The Three Horsemen of Riches: Plague, War, and Urbanization in Early Modern Europe*

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Abstract

How did Europe escape the "Iron Law of Wages?" We construct a simple Malthusian model with two sectors and multiple steady states, and use it to explain why European per capita incomes and urbanization rates increased during the period 1350-1700. Productivity growth can only explain a small fraction of the rise in output per capita. Population dynamics – changes of the birth and death schedules – were far more important determinants of steady states. We show how a major shock to population can trigger a transition to a new steady state with higher per-capita income. The Black Death was such a shock, raising wages substantially. Because of Engel's Law, demand for urban products increased, and urban centers grew in size. European cities were unhealthy, and rising urbanization pushed up aggregate death rates. This effect was reinforced by more frequent wars and disease spread by trade. Both reflected higher per capita incomes after the plague. In this way higher wages themselves reduced population pressure. We show in a calibration exercise that our model can account for the sustained rise in European urbanization as well as permanently higher per capita incomes in 1700, without technological change. Wars contributed importantly to the 'Rise of Europe,' even if they had negative short-run effects. We thus trace Europe's precocious rise to economic riches to interactions of the plague shock with the belligerent political environment and the nature of cities.

JEL: E27, N13, N33, O14, O41

Keywords: Malthus to Solow, Long-run Growth, Great Divergence, Epidemics, Demographic Regime

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1 Introduction

In 1400, Europe's potential to overtake the rest of the world seemed limited. The continent was politically fragmented, torn by military conflict, and dominated by feudal elites. Literacy was low. Other regions, such as China, appeared more promising. It had a track record of useful inventions, from ocean-going ships to gunpowder and advanced clocks (Mokyr, 1990). The country was politically unified, and governed by a career bureaucracy chosen by competitive exam (Pomeranz, 2000). In 14th century Europe, on the other hand, few if any of the variables that predict modern-day riches would suggest that its starting position was favorable.[1] By 1700 however, and long before it industrialized, Europe had pulled ahead decisively in terms of per capita income and urbanization – an early divergence preceded the "Great Divergence" that emerged with the Industrial Revolution (Broadberry and Gupta, 2006; Diamond, 1997).[2]

This early divergence matters in its own right. It laid the foundations for the European conquest of vast parts of the globe (Diamond, 1997). More importantly, it may have contributed to the even greater differences in per capita incomes that followed. In many unified growth models, an initial rise of per capita income is crucial for the transition to self-sustaining growth (Galor and Weil, 2000; Hansen and Prescott, 2002). Also, there is growing evidence that a country's development in the more distant past is a powerful predictor of its current income position (Comin, Easterly, and Gong, 2010). Voigtländer and Voth (2006) develop a model in which greater industrialization probabilities are the direct consequence of higher starting incomes. If we are to understand why Europe achieved the transition from "Malthus to Solow" before other regions of the world, explaining the initial divergence of incomes is crucial.

In a Malthusian economy, the "Iron Law of Wages" should hold – incomes can change temporarily, until population catches up.[3] Nonetheless, many European countries saw marked increases in per capita output. Maddison (2007) estimates that Western European per capita incomes on average grew by 30% between 1500 and 1700. Urbanization rates – often used as a better indicator of per capita output – also rose rapidly.[4] In the most successful economies, both incomes and urbanization rates more than doubled. How could output per capita rise substantially in a Malthusian economy?

We develop a simple two-sector model where shocks to population size can lead to permanently higher incomes. Before describing our mechanism, we briefly review the standard Malthusian model in the left panel of figure 1. Death rates are downward sloping in income, and birth rates are either flat or upward sloping. This generates a unique steady state (C) that pins down wages and population size. Decreasing marginal returns to labor set in quickly as population grows because fixed land is an important factor of production. A decline in population can raise wages, moving the economy to the right of C. However, the

[1] For a recent overview, see Bosworth and Collins (2003), and Sala-i-Martin, Doppelhofer, and Miller (2004).

[2] Western European urbanization rates were more than double those in China (Broadberry and Gupta, 2006; Maddison, 2001). We discuss the evidence at greater length in the section on historical background and context below.

[3] In the words of HG Wells, earlier generations should have always "spent the great gifts of science as rapidly as it got them in a mere insensate multiplication of the common life" (Wells, 1905). This is the intuition behind Ashraf and Galor (2010), who test for long-term stagnation of incomes despite variation in soil fertility and agricultural technology.

