647
Urban population share	160,815	0.029	0.092	0	1
Ln(Terrain ruggedness)	160,815	0.250	0.652	−1.710	1.908
Ln(Distance from the equator)	160,815	3.259	0.786	0.800	3.874
Ln(Distance from the coast)	160,815	6.170	1.230	2.619	7.699
Ln(Elevation)	160,815	6.665	0.802	3.247	7.998
Panel C: Africa					
Malaria stability	115,170	8.770	9.881	0	38.080
Potato suitability	115,170	0.049	0.109	0	0.929
Maize suitability	115,170	0.216	0.214	0	0.954
Cassava suitability	115,170	0.141	0.188	0	0.918
Barley suitability	115,170	0.060	0.121	0	0.859
Wheat suitability	115,170	0.065	0.128	0	0.879
Ln(Population)	115,170	6.939	2.461	−11.012	14.065
Urban population share	115,170	0.015	0.062	0	1
Ln(Terrain ruggedness)	115,170	−0.705	0.783	−2.163	1.824
Ln(Distance from the equator)	115,170	2.543	0.868	−0.627	3.529
Ln(Distance from the coast)	115,170	6.138	0.707	3.651	7.135
Ln(Elevation)	115,170	6.316	0.580	3.200	7.705
Panel D: Oceania					
Malaria stability	30,490	1.587	4.699	0	23.649
Potato suitability	30,490	0.071	0.123	0	0.769
Maize suitability	30,490	0.121	0.163	0	0.703
Cassava suitability	30,490	0.053	0.109	0	0.704

Table 7 (continued)

Variable	Obs	Mean	SD	Min	Max
Barley suitability	30,490	0.091	0.156	0	0.847
Wheat suitability	30,490	0.094	0.161	0	0.889
Ln(Population)	30,490	4.127	2.171	−5.833	12.740
Urban population share	30,490	0.022	0.116	0	1
Ln(Terrain ruggedness)	30,490	−1.656	0.778	−1.942	0.712
Ln(Distance from the equator)	30,490	3.098	0.420	1.868	3.733
Ln(Distance from the coast)	30,490	5.565	0.785	1.500	5.819
Ln(Elevation)	30,490	5.746	0.227	5.258	6.448

Table 8 Summary statistics of PSI for different categories of malaria stability

Malaria category	Mean	Min	Max	Grids	Obs
No endemic ($MSI < 0.06$)	0.197	0	0.978	30,712	330,325
Low endemic ($0.06 < MSI < 1$)	0.188	0	0.981	3691	37,641
Moderately endemic ($1 < MSI < 5$)	0.181	0	0.979	3790	38,726
Highly endemic ($5 < MSI < 10$)	0.199	0	0.956	1982	20,051
Very highly endemic ($10 < MSI < 20$)	0.207	0	0.982	1293	13,102
Extremely endemic ($MSI > 20$)	0.213	0	0.983	796	8511

A.1 Grid-level Data on Potato Suitability and Malaria Stability

Construction of the PSI

As outlined by the Global Agro-Ecological Zones (GAEZ), the construction of the PSI involved four steps, which we summarize below:

In the first step, FAO collected information on the characteristics of 154 different crops. This information was used to assess the ideal environmental conditions required for the cultivation of each crop. The primary characteristics used to determine the ideal environmental conditions required to grow each crop are purely climatic and were taken from a global climatic database that was compiled by the Climate Research Unit at the University of East Anglia. In total, nine variables from the global climatic database were used by FAO: precipitation, frequency of wet days, mean temperature, diurnal (i.e., daily) temperature range, vapor pressure, cloud cover, sunshine, ground-frost frequency, and wind speed.

In the second step, FAO compiled data on the physical environment of 2.2 million grid cells.[22] This second set of data consisted of land characteristics that were taken from FAO's Digital Soil Map of the World and included information such as the slope of soils from the GTOPO30 Database, developed at the U.S. Geological Survey (USGS) EROS Data Center.

In the third step, FAO combined the information on the constraints for the cultivation of each of the 154 crops with the data on the physical environment of each grid cell. By doing

[22] Each cell is 0.5 degrees latitude by 0.5 degrees longitude.

so, FAO estimated the potential yield of each of the 154 crops in each grid cell. To obtain the potential yield for each grid cell and crop, FAO first identified the days of the year when the moisture and temperature requirements of each crop were met. Having the information on the period of time for which the minimum temperature and moisture requirements of the crop were satisfied, FAO was able to determine the exact starting and ending dates for the length of the growing period for each crop and grid cell.

