The Impact of Potatoes on World Population and Urbanization during the 18th and 19th Centuries: Evidence from a Historic Natural Experiment*

Nathan Nunn
Harvard University, NBER

Nancy Qian
Brown University, Harvard Academy

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ABSTRACT: This paper exploits regional variation in suitability for cultivating potatoes together with time variation arising from their introduction to the Old World during the 17th century to estimate the impact of potatoes on population and urbanization. The results show that access to potatoes made a significant contribution to the increase in population and urbanization observed across the world during the 18th and 19th centuries. The evidence suggests that urbanization is driven by increased agricultural productivity from potatoes freeing rural labor and allowing them to move to cities. (History, Development)

1. Introduction

Between 1000 and 1900 AD, world population grew from 200 million to 1.6 billion, and the share of population living in urban areas almost tripled from three to over eight percent. Figure 1 shows that this increase was almost entirely isolated to the latter two or three centuries. The determinants of these phenomena have been subjects of much interest to economists, demographers and historians. Population increases reflect increases in fertility and/or increases in life expectancy. Growth economists have typically focused on the former and its association with factors such as income, while empirical micro economists have studied the determinants of increased life expectancy.[1] Life expectancy at birth, stable at approximately 25 years, changed little in the 1,700 years following the time of the Roman Empire. In 1700, it was only 37 years in England, the second richest country in the world at the time (Wrigley and Schofield, 1981). However, beginning in the 18th century, as mortality declined, life expectancy

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[1] For example, see Galor and Weil (2000) and Jones (2003).

began to grow. By 1820, life expectancy in England was 41 years, and by 1900, it was approximately 50 years (Cutler, Deaton, and Lleras-Muney, 2006).

Seminal empirical studies by Fogel (1984, 1994, 2004) and McKeown (1976) have argued that the main contributing factor of the decline in mortality and increase in life expectancy was improved nutrition. Agricultural yields increased significantly during the eighteenth century. Better nourished people resist most bacterial (although not viral) disease better, and recover more rapidly and more often. Fogel (2004) shows that there was an enormous increase in caloric intake after the middle of the eighteenth century, measured both directly from agricultural output and diary surveys, and indirectly through changes in adult height. Between the middle of the eighteenth century and today, for example, caloric intake per person increased by more than thirty percent, and heights in most of Europe increased by ten centimeters or more (Fogel, 1994). Fogel (1997) uses the known association of mortality and body mass index (BMI) to argue that nearly all of the reduction in mortality from the late eighteenth century to the late nineteenth century and half of the mortality improvement in the twentieth century can be attributed to improved nutrition.

While his work as been widely acclaimed, the evidence provided has not convinced everyone of the importance of nutrition in the observed population increase. First, his work does not show the effect on population directly. Rather, it infers nutrition's effect on population through its effect on height and mortality. This is problematic if, as some have argued, the increase in life expectancy in England during the 18th century was just one of the fluctuations in mortality that characterized pre-industrial Europe rather than being emblematic of the general world trend we see in Figure 1. Wrigley and Schofield (1981) estimate that life expectancy in 1600 was the same as in 1820, reaching a minimum in 1750. And based on skeletal remains, Steckel (2004) argues that people were taller (and therefore probably better nourished) in early medieval times. Second, cross-sectional evidence from the 18th and 19th century does not show that better nourished populations have longer life expectancy (Livi-Bacci, 1991). Finally, supporters of the importance of nutrition must argue against the claim that it is improvements in modern medicine and public sanitation that improved life expectancy rather than nutrition.[2]

This study attempts to address this debate by investigating the effect of improved nutrition caused by the introduction of more calories (via potatoes) from the New World to the Old World on population and population growth in the latter. Our study does not attempt to establish the importance of nutrition relative to medicine or sanitation. Most likely, health is an outcome of complex interactions between all three factors.[3] The lack of the necessary data to estimate such complex interactions

[2]Preston (1975, 1980, 1996) famously discusses the importance of public sanitation. For examples of the evidence of medical improvement on mortality, see Cutler (2004) and Cutler and Miller (2005).

[3]See Cutler *et al.* (2006) for a detailed discussion of the literature on the determinants of reduced mortality.

forces our study to be more modest. We provide evidence for the importance of nutrition by directly identifying the causal effect on population outcomes. We ask the question: how much does food matter?

In addition, we ask the related question of whether improvement in nutrition caused urbanization. The view of potatoes as a shock on technology in agricultural production relates this study to the debate in development economics about the importance of developing the agricultural sector. A productivity shock in agriculture produces two offsetting effects on urbanization. On the one hand, developing agriculture may delay urbanization as workers are attracted to the relatively more productive sector in the rural areas. On the other hand, by increasing productivity in food production and decreasing the price of calories, agricultural development may free workers from rural labor and spur industrialization and urbanization. In this paper, we test whether potatoes decreased the price of food more than it increased the product of marginal productivity of land and labor by estimating its effects on urbanization.

This study faces two main empirical difficulties that arise from the endogenous nature of nutrition improvement. First is the problem of reverse causality. For example, Cullen (1968) argues that in Ireland, population expansion led to the adoption of the potato, and not the other way around as many others have argued.[4] In that case, the correlation of improved nutrition from new foods and population will reflect a reverse-causal relationship. Second is the problem of omitted variable bias. Population growth and improved nutrition may both be outcomes of an unobserved factor such as political stability.

The principal contribution of our study is to resolve these problems and estimate the causal effect of the increased nutrition by using the introduction of potatoes to the Old World from the Americas together with regional variation in suitability for potato cultivation as a source of exogenous variation in nutrition. We argue that potatoes are superior to existing crops in terms of the nutrition it provides given the amount of inputs. Then, we proxy for access to improved nutrition with the amount of land that is suitable for cultivating potatoes. To address the possibility that regions suitable for potato cultivation may systematically differ from other countries in many other respects, we use the introduction of potatoes to the Old World as a second source of variation. Our empirical strategy is similar in spirit to a differences-in-differences estimator. We compare the change in outcomes before and after the introduction of potatoes between regions that were suitable for cultivating potatoes and regions that were less suitable. To address the concern that suitability for potatoes is correlated with other factors that may affect the outcomes of interest during the 18th and 19th centuries, we control for factors such as suitability for overall agricultural production and production of existing Old World staples, and a

[4] For views arguing the reverse causality see Salaman (1949) and Connell (1962). Also, see the empirical evidence from Mokyr (1981).

large set of institutional variable. The identification assumption is that access to improved nutrition via potatoes is exogenous to other (time-varying) factors, beyond our set of controls, that influence population and urbanization differentially before and after introduction. We examine the validity of our identification assumptions in series of robustness checks.

We use historical data on population and city population from existing sources. The data are reported at the city and country level for each century between 1100 and 1900. From this data, we calculate population levels, population growth, urbanization and changes in urbanization. Suitability for crops are computed from models and data provided by the Food and Agriculture Organization (FAO) Global Agriculture Ecological Zones (GAEZ) database. We combine the data to form a panel of countries and a panel of cities. Our population results show that regions that were suitable for potato cultivation experienced disproportionately higher higher population growth rates after the introduction of potatoes. Our finding could occur for a number of reasons. It could reflect population increase from increased fertility and decreased mortality in response to the increased nutrition, or it could results from migration as people move from less suitable to more suitable regions. We test for the latter channel by estimating the effect of suitability in neighboring countries. We find that suitability in neighboring countries does not have negative effects. This suggests that the main results reflect overall population increases. Our results for urbanization are similar to our population results. They show that suitability for potatoes had a large positive effect on urbanization rates and after the adoption potatoes.

These results provide evidence that is consistent with the previous qualitative and quantitative research of historians arguing that the potato had large impacts in the Old World. A back of the envelope calculation with our most conservative estimates indicate that the introduction of potatoes accounts for up to 9.5% of the increase in population, 21% of the increase in population growth rate, 43% of the increase in urbanization, and 48% of the increase in urbanization growth rates.

In addition to the main results, we also explore several potential mechanisms. First, we investigate whether migration or trade contributes to the impact of potatoes. We find that the effect of potatoes is decreasing with neighbor's suitability. This suggests that two possibilities: 1) potato suitability is attracting migration from neighboring countries; and, or 2) the benefits of the technological shock provided by potatoes along the lines of comparative advantage decreases if neighboring countries also receive the same shock . To investigate the latter, we examine whether the effect of potatoes vary with respect to access to trade. Consistent with the evidence that potatoes are typically not traded, we find that the effect does not vary with trade. These results suggests that migration may contribute to the effect on population.

Next, we investigate whether the effect on urbanization is more influenced by growth in rural areas pushing population into urban areas or rising demands for urban labor pulling population into cities. We use urbanization levels in 1700 as a proxy for urban demand for labor and estimate the differential effect of suitability for potatoes across different levels of this measure. Our results indicate that the effect of potatoes on the increase in the urbanization rate was lower in countries that had higher levels of initial urbanization. This suggests that the *push* was the main force for urbanization.

Finally, we ask if the population pushed into cities were laborers freed from agricultural labor or rent-earning landlords. In the former case, one would think that urbanization reflect positive development. In the extreme, for the latter case, urbanization could only reflect increased rents earned by "fat cats". To investigate this, we proxy for the capacity for elites to capture rents with a variable indicating whether serfdom was legal in 1700, and examine whether the effect of potatoes on urbanization was larger for countries with serfdom. We find that there is no difference. This suggests that the effects on urbanization is not driven by the increase in "fat cats". This result is particularly interesting because the biggest effect of potatoes occurred in Eastern European countries, where serfdom was prevalent at the time.

There has been only one previous study that empirically examines the effect of the introduction of the potato. This is a study by Joel Mokyr (1981) that looks at a cross-section of counties within Ireland in 1845 and tests for a relationship between potato cultivation and population growth. To address the problem of endogenous adoption, Mokyr estimates a system of two equations using 2SLS. He finds that potato cultivation resulted in a statistically significant increase in population growth. He also finds no evidence that the potato was adopted in response to rapid population growth. Our study differs from Mokyr's (1981) in two ways. First, our difference-in-differences estimation strategy is very different from Mokyr's IV strategy. Second, our data allow us to examine the impact of potatoes beyond the Irish context, and we also examine the impact of the potato on long-term economic development.[5]

Our study makes several contributions. First, it compliments recent studies on the effect of medical improvements on life expectancy such as that by Acemoglu and Johnson (2007) for enhancing our understanding of the determinants of historical rises in population. Second, our results shed light on some of the mechanisms underlying of urbanization during the 18th and 19th centuries. The results show that increasing the population carrying capacity of land freed up rural population from agricultural labor and allowed them to move into cities. To the best of our knowledge, our paper is the first to provide rigorous empirical evidence for this hypothesis. Finally, as an estimate of the effect

[5]The only other piece of empirical evidence about the effects of the potato, although indirect, is from Baten and Murray (2000). The authors examine the determinants of the heights of 4,100 men and women that were incarcerated and sent to two prisons in Bavaria between 1856 and 1908. They find that men and women from regions with greater potato production were taller. This is also true for regions with greater milk production, but is not true for the production of bread grains, which is found to have a negative effect on heights.

of an agricultural productivity shock, we present evidence that under certain conditions, these shocks can spur growth.