[4] Maddison considers urbanization as one of many factors influencing his estimates of GDP. The latest installments of his figures contain numerous, country-specific adjustments based on detailed research by other scholars.

increase in output per capita is only temporary. Birth rates now exceed death rates and population grows, which in turn will depress wages – the "Iron Law of Wages" holds.[5] We modify the standard Malthusian model to explain how early modern European incomes could rise permanently. We do so by introducing a particular mortality regime. In the right-hand panel of figure 1, we show a Malthusian model where death rates increase with income over some range. We refer to the upward-sloping mortality schedule as the 'Horsemen effect.' Steady state E_0 combines low income per capita with low mortality, while steady state E_H is characterized by higher wages and higher mortality. Point E_U is an unstable steady state. Suppose that the economy starts out in E_0. A major positive shock to wages (beyond E_U) will trigger a transition to the higher-income steady state.

[Insert Figure 1 here]

The Black Death was a shock that raised incomes significantly. It killed between one third and half of the European population in 1348-50. This raised land-labor ratios, and led to markedly higher wages. In figure 1, such a shock moves the economy beyond point E_U. From there, it converges to E_H. This is equivalent to a 'ratchet effect:' Wage gains after the Black Death should have been temporary in a standard Malthusian economy. Instead, they became permanent.[6]

The crucial feature to obtain multiple steady states in figure 1 is an upward-sloping part of the death schedule. This reflects the historical realities of early modern Europe. According to Malthus (1826), factors reducing population pressure include "vicious customs with respect to women, great cities, unwholesome manufactures, luxury, pestilence, and war." We focus on three – great cities, pestilence, and war. All of them increased in importance after the plague because of higher per capita incomes. High wages were partly spent on manufactured goods, mainly produced in urban areas. Cities in early modern Europe were death-traps, with mortality far exceeding fertility rates. Thus, new demand for manufactures pushed up aggregate death rates. War and trade reinforced this effect. Between 1500 and 1800, the continent's great powers were fighting each other on average for nine years out of every ten (Tilly, 1992). This was deadly mainly because armies on the march often spread epidemics. Wars could be financed more easily when per capita incomes were high. The difference between income and subsistence increased, leaving more surplus that could be appropriated by princes and spent on war. In addition, trade grew as people became richer. It also spread germs.[7] In this way, the initial rise in wages after the Black Death was made permanent by the 'Horsemen effect,' pushing up mortality rates and producing higher per capita incomes. Thus, Europe experienced a simultaneous rise in war frequency, in deadly disease outbreaks, and in urbanization. The Horsemen of the

[5] Technological innovation has an affect akin to a drop in population: Wages rise temporarily but eventually converge back to the unique steady state.

[6] A large positive shock to technology could theoretically also cause this transition. However, pre-modern rates of productivity growth are much too low to trigger convergence to the high-income steady state.

[7] Numerous studies have focused on the interaction between domestic armed conflict and income. Many find that civil wars decline in frequency after positive growth shocks (Collier and Hoeffler, 1998, 2004; Miguel, Satyanath, and Sergenti, 2004). In contrast, Grossman (1991) has argued that higher incomes should promote wars ("rapacity" effect), as there is more to fight over. Martin, Mayer, and Thoenig (2008) find that more multilateral trade can lead to more war.

Apocalypse effectively acted as 'Horsemen of Riches.'[8]

To our knowledge, this study is the first to investigate quantitatively the factors that led to Europe's early rise to riches. We do so in a comparative perspective. The great 14^{th} century plague also affected China, as well as other parts of the world (McNeill, 1977). Why did it not have the same effects there? We argue that the Chinese demographic regime did not feature multiple steady states. Similar shocks did not lead to permanently higher death rates for two reasons. Chinese cities were far healthier than European ones, for a number of reasons involving cultural practices and political conditions. Also, political fragmentation in Europe ensured continuous warfare once the growing wealth could be tapped by belligerent princes. This was the case after 1400. China, on the other hand, was politically unified, except for brief spells of turmoil. There was no link between p.c. income and the frequency of armed conflict. In Western Europe, a unique set of geographical and political starting conditions interacted with the plague shock to make higher wages sustainable; where these starting conditions were absent, transitions to higher incomes were much less likely. China can thus be represented by the standard Malthusian model in the left panel of figure 1, with a unique low-income steady state.