The next step was the construction of the numerical index. First, if the minimum requirements for cultivation were not satisfied, the grid cell was considered unsuitable for the cultivation of the crop. On the other hand, if the minimum requirements were met, then FAO would determine the potential (constraint-free) crop yield. Finally, FAO identified additional constraints that exist in each cell for each crop. The procedure quantified the agro-climatic constraints, such as soil erosion, the existence of pests and weeds, and the variability in the water supply of each grid cell.

Construction of the MSI

As outlined by Kiszewski et al. (2004), the construction of the MSI involved four steps, which we summarize below:

First, Kiszewski et al. (2004) identified the regionally dominant species of mosquitoes around the world. The final tally included a total of 260 regions infested by 36 different types of vector anopheles.

Second, the vector stability index was specifically derived for each region of the world. To do so, a subset of the biological characteristics of mosquitoes, such as the type of dominant vector, the daily survival rate, and the length of the extrinsic incubation period in days, was used. These factors depend on the average temperature and differ between the P. falciparum and the P. vivax. Importantly, the number of mosquitoes and the number of infected people, or their recovery rates, were not considered or used in these calculations.

The third step involved a parameterization of the stability index. In this step, the estimated survival period of mosquito larvae, expressed in days for each of the 34 dominant vector anophelines, was included in the data.

In the last step, the stability index was adapted to a fine geographic scale considering relevant climatic data such as monthly precipitation rates, temperature levels (minimum, average, and maximum), and humidity levels. The inclusion of micro-climatic variables allowed the creation of a final map (Fig. 3) of malaria stability around the world (MSI).

Figure 8 plots the spatial heterogeneity in the two main variables of interest, namely the Potato Suitability Index (PSI) and the Malaria Stability Index (MSI), respectively. We show that there exists a correlation between suitability for potato cultivation and stability of malaria. In particular, some areas highly suitable for potato cultivation show high stability for malaria transmission as well.[23]

Non-gridded control variables, such as the country-level extent of cropland and tropical area, the elevation, the distance from the equator, and the nearest coast, are drawn from Nunn and Qian (2011) 's original replication data. For the country-level regressions, zonal statistics for the mean of spatially-explicit datasets, i.e., Malaria Stability Index and potato suitability, as well as for the suitability of an array of control crops, namely maize, wheat, cassava, and barley (again, with medium-input, rain-fed, historical average parameters), are produced for each grid cell.

[23] Areas highly suitable for potato cultivation have a Potato Suitability Index > 0.8 as defined by FAO.

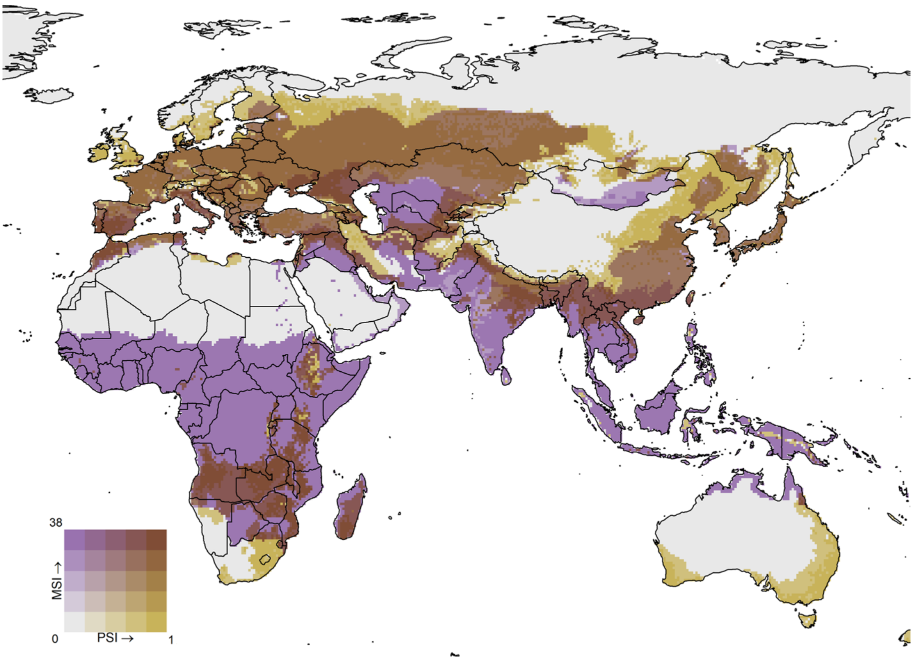


Fig. 8 Maps of the spatial distribution of the MSI and PSI intersected with country borders