The paper is organized as follows. Section two discusses the background on potatoes. Section three presents the empirical strategy. Section four describes the data. Section five discusses the results. Section six offers concluding remarks.

2. Potatoes

A. *Nutrition*

From a nutritional point of view the potato is a truly remarkable food for two reasons. First, it is the single food that can best support life when fed as the sole article of diet (Davidson, Passmore, Brock, and Truswell, 1975, p. 213, Reader, 2008). Potatoes contain nearly all of the important vitamins and minerals. For example, humans can subsist healthily on a diet of only potatoes and milk, which provides vitamins A and D. Based on data from the (U.S. Department of Agriculture, 2007), a medium potato (150g/5.3 oz.) with the skin provides 29.55 mg. vitamin C (45% of the daily value (DV)), the necessary deterrent for scurvy. This important since the other staple crops, wheat, oats, barley, rice, and maize, do not contain any vitamin C. In contrast, the average Irish diet of 4.5 to 6.5 kilograms of potatoes per day provided 40 to 60 times the quantity of Vitamin C required to prevent scurvy (Hughes, 2000). For much of Northern Europe the potato provided the only source of vitamin C and protection against scurvy. A medium potato also contains 632 mg. of potassium (18% of DV), 0.44 mg. vitamin B6 (20% of DV), as well as significant amounts of thiamin, riboflavin, folate, niacin, magnesium, phosphorus, iron, and zinc. Moreover, the fiber content of a potato with skin (3.5 grams) is similar to that of many other cereals such as wheat.

The second remarkable fact about the potato is that it yields more energy per acre than any Old World cereal crop and requires less labor input. Direct evidence of the historic superiority of the potato over all pre-existing Old World crops is shown in Table 1. The table reports data collected by Arthur Young (1771) in a survey of farming communities throughout England in 1770. The first two columns compares the average yields, measured in either bushels or kilograms per acre, of oats, wheat, barley, and potatoes. As shown, yields measured in bushels or kilograms are well over 10 times higher for potatoes relative to any of the other Old World crops. However, part of this reflects the fact that potatoes are 75–80% water and therefore naturally more bulky than the other crops. Column 3 compares the energy value of the yields in columns 1 and 2. As shown, an acre of potatoes yields approximately three times more energy than the other crops. The final column reports this fact in a slightly more intuitive manner. It shows the number of acres required to provide the total energy needs of a family of two adults (a man and a woman) and three young children, which is estimated to be 42 mega joules (or approximately 10,000 calories) per day. While this family could subsist cultivating a plot of only 1/2 acre of potatoes, it would need to cultivate 1.5 acres if it was to grow wheat, oats, or barley.

The data from Table 1 are consistent with the historic fact that a single acre of land cultivated with potatoes and one milk cow was nutritionally sufficient to feed a large family of six to eight (McNeill, 1999, Langer, 1963). This typical Irish diet of potatoes and milk, although monotonous, was able to provide one with sufficient amounts of protein, calcium, iron, and all vitamins (Connell, 1962).

Potatoes also had two additional benefits that further increased the amount of calories available. First, due to easy storage during the winter, potatoes provided excellent fodder to livestock. This meant that potatoes increased both meat available for consumption and manure which was used as an input in agriculture. Second, potatoes increased the efficiency of land in producing indigenous grain crops. It was often planted before grain crops during crop rotations. Typically, on land under grain cultivation between 1/3 and 1/2 of the land was left fallow each year. Fallowing was a strategy that was undertaken to control weeds. One benefit of potatoes was that they could be planted on the fallow land between periods of grain cultivation (Mokyr, 1981, McNeill, 1999). Thus, even if land was not converted from the cultivation of grains to the cultivation of potatoes, the introduction of the potato still increased the supply of food from a given plot of land.

B. *Diffusion from the New World to the Old World*

Archeological evidence suggests that the potato was first cultivated in the Andes between 7,000 and 10,000 years ago (Messer, 2000*b*). After the discovery of the Americas by Christopher Columbus in 1492, the potato was soon introduced to Europe by the Spanish in the late sixteenth century. It was first cultivate in the Spanish Canary Islands around 1570. The first documented introduction of potatoes to continental Europe was in 1601 when Carolus Clusius reported in his *Rariorum Plantarum Historia* that potatoes were planted in Northern Italy (McNeill, 1999, p. 73). In England by the 1690s, the potato begun to be cultivated and was used as a supplement to bread (Langer, 1963, McNeill, 1999).

Approximately one hundred and fifty years elapsed between when potatoes were first introduced to continental Europe and when it had been adopted as a common field crop. By historical standards, the diffusion of potatoes throughout Europe was rapid if not instantaneous. By most accounts, this is less than the time it took for gunpowder to diffuse through Europe during the 13th Century. The rapid adoption is all the more surprising since at first potato was generally viewed either as an strange exotic gift and botanical curiosity, or as a poisonous and dirty plant that caused leprosy (Langer, 1975). Adoption was probably encouraged by failures of existing crops during the "Little Ice Age" and the wars and famines of the period. In many countries, adoption was encouraged by policy. For example, in 1744, Prussia's Frederick the Great ordered his subjects to grow potatoes as insurance against cereal crop failure and distributed free seed potatoes with instruction on how to plant them. The French scientist, Antoine Parmentier, influenced by his observation of the benefit of potatoes in Prussia during the Seven Years war (1756–1763), devoted his research to investigating and extolling the virtues of the potato. In the late 18th and early 19th centuries a number of countries, like France, Austria and Russia, used government policy to encourage domestic cultivation of potatoes (Langer, 1963, McNeill, 1999). Once persuaded to plant potatoes, European farmers quickly recognized their advantages over other crops, and soon potatoes became the staple field crop that they are today.

The potato was spread to the other parts of the New World by European mariners who carried potato plants to ports across Asia and Africa. Although we do not have historical evidence on the exact date of its first introduction, the existing evidence suggests that the potato was probably brought to the Philippines in the late 16th century and later brought to Java in the 17th century by the Dutch (Burkill, 1935). The potato's introduction to China probably occurred several times during the seventeenth century. The potato was cultivated as early as 1603 by Dutch settlers of the Penghu Islands, and later in Taiwan after the Dutch occupied the island from 1624 to 1662. Given the Dutch initiated trade links between Taiwan and the coastal province of Fujian, it was likely that the potato was also introduced to mainland China during this time. There is evidence from a document dating back to 1700 of potato cultivation in a mountainous area of northern Fujian. According to (Lee, 1982, p. 738), by 1800 the populations in Southwest China had replaced the traditional lower yields crops of barley, oats, and buckwheat with either potatoes or another New World crop, maize.[6]

Historic evidence suggest that the potato first reached India not much later than Europe, taken there by either the British or the Portuguese. The earliest known reference to the potato in India is from an account by Edward Terry, who was chaplain to Sir Thomas Roe, British ambassador to the court of the Mughal Emperor Jahanagir from 1615 to 1619, in Northern India. British colonial governor Warren Hastings promoted potato cultivation during his term (1772 to 1785) and by the late eighteenth to early nineteenth century, potatoes were well established in the hills and plains of India (Pandey and Kaushik, 2003).

In Africa, the potato arrived slightly later, around the end of the 19th century. In Ethiopia, the potato was introduced in 1858 by a German immigrant named Wilhelm Schimper. The subsequent adoption by native farmers occurred gradually over several decades. According to Laufer (1938), by the 1930s the potato had become naturalized in southern Ethiopia and southeastern Sudan.

As the historical evidence illustrates, the actual date of the adoption of potatoes as a field crop

[6]We discuss in detail below and examine empirically the effect of maize and other New World food crops on Old World population growth and economic development. As we show, other maize and other New World crops did not have the same impact as the potato.

varied significantly across the Old World within a one hundred and fifty year window. This was due in large part to idiosyncratic factors, such as the views of individuals and the ability and desire of governments to promote the adoption of the crop. For our estimates, we wish to avoid endogenous factors related to adoption and use the first date of introduction to continental Europe, the early 1600s, as the date of when potatoes become available. Unfortunately, our outcome data are only observed at the century level. This forces us to round up and use 1700 as the approximately treatment date. We do not take this date for granted. We will estimate a flexible equation allowing the effect of potatoes to vary for each century to observe the timing of the effect before we estimate the main DD specification. Please see the following section.

C. *Other New World Crops*

New World crops, other than potatoes, were also introduced to the Old World. These other New World crops include maize, tomatoes, chilli peppers, cacao, and the sweet potato. The crops that became calorie producing staples in the Old World are maize and sweet potato.

Maize is unable to rival potatoes in terms of nutrients or calories. Further, while one can subsist on a diet of potatoes and little else, this is not true of maize. Significant consumption of maize is associated with Pellagra, which is a disease caused by niacin deficiency. It was first observed among poor populations throughout Europe, the Middle East, and the United States whose diet relied heavily on corn. The effects of Pellagra include skin disorders, digestion disorders, mental disorders, and death. The disease was first observed in the 1730s in Italy and even today continues to affect poor populations with diets that rely too heavily on corn. An additional adverse effect of a primarily corn diet is protein deficiency (Messer, 2000*a*). Given the negative effects associated with diets too heavily dependent on corn, one would not expect corn to have the same positive effects as potatoes.

Although sweet potatoes are very nutritious, there are two reasons why they may have not have had a large impact on population growth and economic development. First, the archaeological evidence suggests that sweet potatoes reached Oceania long before European contact with the New World. Therefore, their impact on the increase in population and urbanization growth after 1700 will be diminished by this fact. For many of the countries in our sample, their impact would have been felt as early as 1000 AD (Hather and Kirch, 1991). As well, a close substitute to the sweet potato, the yam, had already spread throughout the Old World long before 1700 (O'Brien, 2000). This also serves to dampen the impact of the diffusion of sweet potato after the discovery of the Americas.

In the regression analysis, we will control for suitability for other New World crops as a robustness check.

3. Empirical Strategy

Our first estimating equation imposes very little structure on the data and simply examines how the relationship between population growth or economic development and a country's suitability for growing potatoes changes over the time periods in our sample.

$$Y_{it} = \sum_{j=1400}^{1900} \beta_j \, Potato_i \times I_t^j + \sum_{j=1400}^{1900} \delta_j \, AllCrops_i \times I_t^j + \sum_c \gamma_c \, I_i^c + \sum_{j=1400}^{1900} \rho_t \, I_t^j + \varepsilon_{it} \tag{1}$$

where i indexes countries and t indexes time periods, which are for the years 1000, 1400, 1500, 1600, 1700, 1800 and 1900. Y_{it} denotes our outcome of interest, either population, average annual population growth, the urbanization rate, or the average annual change in the urbanization rate. The equation includes country fixed effects $\sum_c I_i^c$, which capture average time invariant differences in country characteristics that affect the outcome variable. Similarly, the time period fixed effects $\sum_j I_t^j$ capture time specific shocks that affect all countries.

The variable $Potato_i$ measures the fraction of total land in country i that is suitable for the cultivation of potatoes. By interacting the variable with the time period indicator variables, we are able to estimate a period specific relationship between potato suitability and the outcome variable. These β_j's are our coefficients of interest. If population growth or economic development increased due to the adoption of potato cultivation after 1700, then we expect to find that after 1700, countries with great potato suitability experience disproportionately faster growth. Therefore we expect to find that: $\hat{\beta}_{t>1700} > \hat{\beta}_{t\leq 1700} \approx 0$. Because $Potato_i$ is time invariant, the estimated β_t's must be relative to a baseline time period, which we take to be 1000.