We are not the first to argue that higher death rates can have beneficial economic effects. Young (2005) concludes that HIV in Africa has a silver lining because it reduces fertility rates, increasing the scarcity of labor and thereby boosting the consumption of survivors.[9] Clark (2007) highlights the benign effect of higher death rates on p.c. income in the Malthusian period. Lagerlöf (2003) also examines the interplay of growth and epidemics, but argues for the opposite causal mechanism. He concludes that a decline in the severity of epidemics can foster growth if they stimulate population growth and human capital acquisition.[10] Brainerd and Siegler (2003) study the outbreak of "Spanish flu" in the US, and conclude that the states worst-hit in 1918 grew markedly faster subsequently. Compared to these papers, we make three contributions. First, we use the Malthusian model to explain permanently higher wages, not stagnation at a low level. Second, we are the first to demonstrate how specific European characteristics – political and geographical – interacted with a large mortality shock to drive up incomes over the long run, leading to the 'First Divergence.' Third, we calibrate our model to show that it can account for a large part of the 'Rise of Europe' in the early modern period.

Other related literature includes the unified growth models of Galor and Weil (2000) and Galor and Moav (2002). In both, before fertility limitation sets in and growth becomes rapid, a state variable gradually evolves over time during the Malthusian regime, making the final escape from stagnation more and more likely. In Galor and Weil (2000), Jones (2001), and Kremer (1993), the rise in population which in turn

[8] This is the opposite of the negative effect of wars, civil wars, disease, and epidemics on income levels found in many economies today (c.f. Murdoch and Sandler, 2002; Hoeffler and Reynal-Querol, 2003; Hess, 2003). The main reason for this difference is that human capital is crucial for development today, while it was not in pre-modern times, when decreasing returns to (unskilled) labor in agriculture dominated the production pattern.

[9] In contrast, Lorentzen, McMillan, and Wacziarg (2008) argue that higher mortality in Africa – including from AIDS – reduces incentives to accumulate capital, and thus reduces growth.

[10] In a similar vein, Kalemli-Ozcan (2002) argues that declines in mortality were growth-enhancing. Lagerlöf (2010) studies income in a Hansen-Prescott type two-sector long-run growth model with war-induced deaths. He shows that the transition to a Solow economy can explain the decline in warfare in the 19^{th} century, i.e., after the period that we focus on.

produces more ideas is a key factor; in Galor and Moav (2002), it is the quality of the population.[11] Cervellati and Sunde (2005) argue that the mortality *decline* from the 19$^{\text{th}}$ century onwards was an important element in the transition to self-sustaining growth, by reducing fertility and increasing human capital formation. Hazan (2009) raises doubts about the underlying Ben-Porath mechanism. Hansen and Prescott (2002) assume that productivity in the manufacturing sector increases exogenously, until part of the workforce switches out of agriculture; Desmet and Parente (2009) claim that market size was key, interacting with product and process innovation in fostering takeoff. Strulik and Weisdorf (2008) argue that in a Malthusian regime with a strong preventive check, productivity growth in industry raised the relative cost of having children.[12]

Our model emphasizes changes in death rates as a key determinant of output per head. We also show that technological change can only explain a small fraction of the rising p.c. income in early modern Europe. One of the key advantages of our framework is that it can be applied to the cross-section of growth outcomes. In contrast, the majority of existing unified growth papers implicitly uses the world as their unit of observation. We deliberately limit our attention to the early modern divergence between Europe and China. While models such as Kremer (1993) and Hansen and Prescott (2002) try to explain the entire transition to self-sustaining growth, we simply ask what allowed an initial divergence of incomes to occur, long before technological change became rapid.[13]

Our paper adds to the literature on the origins of European exceptionalism. Diamond (1997) argued that a combination of geographical factors with grain and animal endowments in pre-historic times strongly influenced which continent did best after 1500. Mokyr (1990) emphasized Europe's superior record of invention after 1300. Jones (1981) sees a relatively liberal political environment as key. In contrast to the Far East, European rulers stifled entrepreneurs and traders much less. In the same vein, Acemoglu, Johnson, and Robinson (2005) argued that in Northwestern Europe, Atlantic trade helped to constrain monarchical powers, accelerating growth after 1500. Their contribution reverses the conclusion of an earlier literature, which had questioned the discoveries' importance for the 'Rise of Europe' (O'Brien, 1982; Engerman, 1972). Our paper emphasizes a combination of geographical and political factors, as well as the peculiar conditions of urban life. These starting conditions interact with the exogenous shock of the plague in a unique way that could not have occurred in the consolidated imperial states of the Far East. The large number of European states ensured that higher incomes translated into more wars. Combined with the filth and overcrowding of European cities, this turned one-off increases in wages into permanently higher incomes.

We proceed as follows. The next section provides a detailed discussion of the historical context. Section 3 introduces a simple two-sector model that highlights the main mechanism. In section 4, we calibrate our model and show that it captures the salient features of the 'First Divergence.' The final section summarizes

[11] Clark (2007) finds some evidence in favor of the Galor-Moav hypothesis, with the rich having more surviving offspring.