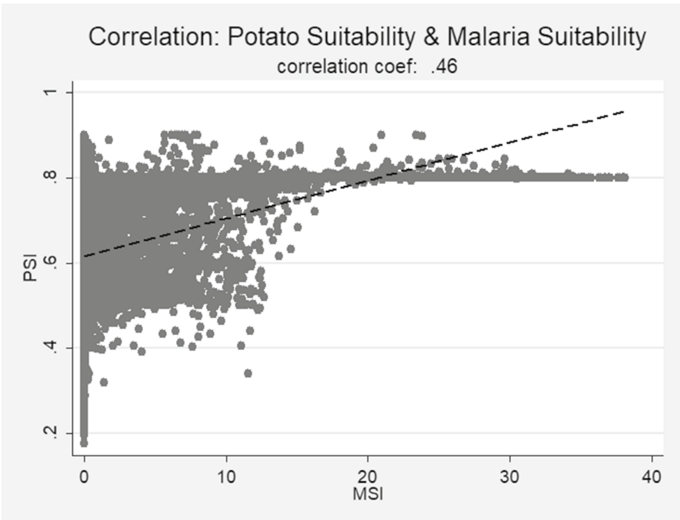


Fig. 9 Correlation of the MSI and PSI

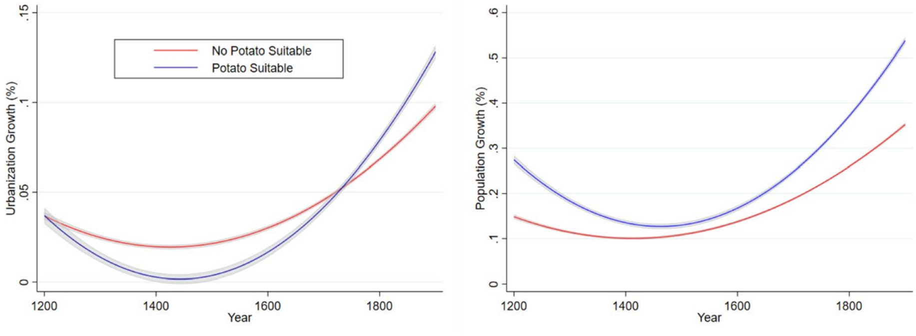


Fig. 10 Historical urbanization (left) and population (right) growth rates in potato-suitable locations vs non-potato-suitable ones from 1200 to 1900

A.2 Grid-level Data on Population and Urbanization

Grid-level data on population and urbanization rates for the years between 1100 and 1980 are retrieved from the HYDE database.[24] The total population is represented by maps of the urban, rural population, population density, and built-up area. The process of estimating population and urbanization involves a series of steps outlined as follows: First, estimated population totals at the state or province level by using a variety of historical sources. The basis for the state-level population data is the United Nations World Populations Prospects (2008 Revision) for the 1950–2017 period. The pre-1950 historical estimates were largely taken from the first Atlas of World Population History (McEvedy and Jones 1978; Livi-Bacci 2006; Maddison 2006). Klein Goldewijk et al. (2011) supplemented these sources with the sub-national population numbers of Populstat (Lahmeyer, personal communication, 2004) and many other country-specific sources. The country-specific sources of population estimates are outlined in the supplementary information of their methodology. Second, they use interpolation techniques to fill in gaps between population sources.

We use version 3.2 of the HYDE database. This is a combination of gridded historical population and land use estimates. Klein Goldewijk et al. (2011) used historical records to model population at the province level and land use areas at the national level through time; then used algorithms to spatially distribute the total population and land use areas to 5 arc minute pixels (about 10 kms at the equator). We extract data on population and urbanization from the HYDE dataset into a global regular grid shapefile with a resolution of 0.5° latitude and 0.5° longitude. A spatial join is performed between the regular grid and the GADM shapefile to create a country attribute in the regular grid shapefile matching the underlying country name.

A possible relevant issue arising with the use of grid-level estimated historical population data from HYDE is the measurement error of the latter. For instance, estimated historical population and urbanization data for country A might be very highly inaccurate, thus having adverse effects on the performance of the indicators (Millimet 2011; Gooch 2017). We address this concern by including country-specific time trends in the grid-level empirical strategy. This allows for a comparison of each grid within the same

[24] Population and Urbanization data are available at time steps of 100 years until 1700, 50 years from 1700 to 1900, and 10 years from 1900 to 1980.

country. Second, both the potato suitability and malaria stability indexes are void of this problem, being time-invariant and computed using weather and soil variables.