We control for the share of land suitable for agriculture overall interacted with the time period dummy variables $\sum_j \delta_j \, AllCrops_i \times I_t^j$ to ensure that the effect of introducing potatoes is not confounded by other changes in the importance of agricultural productivity over time. $AllCrops_i$ is measured as the fraction land that is suitable for growing any crop.

Our main estimating equation examines the impact of the introduction of potatoes in a more structured manner, using a strategy that similar to difference-in-differences. This strategy compares the relative difference in population growth and economic development, before and after the introduction of potatoes, between countries more suitable for potato cultivation to countries less suitable.

To avoid the endogeneity of adoption, we use the approximate date of the introduction to Europe, 1700, rather than the actual date of adoption. Similarly, we use a country's suitability for cultivating potatoes rather than the extent of actual cultivation. We interact suitability with a dummy variable for the post adoption period. One rightly suspects that suitability for potato cultivation is correlated with many other factors that affect population. In Table 2, we show the pair-wise correlations between suitability for potatoes and suitability for other crops and geographic conditions that may affect population. The correlation is statistically significant in many cases. Therefore, we will need to control for these factors in the main estimation. Since these factors are also time invariant, we control for their interactions with the post dummy variable. Only the interaction term of potato suitability with post conditional on the controls should be interpreted as plausibly exogenous. We estimate the following baseline equation.

$$Y_{it} = \beta\, Potato_i \times I_t^{Post} + \delta\, AllCrops_i \times I_t^{Post} + \mathbf{X}_{it}'\eta + \sum_c \gamma_c\, I_i^c + \sum_{j=1400}^{1900} \rho_t\, I_t^j + \varepsilon_{it} \tag{2}$$

As before Y_{it} denotes our outcome of interest, $\sum_c I_i^c$ and $\sum_j I_t^j$ are country and time period fixed effects. Our measure of potato suitability $Potato_i$ is now interacted with an indicator variable that equals one after 1700, I_t^{Post}. We control for suitability for Old World staples (e.g. rice and wheat) or the suitability for all New World crops (e.g. potato, sweet potato, maize), suitability for overall agriculture, elevation, ruggedness, and the fraction of land that is comprised of desert. To address the correlation to tropics, we will repeat the estimation on a sample where tropical countries are excluded in the section on robustness.

Our coefficient of interest is β, which is the estimated impact of potato suitability on the difference in the outcome variable before and after 1700. Consider population growth as the dependent variable. The estimated coefficient, $\hat{\beta}$, measures how the difference in average population growth after 1700 related to the prior period differs for countries with different levels of potato suitability. If the coefficient is positive, then this indicates that countries with an geographic environment more suitable for growing potatoes witness a greater increase in population growth after 1700 relative to prior 1700.

Our estimation strategy has all of the potential advantages and hazards of standard DD estimators. If countries suitable for potato production are different from countries that are not in ways that do not change over time (and whose effect on the dependent variable does not change over time), then this difference is controlled for by the country fixed effects. Similarly, if there are secular trends in population or urbanization that are similar across countries, then this difference is controlled for by the time period fixed effects. Our identification relies on there not being any systematic changes correlated with suitability for potatoes that occurred around 1700 when potatoes were introduced beyond the factors that we control for. This assumption should not be taken for granted since many changes occurred during the 18th and 19th centuries which could affect population and urbanization. In the section on robustness, we will consider, and control for, alternative country characteristics along with historic events that may potentially bias our results.

For example, one may be concerned that potatoes are unsuitable for tropical climates. Therefore, our strategy could be capturing the effect of cooler climates rather than the effect of potatoes. Another concern is that countries that are more suitable for cultivating potatoes are also countries that industrialized earlier. Therefore, the strategy may simply capture spurious correlations to industrialization. To address these concerns, we conduct a series of robustness checks. We first check that our results are not driven by outliers or climate by omitting those groups from the estimating sample. Then, we control for a set of potentially confounding institutional variables to see whether our baseline estimates are robust.

In addition to the main results, we are also able to investigate several mechanisms. First, we investigate whether our cross country comparisons are driven by population displacement. Populations from countries that are unsuitable for potatoes may move to countries that are suitable after its introduction. In the extreme scenario, this means that our results will reflect a spatial re-distribution rather than increases in overall population. To investigate this, we control for the suitability for potatoes in neighboring countries. If the results are driven by displacement, then neighbor's suitability should have negative effects on a country's population.

A related issue is migration. If there is displacement, then there must have been migration. But even if there was no displace, there could still be migration. When suitable countries obtain potatoes, the carrying capacity of their land increases. The population increase we observe could capture fertility increases, mortality decreases and in-migration. As along as the migration outflow from the originating countries are replaced by increased fertility in those countries, this would not be a displacement effect. To examine whether our estimates are in partly driven by migration, we examine whether the benefit of potato suitability is smaller for countries who have neighbors that are also suitable. If this triple interaction term of potato suitability, neighbors' potato suitability and post, is negative, then we would think that there may be migration. An alternative explanation is that comparative advantage decreases if neighboring countries receive the same technological shock. Hence, we also investigate whether the benefits for potatoes differ for regions with better access to trade routes.

Next, we investigate whether the effects on urbanization is more influenced by growth in rural areas pushing population into urban areas or rising demands for urban labor pulling population into cities. We use urbanization levels in 1700 as a proxy for urban demand for labor and estimate the differential effect of suitability for potatoes across different levels of this measure. Our results indicate that the effect of potatoes on urbanization was lower in countries that had higher levels of pre-existing urbanization. This suggests that the *push* was the main force for urbanization.

Finally, we ask if the population pushed into cities were laborers freed from agricultural labor or rent-earning landlords. In the former case, one would think that urbanization reflected development and growth. In the latter, urbanization could only reflect the increase in rent earned by the "fat cats", which would not correspond to economic growth. To investigate this, we proxy for the capacity for elites to capture rents with a variable indicating whether serfdom was legal in 1700, and examine whether the effect of potatoes on urbanization was larger for countries with serfdom. We find that there is no difference. This suggests that the effects on urbanization is not driven by the increase in "fat cats". This result is particularly interesting because the biggest effect of potatoes occurred in Eastern European countries, where serfdom was prevalent at the time.

4. Data

A. *FAO Data on Crop Suitability*

Data on the suitability of soil for growing crops are from the FAO's *Global Agro-Ecological Zones* (GAEZ), 2000 database. The construction of the GAEZ occurs in two stages. The FAO first collects information on the soil and climatic conditions required to grow 28 core crop types. Each crop requires specific amounts of heat, light, and water to survive. The specific constraints that prevent each crop from being grown are identified.

Next, the FAO compiles data on the physical environment across 2.2 million grid cells that are 5 arc minutes long by 5 arc minutes wide. Five arc minutes is equal to 1/12th of a degree, or 9.3 kilometers (measured at the equator). The primary characteristics used are climatic, and are taken from a global climatic database that has been compiled by the Climate Research Unit (CRU) at the University of East Anglia. The global climatic database includes nine variables (measured monthly) that are used by the FAO in the GAEZ study: precipitation, frequency of wet days, mean temperature, diurnal temperature range, vapor pressure, cloud cover, sunshine, ground-frost frequency and wind speed. The second set of characteristics are land characteristics taken from the FAO's Digit Soil Map of the World (DSMW). Information on the slope of soils is taken from the GTOPO30 database, which was developed at the U.S. Geological Survey (USGS) EROS Data Center.

Combining the information on the constraints for crop cultivation with the data on the actual environment of the different grid cells of the world, the FAO calculates an estimate of the potential yield of each crop in each grid cell for an assumed level of intensity of cultivation and input use. For each grid cell and crop, it is first determined when the temperature and moisture conditions of the crop are met. The FAO then calculates the length of the growing period (LGP), which is defined as the number of days when both water availability and prevailing temperatures permit growth. Depending on its length, the LGP may allow for no crops to be grown per year, for only one growth of the crop, or for multiple growth in a year. Soil and terrain constraint are also identified for each crop. The following constraints are examined: terrain-slope constraints, soil depth constraints, soil fertility constraints, soil drainage constraints, soil texture constrains, and soil chemical constraints.

For each crop, the FAO constructs a raster file that records a classification of the suitability of the environment for growing that particular crop. The FAO has also constructed a country level version of the database, which reports for each country and crop, the proportion of the country's land that is classified under five mutually exclusive categories describing how suitable the environment is for growing the crop in question. The categories are based on the calculated percentage of the maximum yield that can be attained in each grid-cell. The five mutually exclusive categories, and their corresponding yields, are: (*i*) very suitable land (80–100%), (*ii*) suitable land (60–80%), (*iii*) moderately suitable land (40–60%), (*iv*) marginally suitable land (20–40%), and (*v*) not suitable land (0–20%). The measures are provided for three different assumptions about the intensity of cultivation and input use. The categories for input intensity are: (*i*) high intensity, (*ii*) intermediate intensity, (*iii*) low intensity. For all constructed measures, the FAO assumes that cultivation occurs under rain-fed conditions.

Using the FAO's country-level version of the crop suitability data, we construct a country-level measure of the fraction of a country that is suitable potato cultivation. We define land that is suitable for cultivation as land that is classified as either "very suitable", "suitable", or "moderately suitable", assuming an "intermediate intensity" of cultivation and input use. In other words, we define land to be suitable if the maximum yield of the land exceeds 40%. Our measure of suitability is the fraction of a country's land area that is suitable for growing potatoes based on this definition of suitability. This 40% threshold is chosen arbitrarily. The estimated impact of potatoes decreases as we decrease the threshold. But this does not affect the back of the envelope calculations of the average effect because the fraction of suitable land on average increases as the threshold decreases.

The FAO database also provides the same calculations for land that can grow any crop for human consumption (e.g., excluding fodder crops). We use this information to calculate a measure of a country's overall agricultural suitability. We use this as a control variable in our empirical analysis. Like the potato suitability measure, this variable measures the proportion of a country's land area that classified as being either "very suitable", "suitable", or "moderately suitable" for growing any crop assuming an "intermediate intensity" of cultivation use.

Figure 2A shows the underlying grid cell data that the FAO's country level database is based on. The map shows grid-cells which are defined as being either suitable or not suitable based on our 40% yield cut-off. The suitable areas are shaded in dark green and the areas that are not suitable are in light green. Figure 2B shows a map of the same underlying data aggregated to the country level. The map shows the fraction of each country's land area that is suitable by our definition. A darker shade indicates a greater proportion of land that is suitable. The ranges corresponding to each shade are reported in the map's legend. Both maps show only the countries of our sample (i.e., only Old World countries). Figure 2C shows that we can use a similar strategy to compute the suitability for cities. For each city, we define the relevant agricultural region to be a circle with a 100 km radius originating from the city. Suitability for the city is then the fraction of land within the circular region that is suitable.

From the two maps a number of facts are immediately apparent. The first is that most of the world is not suitable for growing potatoes. As a result of this, 51 of the 129 Old World countries in our sample have no land that is suitable for cultivating potatoes. The large number of countries with zero suitability is shown in Figure 3 which shows a histogram of our potato suitability variable. In our empirical analysis we pay particular attention to this fact. As we show, our results are not being driven by zero suitability countries. Our results are unchanged if we omit zero suitability countries from our sample.

The second fact that is apparent from the map in Figure 2B is that areas that have the most land area suitable for potato cultivation appear to be concentrated in Europe. This fact is a potential cause of concern, since we know that after 1700, Western Europe diverged from the rest of the world. The underlying cause of this divergence may bias our estimated impact of the introduction of potatoes on population and economic development. We address this concern explicitly in a number of ways. We show that our estimates do not change if we omit Western European countries or even all European countries, or if we control for underlying determinants of Western Europe's divergent growth after during and after the 18th century.

A final concern with our potato suitability measure is whether the suitability measure calculated in 2000 by the FAO is an accurate indicator of suitability two hundred years ago. However, the nature of the suitability measures suggest that they are. The suitability measures are based primarily on geographic characteristics that do not change over the time span considered by our study. Characteristics, such as temperature, humidity, length of days, sunlight, and rainfall have not changed in any significant way since 1700. In constructing our measure, the FAO intentionally assumes rain fed conditions, avoiding measurement error caused by changes over time in irrigation technology and intensity of irrigation use. Furthermore, the FAP avoided using measures that could change quickly due to human intervention such as soil pH.

As a check of the validity of our potato suitability measure, we examine whether our measure is correlated with historic potato production. The earliest period for which data are available for a cross-section of countries is 1900. These data are from Mitchell (1998, 2003). We construct the natural log of tons of potato production per capita and examine its relationship with our potato suitability measure. The partial correlation between the two measures when overall agricultural suitability is controlled for is shown in Figure 4A. The correlation between the two variables is 6.6, which is statistically significant at the 1% level. Figure 4A only shows Old World countries. If we also include the 11 additional New World countries for which data are available the results are left essentially unchanged.

B. ***Outcome Variables: Population and Urbanization***

The historic populations of land area that today comprise countries are from McEvedy and Jones (1978). In our analysis, we examine the level of population in the following years: 1000, 1400, 1500, 1600, 1700, 1800 and 1900. We do not use the years 1100, 1200 and 1300 because data from that time is very inaccurate due to the population fluctuations caused by the Black Death. We also examine the average annual population growth rate between each time period. This is calculated in the standard manner:

$$\text{Population growth}_{it} = \frac{\ln(\text{Population}_{it}) - \ln(\text{Population}_{it-n})}{n}$$

where n is typically 100 years, except when $t = 1400$. Then $n = 400$.

We also examine the effect of potatoes on economic development. Because per capita income data are unavailable prior to 1500, and even in 1500 they are only available for 22 Old World countries,[7] we use the urbanization rate as an alternative measure of economic development. Data on the populations of urban centers are from Chandler (1987), Bairoch (1988), and Modelski (2003). We measure a country's total urban population to be the number of people living in cities with more than 20,000 inhabitants. We construct each country's urbanization rate by dividing its total urban population by its total population taken from McEvedy and Jones (1978). We measure the urbanization rate in percent; it therefore ranges from zero to 100.

Accuracy is an obvious concern for historic data that spans such a long time horizon and broad cross section. McEvedy and Jones (1978) discuss how the data on population are compiled. We summarize the main methods in the data appendix. Data are typically more accurate for cities which often had censuses. And most of the difficulties in constructing the data relates to rural areas. For country level data, this may be made more difficult by changing national boundaries. The data we use uses contemporary boundaries. This measurement error of our outcome variables should not bias our regression estimates as long as it is random. We have no reason to believe that it is otherwise. But for caution, we collected historical city level data on population and check this assumption by estimating the effects on population at the country level and the city level.

In our analysis we also examine the average annual change in the urbanization rate, which we calculate as follows:

$$\text{Change in urbanization}_{it} = \frac{\text{Urbanization rate}_{it} - \text{Urbanization rate}_{it-n}}{n}$$

Because country population is the denominator, we can only examine urbanization at the country level. In addition to being interesting in and of itself, urbanization can potentially be used as a proxy of income or even economic development (e.g., DeLong and Shleifer, 1993, Acemoglu, Johnson, and

[7] The most extensive and complete historic income data available are from Maddison (2003).

Robinson, 2002, 2005). The validity of urbanization as a measure of income is shown by Acemoglu *et al.* (2002), who document a very strong relationship between urbanization rates and per capita income levels across former colonies in 1995.[8] Using the available historic income data from Maddison (2003), we are able to examine the relationship between urbanization and income back to 1500, looking both in the cross section and in the time series. The strength of the relationship between the two measures is illustrated in the graphs shown in Figure 4B. In the graphs a unit of observation is an Old World country in either 1500, 1600, 1700, 1800, or 1900. It shows the relationship between the natural log of income and urbanization; the correlation is 0.73. The figure provide a visual illustration of a fact that is apparent if one examines the data more formally: there is a very strong relationship between urbanization and per capita income in both the cross-section and the time-series.

By itself, the relationship between income levels and urbanization does not tell us if the latter is a good proxy for economic development. One could imagine two extreme scenarios. In the first one, where agricultural laborers are able to capture all the gains from potatoes, then urbanization reflects an increase in newly freed labor which can help spur the development of non-agricultural sectors. In the second case, where landlords capture all the gains, then urbanization only reflects an increase in rent-earning landlords who move to cities. This does not necessarily lead to economic growth. We address this in our investigation of the mechanisms.

We construct two panels. The first is a panel of countries that includes population and our constructed measure of suitability. The sample consists of 187 countries. With the exception of seven countries, each country is observed in each time period. The second is a panel of cities. There are in total 1,379 cities. The number increases with year, and 78 are observed for six or more years. Our estimated coefficients do not differ dramatically between the full sample or the subsample of 78 cities. Therefore, we only report full sample estimates.

Table 3 describes the data. Cities have on average 92,430 individuals and population growth of approximately 0.4% per year. Countries on average have populations of 3.4 million, where 2.6% reside in cities. Historically, population grew at approximately 0.3% per annum, and the share of population living in cities grew at approximately 0.01% per annum. On average, 7% of total land is suitable for potatoes, 10% is suitable for rice, 12.5% is suitable for wheat, 26.4% is suitable for cereals, 8.6% is suitable for maize, 6.3% is suitable for silage maize, and 8% is suitable for sweet potatoes.

[8]However, there are reasons why one may argue that this relationship does not provide sufficient evidence for the use of urbanization in our context. First, the relationship documented in Acemoglu *et al.* is among former colonies only. Acemoglu *et al.*'s sample is different from the sample in this study since their sample also includes New World countries and does not include Old World countries that are not former colonies. Second, the evidence from Acemoglu *et al.* only shows that there is a relationship in the cross section in 1995. It does not show that there is a relationship in the cross-section in earlier periods and it does not show that there is a relationship in the time series. In other words, it does not show that urbanization rates are a valid measure in a historic panel setting.

The average elevation is 466 meters. On average, 3.5% of a country's land is rugged, 0.03% is comprised of desert, and 0.44% is tropical.

The data for the institutional variables are taken from Acemoglu *et al.* (2005). We see that serfdom was legal in 7% of countries in 1700. On average, 2% of the population in 1700 was living in cities. 3% of the sample was part of the Roman Empire. The average distance to an ice free coast, our measure for access to trade, is approximately 247 km. Total slave exports, taken from Nunn (2008), are measured in millions of slaves. The average value is 0.009.

5. Results

A. *Flexible Estimation*

We plot the estimates from the flexible estimating equation of the effect of suitability for potatoes and the suitability for overall agricultural production on population, population growth, urbanization, and the growth in urbanization and their standard errors in Figure 5. They are reported in Appendix Table A1. The figures show that potatoes had little effect during 1400-1700. But after 1700, it had a positive effect. Overall agricultural suitability had little effect across all periods. The y-axes of the figures are identical so that the magnitudes of the coefficients can be easily compared. The pattern is similar for all four outcomes. The trend break in the effect of potatoes around 1700 supports our assumption that the DD estimates are not capturing spurious trends in growth in countries that our suitable for potatoes.

B. *Differences-in-Differences*

Table 4 shows the DD estimates without controlling for geographic factors. The approximate consistency in the estimated effect on population between column (1) and column (3) gives us some confidence in the country level population data. Note that the effect of population growth at the country level in column (4) is much larger than the city level estimate in column (2). This most likely reflects the fact that the city level estimates cannot capture the rise of new cities. In columns (4) and (6), we estimate the interaction effect of suitability for potatoes and suitability for existing Old World Staples such as wheat, rice and cereals. The latter is computed as the union of the land suitable for any of these three crop categories. The interaction term is negative and statistically significant, indicating that suitability for potatoes had less benefits in regions that were suitable for pre-existing crops. This is consistent with the historical evidence that potatoes were considered inferior to bread, and consumed as a substitute when these other crops were scarce.

Our baseline estimates are reported in Table 5 columns (1) and (7). These estimates control for the full vector of geographic variables. They show that after the introduction of potatoes, a country where 100% of the land is suitable for potato cultivation would experience a 1.3 rise in population in population, a 0.8 percentage-point rise in annual population growth rate, a 13.8% increase in the level of urbanization, and a 0.14 percentage-point rise in annual urbanization growth. Note that since only 7% of land was suitable for potatoes, we need to multiply these coefficients by 0.07 to obtain the average effect.

We show the partial correlation plots between potato suitability and the outcome of interest in Figure 6. Our baseline estimates are represented as the slopes of the regression lines. The eastern region of these plots show that the effect is largest in Eastern and Northern European countries such as Belarus, Denmark, Latvia, and Lithuania. The plots also show that Great Britain, former European colonies such as Australia, New Zealand and Thailand are also outliers. For robustness, we will re-estimate on subsample where the outliers are omitted. But it is clear from Figure 6 that their omission should not greatly affect our estimates.

C. *Robustness*

In Table 5 columns (2)-(6) and (8)-(12), we report our estimates with robustness controls for the fraction of land that is suitable for other New World crops, whether a country was part of the Roman Empire, the natural logarithm of average population during 1000-1400, distance to an ice free coast and net slave exports.

Columns (2) and (8) show that the estimated effect of potatoes are robust to controlling for suitability for other New World crops. This suggests that the estimated potato coefficients do not simply capture the benefits to population and urbanization of other New World crops. This fact is not surprising once one examines the history and nutritional characteristics of these two foods.

The fact that large parts of Europe is suitable for potatoes raises the concern that our estimates capture other factors that may have affect the divergence of Europe during this time period. One explanation of is that many European countries benefited from a history of Roman rule. Acemoglu *et al.* (2005) construct a measure for this determinant of Europe's divergent growth: an indicator variable that equals one if a country was part of the Roman Empire. We control for the interaction terms of these variables with an indicator variable for post 1700. Columns (3) and (9) show that our baseline estimates are robust to this control.

Another potential confounding factor is the occurrence of the Black Death. If this plague, which killed up to 30% of European population, was more severe in regions that were suitable for potatoes, our estimates will over-state the true effect of potatoes. The coefficients in columns (4) and (10) show that our estimates are robust to controlling for pre- existing levels of population.