B. Additional Results

See Table 9

Table 9 The impact of potato suitability on Old World urbanization and population

	Dependent variable					
	Urbanization share			Log population		
	(1)	(2)	(3)	(4)	(5)	(6)
Potato × I^{Post}	0.019***			0.092***		
	(0.003)			(0.009)		
Potato × I^{Post} (No Mal. areas)		0.020***			0.087***	
		(0.002)			(0.009)	
Potato × I^{Post} (Mal. areas)			0.009			0.039
			(0.006)			(0.041)
Maize Suitability Index × Time	0.037***	0.043***	0.020***	1.917***	1.161***	1.118***
	(0.004)	(0.005)	(0.005)	(0.072)	(0.095)	(0.096)
Wheat Suitability Index × Time	0.026	0.045**	−0.046	6.689***	8.419***	−0.072
	(0.018)	(0.020)	(0.033)	(0.367)	(0.404)	(0.780)
Cassava Suitability Index × Time	0.012**	0.101***	−0.006	−0.019	−0.285	0.073
	(0.006)	(0.020)	(0.004)	(0.104)	(0.257)	(0.101)
Barley Suitability Index × Time	0.009	−0.013	0.064*	−0.801**	−1.955***	3.355***
	(0.018)	(0.020)	(0.034)	(0.371)	(0.409)	(0.819)
Log (Rugged) × Time	0.022	0.056	−0.012	0.132	0.052	−2.850
	(74.813)	(52.098)	(39.787)	(411.174)	(153.329)	(724.048)
Log (Elevation) × Time	0.012	−0.008	0.031	0.448	1.342	1.869
	(77.835)	(60.659)	(28.763)	(499.233)	(733.217)	(465.366)
Log (Dist. coast) × Time	0.008	−0.004	0.007	0.262	−1.053	−0.114
	(32.587)	(21.222)	(9.517)	(262.256)	(976.950)	(149.385)
Country × Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Grid FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	457,356	330,325	127,031	457,356	330,325	127,031
Grid-cells	42,264	30,712	11,552	42,264	30,712	11,552

Observations are at the grid-year level. Regressions in columns (1) and (4) use a baseline sample of 42,264 Old-World grid cells. Regressions in columns (2) and (5) use a restricted sample of 30,712 Old-World grid cells with non-endemic climate conditions (i.e., $MSI < 0.06$). Regressions in columns (3) and (6) use a restricted sample of 11,552 Old-World grid cells with endemic climate conditions (i.e., $MSI > 0.06$). Countries in North and South America are excluded. The periods are 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1750, 1800, 1850, and 1900. The dependent variable is either the natural log of the total population of the grid measured in persons (log population) or the share of the population living in urban areas (urbanization share). Potato takes the value of 0 if the grid is not suitable for growing potato (i.e., $PSI < 0.4$), and the value of 1 if the grid is suitable for growing potato (i.e., $PSI > 0.4$). This is interacted with an indicator for each period of the sample. All regressions include year fixed effects and grid-specific fixed effects. Each control variable listed is interacted with a full set of time-period fixed effects. Coefficients are reported with standard errors clustered at the grid level in parentheses