Next, we consider the fact that potatoes were carried around the world by sailors imply that our main estimates may spuriously capture the effect of trade. Columns (5) and (11) show that our estimates are robust to controlling for access to trade, which we proxy with distance to an ice free coast.

The final factor that we consider is the trade in slaves in Africa. The slave trades reached their height in the 1700s, which is approximately the same time that potatoes were being adopted globally. If countries that were least able to adopt potatoes were also African countries from which the most slaves were taken, then this may explain part of the effect of potatoes on increased population growth and economic development after 1700. To capture the potential effects of Africa's slave trades, we include an country-specific measure of the number of slaves taken during the 100 years prior to period t. The results are reported in columns (6) and (12). As shown, including this control changes our estimated potato coefficients very little.

a. Sensitivity to Sample Changes

In Table 6 columns (1)-(2), we report the baseline estimates for samples we omit the outliers. One explanation is that many European countries benefited from a history of Roman rule. Acemoglu, Johnson, and Robinson (2001) have shown that an important determinant of the effect of colonial rule on subsequent development was the initial disease environment. In areas with less disease, better institutions were implemented by the European colonizers, and therefore post-1700 population growth and economic development may be disproportionately higher relative to their pre-1700 levels. To capture this potentially omitted factor, we re-estimate the baseline specification using a sample where we exclude all countries that overlap with the area between the equator and the Tropic of Capricorn. The coefficient for some of the outcomes are slightly reduced but are still large, positive and statistically significant.

The main sample contains only Old World countries because our identification strategy only applies to regions in which potatoes were not indigenous. However, most historians believe that for whatever reason, indigenous populations north of Mezzo America did not cultivate potatoes before European colonials "re-introduced" cultivation. Column (5) shows that the inclusion of North America slightly reduces the magnitude of the effects on population and population growth and increases the magnitude of the effects on urbanization. The estimates are always statistically significant. In column (6), we repeat the estimation with the inclusion of both North and South America. These estimate should be interpreted loosely because the identification strategy is not suitable for South America and because the pre-contact population data are particularly unreliable for the Americas due to the high mortality rates the indigenous population experienced from European diseases. With these caveats, column (6) shows that inclusion of the Americas does not greatly affect the estimates.

D. *Mechanisms*

a. Displacement, Migration and Trade

To investigate whether the main results from cross country comparisons reflect displacement of population from regions that are unsuitable to potatoes into regions that are suitable or by an increase in overall population growth, we estimate the effect of average suitability in neighboring countries. If the effect of a country's own suitability is driven by displacement, then the neighbor's suitability should cause out-migration and hence have a negative effect on population. We define this to be adjacent countries that share a boundary. Columns (1) and (2) in Table 7 show that neighbors' suitability does not have a negative effect. This supports our claim that our main results reflect an increase in overall population. This of course does not rule out that migration played a role. It could very well be that regions suitable for potatoes attracted migration from neighboring countries. And in those countries, the emigrants were replaced by increased fertility.

We examine whether the increase in population reflects migration as well as increases in fertility and reductions in mortality by estimating the interaction effect of potato suitability and the average suitability in a neighbor's country. If migration plays a role, then the effect of suitability should be smaller if the neighboring countries are also suitable. The negative estimates in columns (3)-(4) show that this is indeed the case.

There is a caveat for interpreting this triple interaction. The negative estimate could also be driven by trade mechanisms. If the introduction of potatoes is viewed as a technological shock to agriculture in countries that are suitable, then the same shock given to neighboring countries would reduce the benefits from the shock along the lines of comparative advantage. To explore this possibility, we investigate whether trade matters for the effect of potatoes. We proxy for access to trade with distance to an ice free coast and divide the sample according to the median distance, approximately 226 km. If the differential effect of neighbors' suitability is driven by a reduction of comparative advantage, then under most conditions, the differential effect should be larger for countries that typically trade more i.e. the countries with better access near the coast. A comparison of the estimates in columns (5)-(6) with columns (7)-(8) show that this is not the case. The effect is larger in countries that have less access to trade. This is consistent with our findings that the effects are largest to Eastern and Northern Europe that were relatively isolated. We conclude from these results that migration did play a role in the effect of potatoes on population.

We can also directly examine whether trade affected the impact of potatoes by interaction suitability for potatoes with distance to an ice-free coast. The estimates in Panel A of Table 8 show that the effect of potatoes did not interact with trade.

b. Push versus Pull and Fat Cats

The effect of potatoes on urban population can result from two complimentary forces. Access to potatoes increases the carrying capacity of land in countries that are suitable, freeing workers from agricultural labor. This could push labor into cities. Alternatively, there could have been a rising demand for urban labor which would have pulled labor into cities. The latter is especially relevant during this time period as the manufacturing sector was rapidly developing in many countries. To investigate this, we estimate the interaction effect of suitability for potatoes and the level of urbanization in 1700. The latter is our proxy for pre-existing urban labor demand. If the predominant force driving the effect of potatoes was "pull", then the effect of potatoes should be larger in countries that had higher levels of pre-existing urbanization, and hence the coefficient should be positive. The estimates in columns (3) and (4) of Panel B in Table 8 show that the effect of the triple interaction on urbanization levels is large in magnitude and negative, and that there is no effect on urbanization growth. This suggests that the predominant force of urbanization was a "push".

Next, we explore the possibility that it was rent-earning landlords rather than laborers who were pushed into the cities. Both can result from the increase in agricultural productivity. The difference depends on who captures the rents from the increase. This does not affect our interpretation urbanization as a proxy for income levels. But it has very different implications on how we interpret urbanization in terms of economic development. In most scenarios, the movement of productive laborers into the cities should be more beneficial for economic development than the movement of newly made aristocrats. We investigate this by estimating the interaction effect of potato suitability and the ability of the elite to capture rents in 1700. We proxy for the latter with a variable indicating that serfdom was legal in 1700. This comprises of 26 countries, mostly in Eastern Europe. If the effect on urbanization is driven by the elite, then it should be larger in countries where serfdom was legal. The results in Table 8 Panel C show that this is not the case. Hence, we conclude that the effect on urbanization reflects newly freed agricultural laborers "pushed" into cities.

E. ***Average Effects***

It is well known that after 1700 the world experience an unprecedented increase in the growth of population and in economic development. This well established fact can be seen in Figure 1, which shows the evolution of total Old World population between 1000 and 1900. It is clear from the figure that relative to the period prior to 1700, after 1700 there is a clear increase in both the level and the growth rate of population. This is also shown in the first three rows of Table 9. The first two rows report the averages of each of our four outcome variables across countries during the two time periods. The first row reports averages for the pre-1700 period and the second row reports the averages for the post-1700 period. The third row reports the difference between these two averages. The table confirms that for all four of our outcome variables during the period after 1700 (relative to the period before 1700), countries witnessed a significant increase in average population, population growth, the urbanization rate, and the rate of change of urbanization.

To illustrate the magnitude of our estimates we calculate how much of these pre- and post-1700 differences can be attributed to the introduction of the potato. According to our definition of potato suitability, the average country has approximately 7.7% of its land suitable for cultivating potatoes. We take this as our measure of the average fraction of land that could be used to grow potatoes after 1700. Prior to 1700, since potatoes were not yet introduced, no country was able to grow potatoes and therefore this number was effectively 0%. The introduction of potatoes, therefore, increased this figure from 0 to 7.7%.

Our DD estimates provide a measure of the benefit of being able to cultivate potatoes on increased population growth and economic development after 1700. To be as conservative as possible, we use our lowest estimated effect of potatoes on each outcome from Table 5.

Using these estimates it is straight-forward to calculate the gains from the introduction of potatoes to the Old World. The introduction of potatoes: (*i*) increased the average population across Old World countries by 8% (i.e., $1.07 \times 0.077 = 0.08$), (*ii*) increased the average annual growth rate across Old World countries by 0.06 percentage points, (*iii*) increased the average urbanization rate across Old World countries by 0.97 percentage points, (*iv*) increased the average annual growth in the urbanization rate across Old World countries by 0.01 percentage points. These estimated effects are reported in the sixth row of Table 9.

To help put these figures into perspective we calculate how much of the increase in our four outcome variables is explained by the introduction of potatoes. These numbers are reported in the final row of the table. Take as an example population growth in column (2). The average annual population growth was 0.13% per year between 1000 and 1700 and 0.42% per year between 1700 and 1900 and the difference was 0.29%. Our estimates imply that the introduction of potatoes accounts for 21.1% ($0.06/0.29 = 0.21$) of this increase. Doing this calculation for the estimated effects on all of the outcomes shows that availability of potatoes can explain 9.5% of the increase in population, 21% of the increase in population growth rate, 43% of the increase in urbanization, and 48% of the increase in urbanization growth rates.

Because these figures may seem large to some, we want to be clear about what they mean. Take for example our figure of 18% for population growth. This does not mean that 18% of the total increase in population growth between 1000 and 1900 is explained by potatoes. Nor does it mean that 18% of the increase in population growth after 1700 is explained by potatoes. The statement is that after 1700, relative to the period before 1700, there is an increase in the average rate of population growth. Conceptually, this can be thought of as the kink in Figure 1 at the year 1700. It is this kink, or difference in the average growth between the two periods, that is being explained.

6. Conclusion

This study estimated the effect of the introduction of the potato on Old World population growth and urbanization. The unique history of the potato and its diffusion from the New World allows us to estimate causal effects using a difference-in-differences estimation strategy. According to our most conservative estimates, the introduction of the potato explains 18% of the observed post-1700 increase in population growth and 37% of the increase in the growth of urbanization. These results show that food matters: increasing the nutritional carrying capacity of land can have large effects on population. And this in turn leads to the movement of workers to cities, which could benefit long run economic development.

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Figure 1: World Population and Urbanization

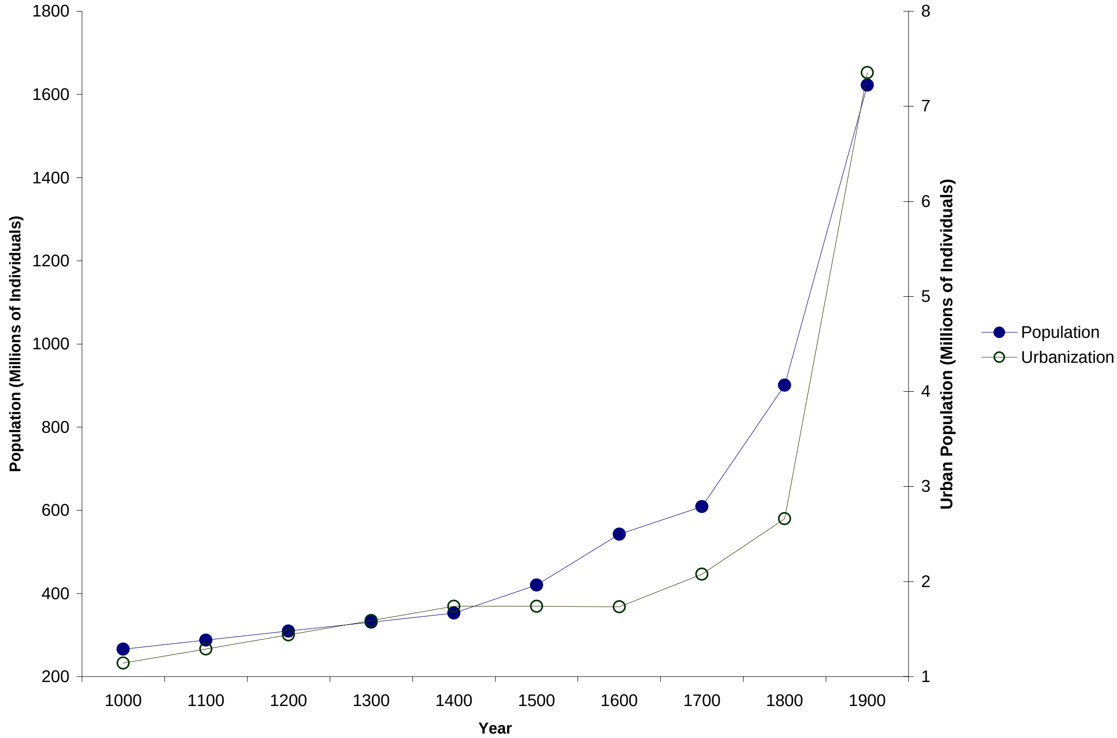


Figure 2B: World Map of Potato Suitability

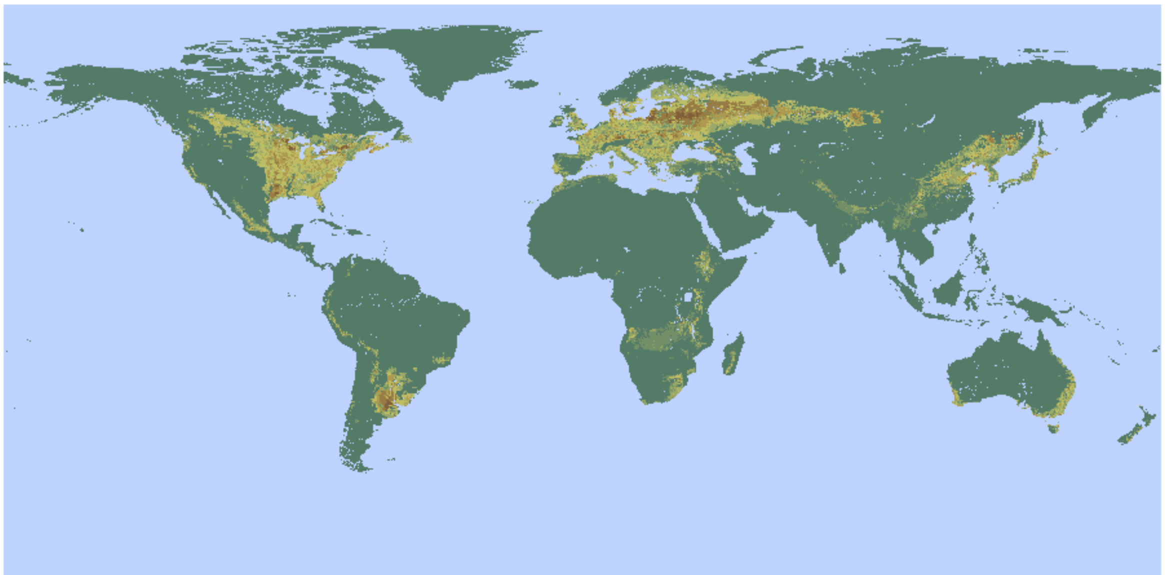


Figure 2C: City Level Potato Suitability

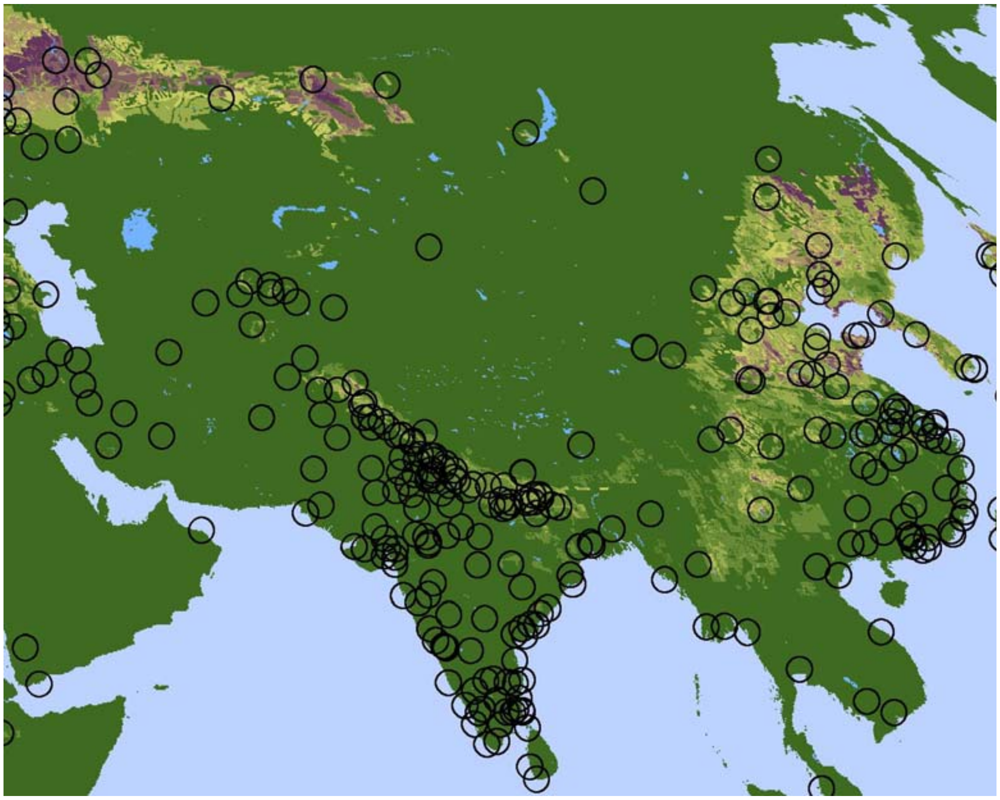


Figure 3: Histogram of Average Potato Suitability across Countries

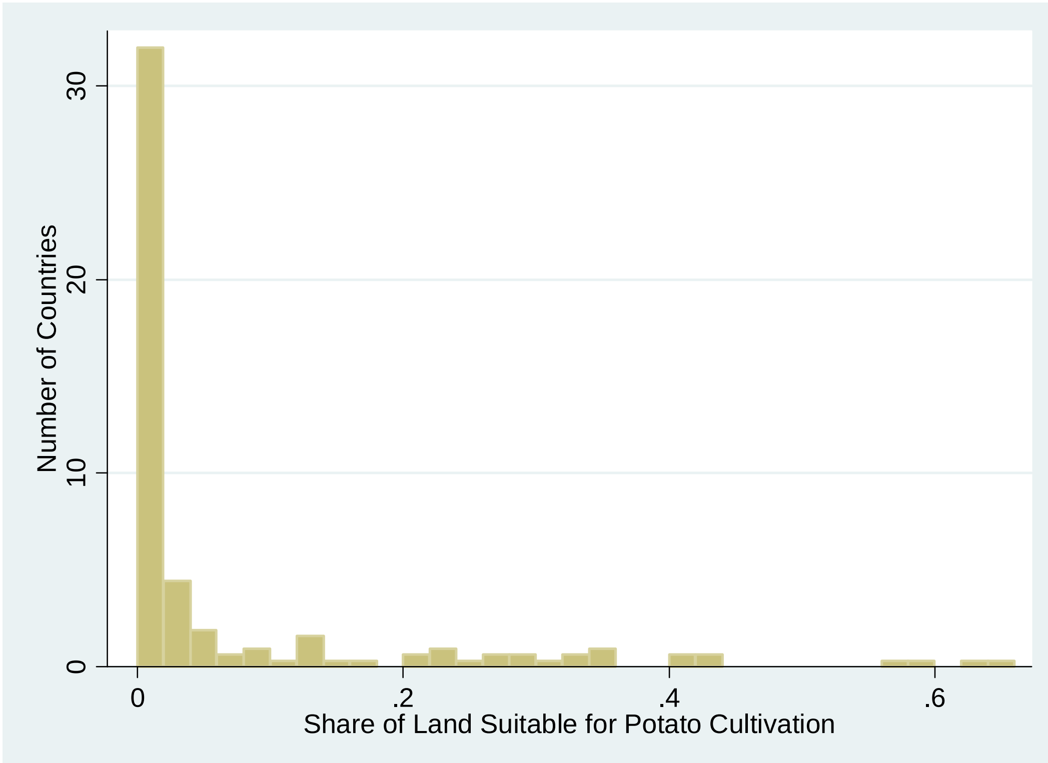


Figure 4A: Partial Correlation between Potato Suitability and Ln Per Capita Production in 1900 (Controls for overall agricultural suitability)