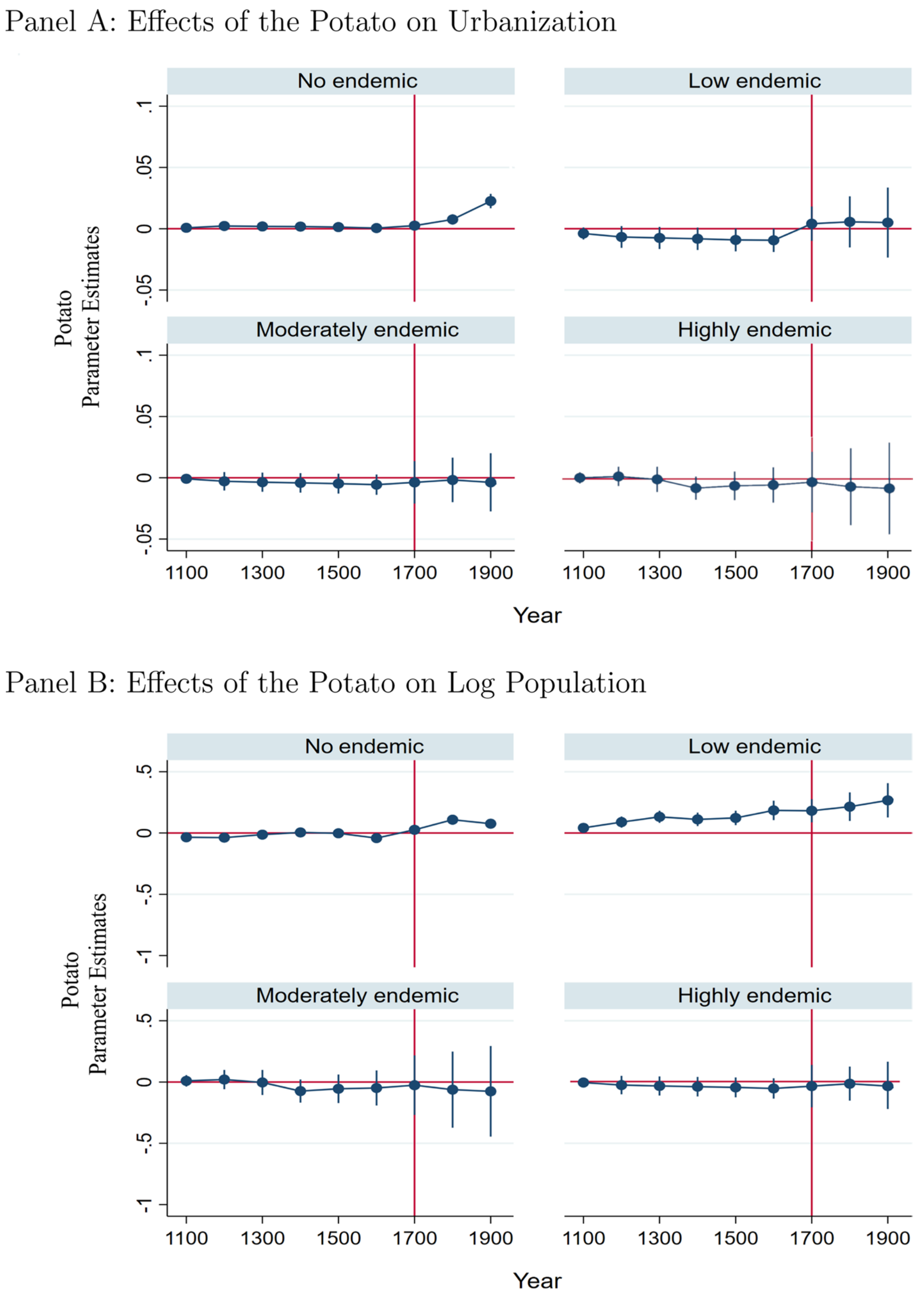
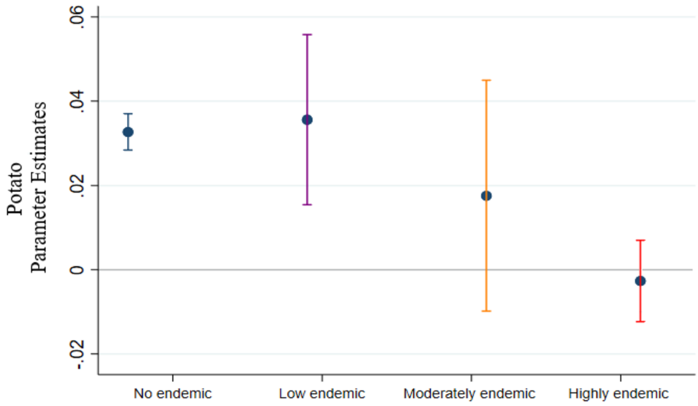


Fig. 11 Flexible estimates of the relationship between potato-suitable areas and urbanization (Panel **A**) and population (Panel **B**) across different malaria stability classes. The sample excludes extremely endemic areas (*MSI* > 20). Blue vertical lines show the 95% confidence intervals and the vertical red lines indicate the year 1700 when the potato was introduced to the Old World

Panel A: Effects of the Potato on Urbanization



Panel B: Effects of the Potato on Log Population

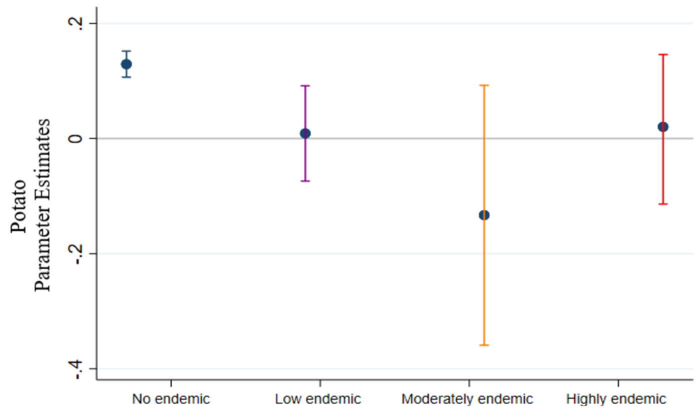


Fig. 12 Effects of the diffusion of the potato on urbanization (left) and population (right) after 1700 across different malaria stability classes. The sample excludes extremely endemic areas (*MSI* > 20). Vertical lines show the 95% confidence intervals

C. Different Definitions of Potato Suitability

The baseline Eq. (1) examines the average effect of the potato on population and urbanization after its introduction on more or less malaria-endemic areas. The main assumption of this strategy is that we define as potato suitable those areas with a Potato Suitability Index > 0.4 (Nunn and Qian 2011). This section shows results obtained using the same specification of Eq. (1) with different definitions of potato-suitable areas.

Table 10 The impact of potato suitability on urbanization and population in endemic vs non-endemic areas (Spain and Portugal excluded)

	Dependent variable					
	Urbanization share			Log population		
	(1)	(2)	(3)	(4)	(5)	(6)
Potato × I^{Post}	0.019***			0.085***		
	(0.002)			(0.009)		
Potato × I^{Post} (No Mal. areas)		0.021***			0.093***	
		(0.005)			(0.009)	
Potato × I^{Post} (Mal. areas)			0.011*			0.025
			(0.006)			(0.041)
Country × Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Grid FE	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	453,594	328,180	125,414	453,594	328,180	125,414
Grid-cells	41,922	30,517	11,405	41,922	30,517	11,405

Observations are at the grid-year level. Countries in North and South America are excluded. The periods are 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1750, 1800, 1850, and 1900. The dependent variable is either the natural log of the total population of the grid measured in persons (log population) or the share of the population living in urban areas (urbanization share). Potato takes the value of 0 if the grid is not suitable for growing potato (i.e., $PSI < 0.4$) and the value of 1 if the grid is suitable for growing potato (i.e., $PSI > 0.4$). This is interacted with an indicator for each period of the sample. All regressions include year-fixed effects and grid-specific fixed effects. Each control variable listed is interacted with a full set of time-period fixed effects. Coefficients are reported with standard errors clustered at the grid level in parentheses

Results are shown in Figs. 15, 13, 14, 16, which show the effects of the estimation of Eq. (1) using cutoff values of potato suitability levels of 0.5, 0.3, 0.2 and 0.1, respectively. Results confirm the decreasing impact of the cultivation of the potato on urbanization and population of potato-suitable locations relative to non-potato-suitable ones after 1700 as the level of Malaria Stability grows.

D. Inclusion of Spatial Dependence

Most empirical work on the effects of local climatic conditions on economic development assumes that observations are independent across space. Here we estimate this relationship following the procedure of Harari and Ferrara (2018) to adjust the standard errors for spatial correlation.

Specifically, we estimate a dynamic model in which we include a symmetric weighting matrix M that exploits variations in the Potato Suitability Index occurring in grids whose centroids are located within 56 km (or within 0.5° latitude x 0.5° longitude) defined as “first-degree neighbors”.

Table 11 The impact of potato suitability on urbanization and population in endemic vs non-endemic areas (European countries excluded)

	Dependent variable					
	Urbanization share			Log population		
	(1)	(2)	(3)	(4)	(5)	(6)
Potato × I^{Post}	0.022 ***			0.044**		
	(0.004)			(0.022)		
Potato × I^{Post} (No Mal. Areas)		0.023***			0.023*	
		(0.004)			(0.014)	
Potato × I^{Post} (Mal. Areas)			0.005			−0.075
			(0.006)			(0.045)
Country × Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Grid FE	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	306,475	192,335	114,140	306,475	192,335	114,140
Grid-cells	27,860	17,485	9,376	27,860	17,485	9,376

Observations are at the grid-year level. Regressions in columns (1) and (4) use a baseline sample of 27,860 grid cells for the Old World, with European countries excluded. Regressions in columns (2) and (5) use a restricted sample of 17,485 grid cells for the Old World, with European countries excluded with non-endemic climate conditions (i.e., $MSI < 0.06$). Regressions in columns (3) and (6) use a restricted sample of 9,376 grid cells for the Old World, with European countries excluded with endemic climate conditions (i.e., $MSI > 0.06$). Countries in North and South America are excluded. The periods are 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1750, 1800, 1850, and 1900. The dependent variable is either the natural log of the total population of the grid measured in persons (log population) or the share of the population living in urban areas (urbanization share). Potato takes the value of 0 if the grid is not suitable for growing potato (i.e., $PSI < 0.4$) and the value of 1 if the grid is suitable for growing potato (i.e., $PSI > 0.4$). This is interacted with an indicator for each period of the sample. All regressions include year-fixed effects and grid-specific fixed effects. Each control variable listed is interacted with a full set of time-period fixed effects. Coefficients are reported with standard errors clustered at the grid level in parentheses