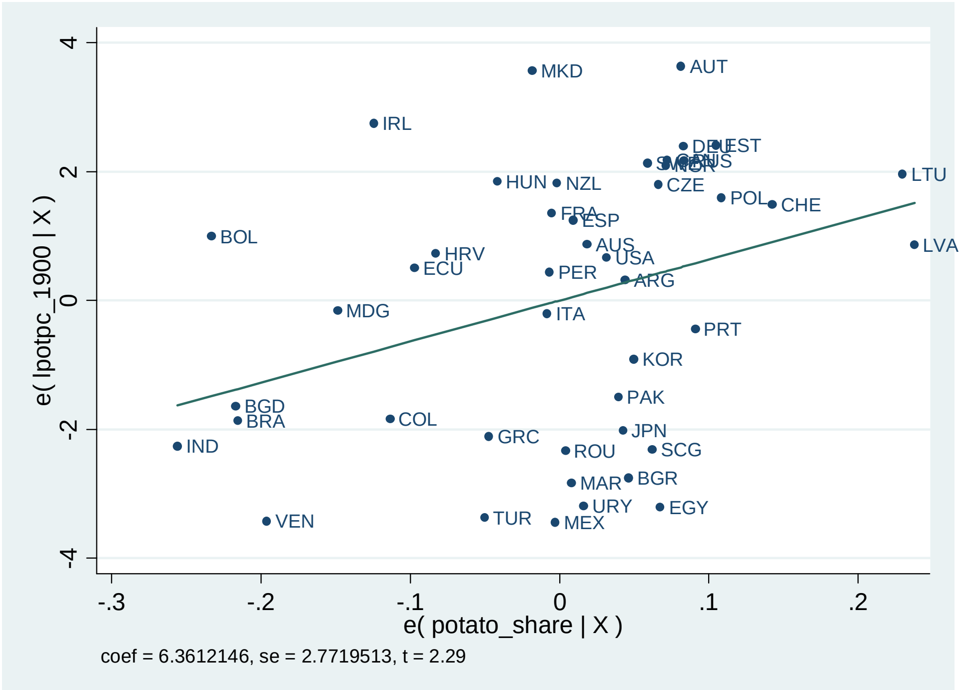


Figure 4B: Bivariate Correlation between Ln Per Capita GDP and Urbanization

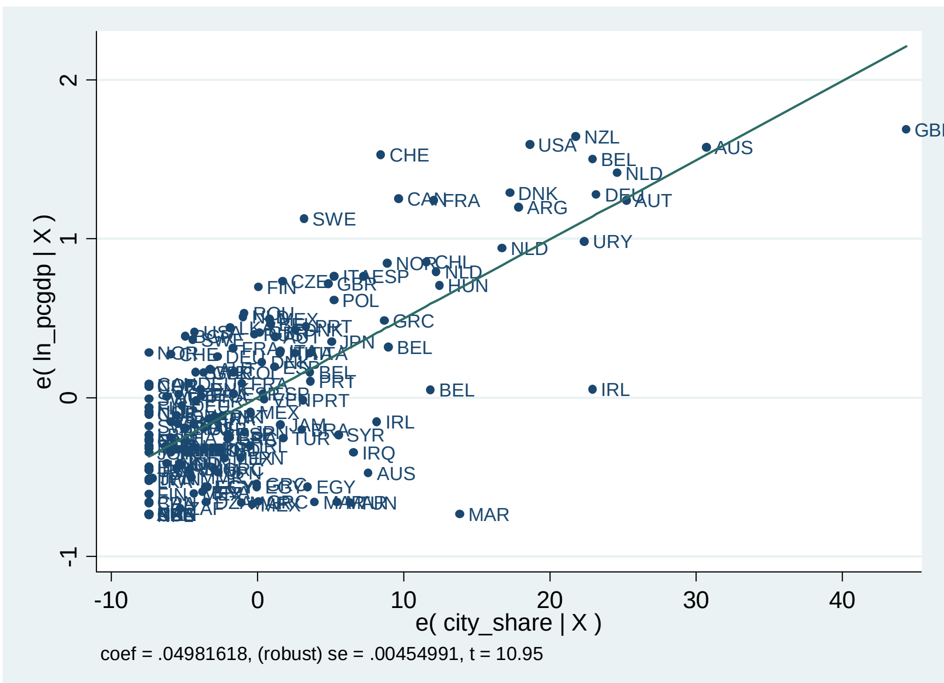


Figure 5: Yearly Estimates of the Effect of Suitability

Coefficients of the interaction terms of suitability (for potatoes or for all crops) and year dummy variables

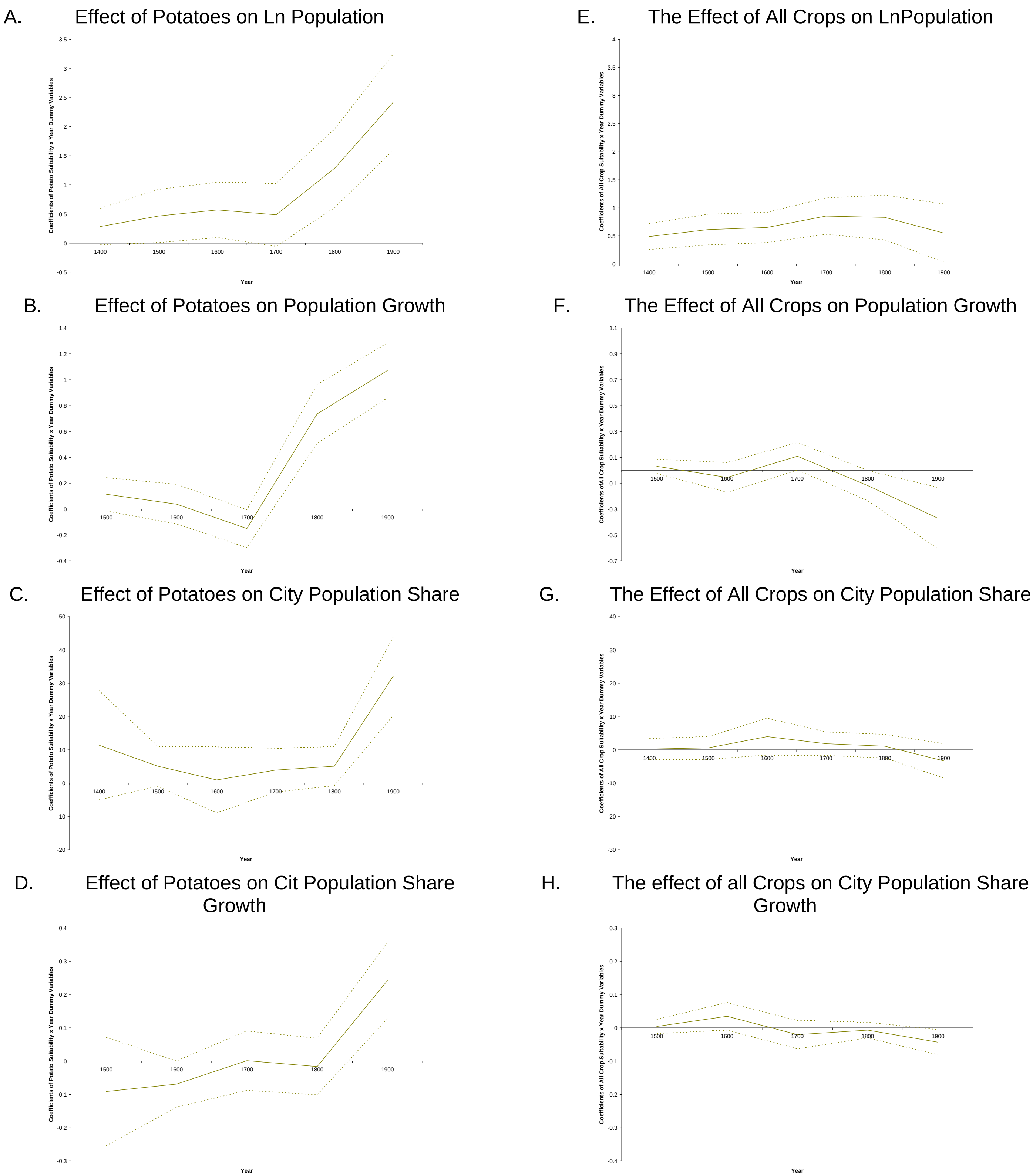
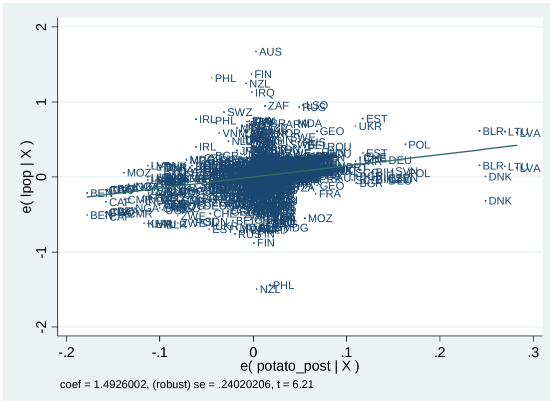


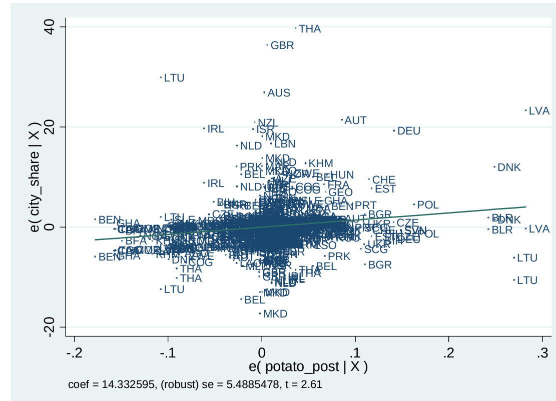
Figure 6: Partial Correlation Plots of Potato Suitability

Coefficients of potato x post

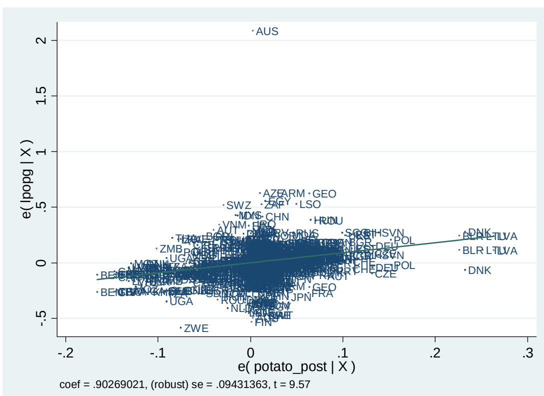
A. Partial Correlation Plot of Potato x Post and Ln Population



C. Partial Correlation Plot of Potato x Post and City Population



B. Partial Correlation Plot of Potato x Post and Population Growth



D. Partial Correlation Plot of Potato x Post and City Population Growth

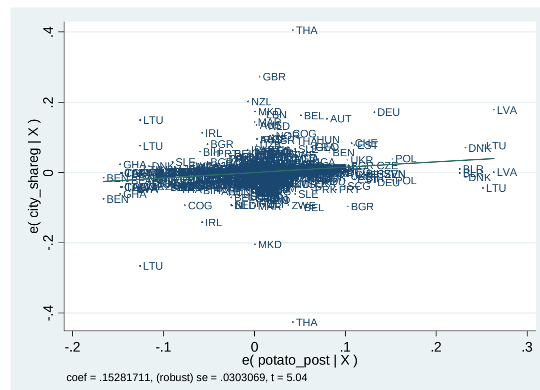


Table 1: Historical Potato Yields

Average Yields from English Farms in the 18th Century				
	Average Yield per Acre		Energy Value of Crop	Land required to provide 42 MJ daily for one year
	Bushels	Kilograms	Megajoules	
Wheat	23	650	8,900	1.7
Barley	32	820	11,400	1.4
Oats	38	690	9,300	1.6
Potatoes	427	10,900	31,900	0.5

Notes: Data are from 18th century England, recorded in Young's (1771, p. 20) *The Farmer's Tour through the East of England* reproduced in Davidson et al. (1975).

Table 2: The Correlation between Suitability for Potatoes and Other Factors

		Potato
Suitability	Potato	1
	Neighbor's Potato	0.6433*
	Rice	-0.3006*
	Wheat	0.9296*
	Cereal	0.5719*
	Maize	0.0825
	Silage Maize	0.9272*
	Sweet Potato	-0.3084*
Geography	Elevation	-0.2004*
	Ruggedness	-0.0613
	Desert	-0.1694*
	Tropics	-0.3924*

* Indicates 5% significance of the correlation coefficients.