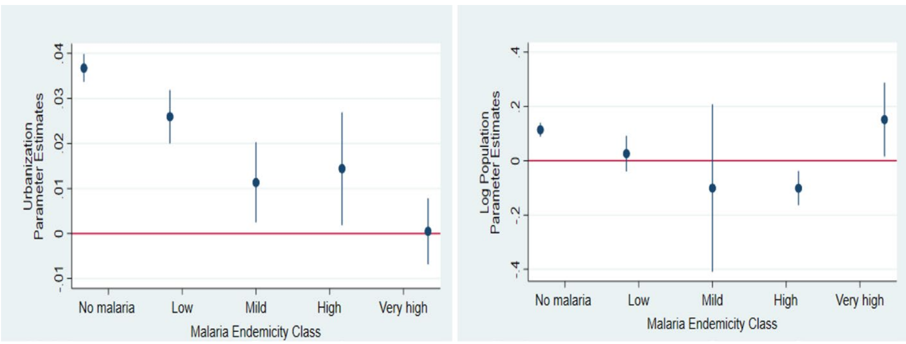


Fig. 13 Effects of the introduction of the potato in the Old World on urbanization (left) and on population (right) for each category of Malaria Stability. Potato suitable areas are defined as $PSI > 0.3$. 95% confidence intervals

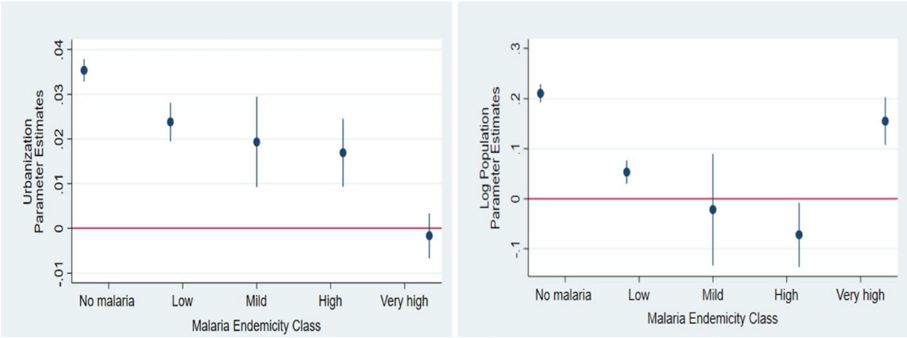


Fig. 14 Effects of the introduction of the potato in the Old World on urbanization (left) and on population (right) for each category of Malaria Stability. Potato suitable areas are defined as $PSI > 0.2$. 95% confidence intervals

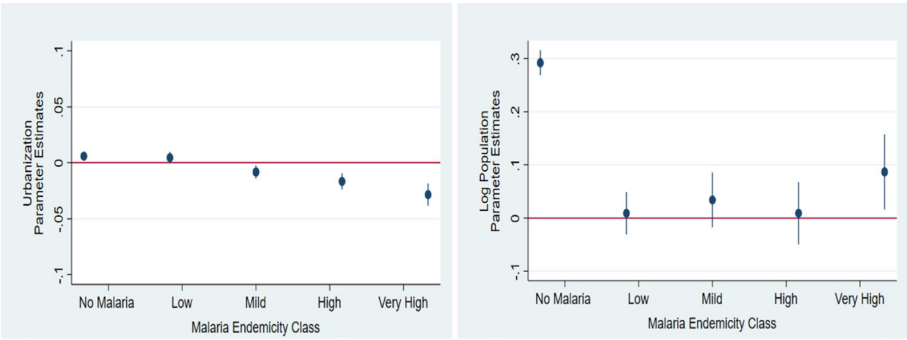


Fig. 15 Effects of the introduction of the potato in the Old World on urbanization (left) and on population (right) for each category of Malaria Stability. Potato-suitable areas are defined as $PSI > 0.5$. 95% confidence intervals

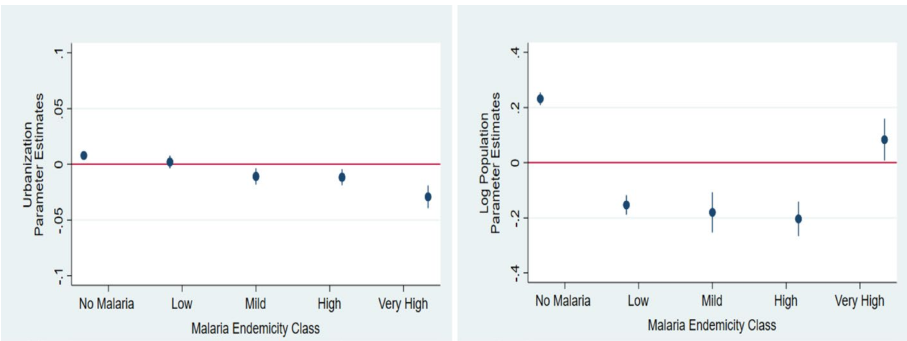


Fig. 16 Effects of the introduction of the potato in the Old World on urbanization (left) and on population (right) for each category of Malaria Stability. Potato-suitable areas are defined as $PSI > 0.1$. 95% confidence intervals

The spatial dependence structure is defined by the symmetric weighting matrix M, and the spatial lag of a variable is obtained by multiplying the matrix M by the vector of observations, as follows:

$$\begin{aligned} y_{i,c,t} = \alpha + \beta_1 \mathbf{M} \cdot y_t + \beta_2 (\text{Potato})_i \cdot I_t^{Post} + \beta_3 \mathbf{M} \cdot (\text{Potato})_i \cdot I_t^{Post} \\ + \boldsymbol{\gamma}\, \mathbf{M} \cdot \mathbf{X}_i' + \omega_i + \delta_t + \sigma_{2,ctrend} + \epsilon_{i,c,t} \end{aligned} \tag{6}$$

where $y_{i,c,t}$ denotes either the urbanization share or the natural logarithm of the population of grid i, in country c in century t. As in Eq. (1), we denote with X the vector of all grid-specific controls.

We chose to estimate a model including spatially and temporally autoregressive terms since, as highlighted in Harari and Ferrara (2018), ignoring the term $M \cdot Y$ can lead to omitted variable bias. As a result, urbanization and population growth would possibly be attributed to unknown determinants that happen to be clustered spatially, and the impact of the potato and malaria would tend to be overestimated. Results are reported in Table 12 below.

Results of Eq. 6 confirm the positive demographic impact of the diffusion of the potato in the Old World. According to the estimates in column (1), grid-cells that were suitable for potato cultivation (i.e., those with $PSI > 0.4$) experienced a 0.2 percentage point increase in urban population share compared to non-suitable grid-cells.

Table 12 The impact of potato suitability on urbanization and population. Inclusion of spatial dependence

	Dependent variable					
	Urbanization share			Log population		
	(1)	(2)	(3)	(4)	(5)	(6)
Potato × I^{Post}	0.002**			0.008**		
	(0.001)			(0.004)		
Potato × I^{Post} (No Mal.)		0.002**			0.008**	
		(0.001)			(0.004)	
Potato × I^{Post} (Mal.)			0.002			0.008
			(0.004)			(0.019)
M * (Potato)	0.214***	0.216***	0.216***	0.703***	0.707***	0.706***
	(0.034)	(0.036)	(0.035)	(0.105)	(0.110)	(0.109)
M * (Urb. Share)	1.023***	1.031***	0.972***			
	(0.009)	(0.009)	(0.030)			
M * Ln (Pop)				1.003***	1.003***	1.003***
				(0.006)	(0.008)	(0.007)
Country × Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Grid FE	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	454,552	339,158	115,394	454,552	339,158	115,394
Adj. R^2	0.841	0.831	0.774	0.911	0.889	0.815

In addition, the estimated coefficient of the total population in column (4) suggests that the population in areas suitable for potato cultivation increased by 0.8 percentage points relative to areas not suitable for growing potatoes.

Once again, not all people living in potato-suitable areas could benefit from the positive effects generated by the diffusion of the potato. Columns (2) and (5) in Table 12 show that only *non-endemic* (*MSI* < 0.06) areas have benefited from the positive impacts of the diffusion of the potato. The non-endemic potato-suitable areas increased their urbanization share by 0.2 percentage points, and their population rose by 0.8 percentage points relative to non-suitable locations. On the other hand, the suitability for cultivating the potato had no statistically significant impact on endemic areas (*MSI* > 0.06), as the estimated coefficients in columns (3) and (6) suggest.

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Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

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