Table 3: Descriptive Statistics

	Observations	Mean	Standard Errors
	City Level Data		
A. Demographic Variables			
Population	2251	92429.440	(3882.524)
Population Growth	837	0.405	(0.026)
	Country Level Data		
Population	1373	3.433	(0.539)
City Population Share	1351	2.653	(0.211)
Population Growth	1153	0.284	(0.013)
City Population Share Growth	1153	0.010	(0.002)
B. Agricultural Suitability of Land			
Potato Share	1106	0.070	(0.004)
Potato Share in Neighboring Countries	1155	0.062	(0.003)
Rice Share	1106	0.099	(0.005)
Wheat Share	1106	0.125	(0.006)
Cereal Share	1106	0.264	(0.006)
Maize Share	1106	0.086	(0.004)
Silage Maize Share	1106	0.063	(0.004)
Sweet Potato Share	1106	0.080	(0.004)
C. Geography			
Elevation	1687	466.138	(12.503)
Ruggedness	1687	3.483	(0.084)
Desert Share	1687	0.027	(0.002)
Tropics Share	1687	0.439	(0.011)
D. Institutions			
Legal Serfdom in 1700	1702	0.070	(0.006)
City Population Share in 1700	1358	2.069	(0.128)
Part of Roman Empire	1702	0.033	(0.004)
Distance to Ice Free Coast	1687	246.772	(9.237)
Net Slave Exports	1701	-15.129	(0.080)

Table 4: The Correlation between Potato Suitability and Population at the City and Country Levels

	Dependent Variables					
	City Level		Country Level			
	(1)	(2)	(3)	(4)	(5)	(6)
	Ln Pop	Pop Growth	Ln Pop	Ln Pop	Pop Growth	Pop Growth
Potato x Post	1.060	0.5970	1.493	3.105	0.903	1.418
	(0.293)	(0.2336)	(0.222)	(0.799)	(0.086)	(0.430)
Potato x Old World Crops x Post				-2.778		-0.878
				(1.160)		(0.645)
Old World Crops x Post	N	N	N	Y	N	Y
Observations	1711	705	901	901	772	772

All regressions control for All Crops x Post, country and year fixed effects.
Standard errors are clustered at the country level.

Table 5: The Effect of Potato Suitability

	Dependent Variables											
	(1) Baseline	(2)	(3)	(4)	(5)	(6)	**(7) Baseline**	(8)	(9)	(10)	(11)	(12)
	Ln Population						Population Growth					
Potato x Post	**1.320**	1.461	1.297	1.073	1.278	1.214	**0.844**	0.912	0.860	0.821	0.827	0.789
	(0.239)	(0.249)	(0.239)	(0.169)	(0.240)	(0.256)	**(0.093)**	(0.098)	(0.094)	(0.096)	(0.094)	(0.102)
Old World Crops x Post	Y	N	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
New World Crops x Post	N	Y	N	N	N	N	N	Y	N	N	N	N
Roman x Post	N	N	Y	N	N	N	N	N	Y	N	N	N
Ln Pop 1000-1400	N	N	N	Y	N	N	N	N	N	Y	N	N
Distance to Sea	N	N	N	N	Y	N	N	N	N	N	Y	N
Slave	N	N	N	N	N	Y	N	N	N	N	N	Y
Observations	901	901	901	889	901	901	772	772	772	762	772	772
	City Population Share						City Population Share Growth					
Potato x Post	**13.762**	16.437	12.605	13.665	14.024	12.664	**0.139**	0.147	0.136	0.141	0.138	0.132
	(5.584)	(5.135)	(5.625)	(5.677)	(5.620)	(5.872)	**(0.029)**	(0.029)	(0.030)	(0.029)	(0.029)	(0.030)
Old World Crops x Post	Y	N	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
New World Crops x Post	N	Y	N	N	N	N	N	Y	N	N	N	N
Roman x Post	N	N	Y	N	N	N	N	N	Y	N	N	N
Ln Pop 1000-1400	N	N	N	Y	N	N	N	N	N	Y	N	N
Distance to Sea	N	N	N	N	Y	N	N	N	N	N	Y	N
Slave	N	N	N	N	N	Y	N	N	N	N	N	Y
Observations	901	901	901	889	901	901	772	772	772	762	772	772

All regressions control for All Crops x Post, elevation x post, ruggedness x post, desert x post, country FE and year FE.
Standard errors are clustered at the country level.

Table 6: Robustness – The Effect of Potato Suitability

	Omitted (Included) Groups					
	Omitting BLR, DNK, LVA, LTU	Omitting AUS, GBR, NZL, THL	Omitting Tropics	Omitting Zero Suitability	Including North America	Including North and South America
	(1)	(2)	(3)	(4)	(5)	(6)
	A. Dependent Variable: Ln Population					
Potato x Post	1.346	1.113	0.998	1.100	0.795	0.646
	(0.273)	(0.185)	(0.187)	(0.257)	(0.355)	(0.352)
Observations	873	874	782	544	999	1074
	B. Dependent Variable: Population Growth					
Potato x Post	1.223	1.018	1.018	0.828	0.912	0.739
	(0.153)	(0.138)	(0.143)	(0.173)	(0.257)	(0.270)
Observations	748	749	670	466	856	919
	C. Dependent Variable: City Population Share					
Potato x Post	10.644	8.498	8.656	8.978	9.633	9.035
	(3.969)	(5.501)	(5.894)	(6.713)	(5.917)	(5.668)
Observations	873	874	782	544	999	1074
	D. Dependent Variable: City Population Share Growth					
Potato x Post	0.088	0.090	0.094	0.077	0.115	0.111
	(0.023)	(0.021)	(0.022)	(0.030)	(0.038)	(0.036)
Observations	748	749	670	466	856	919

Regressions control for old world crops x post, country specific time trends, country and year fixed effects. Standard errors clustered at the country level.

Table 7: The Effect of Neighbors' Suitability

	Dependent Variables							
	Full Sample				Near Ice Free Coast		Far from Ice Free Coast	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Ln Pop	Pop Growth	Ln Pop	Pop Growth	Ln Pop	Pop Growth	Ln Pop	Pop Growth
Potato x Post	0.835	0.833	1.462	1.019	0.762	0.353	2.269	1.653
	(0.318)	(0.263)	(0.366)	(0.270)	(0.678)	(0.536)	(0.525)	(0.319)
Neighbor's Potato x Post	0.691	0.343	0.633	-0.546	0.407	0.203	1.878	-0.775
	(0.467)	(0.399)	(0.971)	(0.735)	(1.592)	(1.303)	(1.613)	(0.888)
Potato x Neighbor's Potato x Post			-14.653	-11.926	-11.907	-9.090	-33.279	-25.597
			(4.259)	(2.899)	(4.194)	(3.030)	(9.777)	(6.906)
Observations	811	695	811	695	399	342	412	353

All regressions control for all crops x post, country specific time trends, country and year fixed effects. Regressions in columns (3)-(8) also control for their interaction terms all crops x neighbor all crops x post, neighbor all crops x post, potato x neighbor all crops x post, all crops x neighbor potato x post.

Near and Far from Ice Free Coast are defined as countries whose distance is above or below the sample mean distance, 265 km.

Standard errors are clustered at the country level.

Table 8: The Effects of Access to Trade and Pre 1700 Urbanization

	Dependent Variables			
	(1)	(2)	(3)	(4)
	LnPop	Pop Growth	City Share	City Share Growth
A. Differential Effects with Trade				
Potato x Post	0.9603	0.9433	10.3530	0.0807
	(0.2498)	(0.2147)	(7.1631)	(0.0316)
Potato x Dist to Ice Free Coast x Post	0.0009	0.0003	-0.0014	0.0001
	(0.0009)	(0.0006)	(0.0104)	(0.0001)
Observations	818	701	818	701
B. Differential Effects with Pre-Urbanization Levels				
Potato x Post	1.384	1.139	17.360	0.112
	(0.250)	(0.157)	(4.431)	(0.026)
Potato x 1700 City Share x Post	-0.054	-0.046	-2.333	0.000
	(0.038)	(0.028)	(1.189)	(0.005)
Observations	818	701	818	701
C. Differential Effects with Elite Capture				
Potato x Post	1.349	1.034	8.162	0.096
	(0.274)	(0.150)	(8.508)	(0.027)
Potato x Serfdom in 1700 x Post	-1.088	-0.247	0.148	-0.046
	(0.404)	(0.361)	(10.256)	(0.049)
Observations	818	701	818	701

Regressions control for all crops x post, country specific time trends, country and year fixed effects. Regressions also control for distance to ice free coast x post in Panel A, 1700 City Share x Post in Panel B, and serfdom in 1700 x post in Panel C.

Standard errors clustered at the country level.

Table 9: The Contribution of Potatoes to Population and Urbanization Increases

		Outcomes			
		(1)	(2)	(3)	(4)
		LnPop	Pop Growth	Urban	Urban Growth
(1)	1000-1700 Average	-0.43	0.13	2.06	0.00
(2)	1800-1900 Average	0.44	0.42	4.33	0.02
(3)	Difference: (2) -(1)	0.87	0.29	2.26	0.02
(4)	Estimated Effect of being 100% Suitable for Potatoes	1.07	0.79	12.61	0.13
(5)	Average Suitability for Potatoes	0.08	0.08	0.08	0.08
(6)	Average Effect of Potato Suitability: (4) x (5)	0.08	0.06	0.97	0.01
(7)	**Percent of Change Explained by Potatos: (6)/(3) x 100**	**9.48%**	**21.12%**	**42.91%**	**47.67%**

Notes : The first row of the table reports the average outcome for all countries in each time period between 1000 and 1700. The second row reports the same averages for the time periods after 1700 (i.e., 1800 and 1900). The difference between the two averages is reported in row 3. The fourth row reports the most conservative regression coefficient for the effect of having 100% of land suitabile for potatoes. The fifth row reports the average suitability across countries. The sixth row reports the impact from the introduction of the potato, the product of the fourth and fifth row. The final row reports the percentage of the total difference between the pre- and post-1700 periods that is explained by the introduction of potatoes. This is equal to row 6 divided by row 3 multiplied by 100.

Appendix Table A1: Yearly Estimates of the Correlation of Potato Suitability

	Dependent Variable			
	(1) Ln Pop	(2) Pop Growth	(3) Urban	(4) Urban Growth
Potato x 1400	0.305		11.670	
	(0.158)		(8.431)	
Potato x 1500	0.495	0.127	5.182	-0.094
	(0.231)	(0.067)	(3.061)	(0.084)
Potato x 1600	0.614	0.046	1.154	-0.070
	(0.242)	(0.078)	(4.985)	(0.035)
Potato x 1700	0.549	-0.136	4.055	0.000
	(0.273)	(0.073)	(3.343)	(0.045)
Potato x 1800	**1.345**	**0.725**	4.490	-0.024
	(0.346)	**(0.113)**	(3.094)	(0.051)
Potato x 1900	**2.494**	**1.079**	**33.587**	**0.262**
	(0.421)	**(0.108)**	**(6.062)**	**(0.054)**
All Crops x 1400	0.499		0.257	
	(0.117)		(1.576)	
All Crops x 1500	0.609	0.037	0.470	0.003
	(0.138)	(0.027)	(1.733)	(0.011)
All Crops x 1600	0.658	-0.057	3.901	0.033
	(0.135)	(0.058)	(2.754)	(0.021)
All Crops x 1700	0.856	0.100	1.825	-0.019
	(0.163)	(0.054)	(1.769)	(0.021)
All Crops x 1800	0.828	-0.126	1.088	-0.006
	(0.200)	(0.058)	(1.780)	(0.012)
All Crops x 1900	0.549	-0.377	-3.431	-0.044
	(0.259)	(0.120)	(2.580)	(0.019)
F: Potato x 1800 = Potato x 1900 =0	44.65	60	20.18	21.98
Observations	900	770	900	770

All regressions control for country and year fixed effects.

All standard errors clustered at the country level.