[12] Strulik and Weisdorf (2009) show how falling prices of manufactured goods can lead to fertility decline and thus higher wages in steady state

[13] Galor and Weil (2000) distinguish between a Malthusian, a Post-Malthusian, and a Solow period of growth. We argue in effect that a period of Malthusian dynamism superseded aeons of Malthusian stagnation, and that doing so prepared the ground for the Post-Malthusian world.

our findings.

2 Historical Context and Background

A number of factors contributed to the 'First Divergence' under Malthusian conditions. In this section, we first describe Europe's comparative economic performance after 1300, emphasizing its record of urban growth and high per capita incomes. We then discuss the four central elements in our story – the impact of the plague, Europe's high urban mortality penalty, and the effects of war and trade.

Early Modern Output Growth and Urbanization

European incomes increased substantially during the early modern period. Wage and output gains after the Black Death (1348-50) were massive, and were not fully reversed during the early modern period. Also, output growth between 1700 and 1850 is now widely believed to have been quite slow (Crafts and Harley, 1992). Hence, given the high level of output in 1850, production in 1700 must have been sizable already. Europe's transition to a highly urbanized economy is an additional indicator of its progress during the early modern period.

Real-wage gains after the Black Death are well-documented. During the "golden age of labor" (Postan, 1972) in England after 1350, wages approximately doubled (Phelps-Brown and Hopkins, 1981; Clark, 2005). Afterwards, the older Phelps-Brown and Hopkins series suggests a strong decline. Clark (2005) shows that wages fell back from their peak somewhat, but except for crisis years around the English Civil War, they remained above their pre-plague level.[14] Loschky's (1980) reworking of the data suggest gains of between a quarter and more than sixty percent after 1600. In this sense, the existing wage series offer qualified support to the optimistic GDP figures provided by Maddison (2007), who estimates that European p.c. income grew by one third between 1500 and 1700.

Not all of Europe did equally well. Allen (2001) found that real wage gains for craftsmen after the Black Death were only maintained in Northwestern Europe. In Southern Europe – especially Italy, but also Spain – stagnation and decline after 1500 are more noticeable. Described by Acemoglu et al. (2005) as the 'Rise of Atlantic Europe,' the North-West overtook Southern Europe in terms of urbanization rates and output. Nonetheless, every European country with the exception of Italy had higher per capita GDP in 1700 than in 1500 – despite rising population. This indirectly suggests that standard Malthusian predictions did not hold during the period.[15]

The relative riches of England are also well-established, since GDP in 1850 can be determined with a high degree of accuracy. Growth before 1850 is now widely accepted to have been slow, using the out-

[14]What matters for the predictions of the Malthusian model is per capita output, not wages as such. National income in the aggregate will be equivalent to the sum of wages, rents, and capital payments. Since English population surpassed its 1300 level in the eighteenth century, it is likely that rental payments were higher, too.

[15]Maddison assumes that subsistence is equivalent to approximately $400 US-Geary Khamy dollars. Even relatively poor countries like Spain and Portugal had per capita incomes more than twice as high in 1700.

put corrections offered by Crafts and Harley (1992). Subsequent research using the productivity dual has supported their conclusions (Antràs and Voth, 2003).

Urbanization rates strongly support the view that Europe's economy performed well during the early modern period. Urbanization has been widely used as an indicator of economic development (e.g., Acemoglu et al., 2005). By this measure, Europe overtook China at some point between 1300 and 1500, extending its lead thereafter (see below, in particular figure 2). What had been a few urban nuclei in Europe in the medieval period evolved into a dense network of urban centers by 1700. Historians of urban growth have used different definitions of what a town or city is. However, there is a broad consensus that European urbanization rates increased substantially during the early modern period. De Vries (1984) uses a cut-off of 10,000 inhabitants to define cities. He shows that the proportion of Europeans living in cities grew from 5.6 to 9.2 percent between 1500 and 1700 – a gain of 3.6 percent. De Vries' figures only start in 1500. To provide earlier data, we construct a comprehensive series of European urbanization based on Bairoch, Batou, and Chèvre (1988). Figure 2 shows the data, and appendix A.1 provides a detailed description. The Bairoch et al. numbers – based on cities with a population of more than 5,000 – imply an increase in urbanization of 5.3 percent between 1300 and 1700. They also suggest a marked acceleration of urban growth after 1350. In addition, we use our Bairoch et al. based figures to extrapolate De Vries' numbers. This suggests an increase of urbanization in cities with more than 10,000 inhabitants from about 3 to 9 percent throughout the three centuries after the Black Death. Prior to the Black Death, Medieval Europe did not experience a similar upward trend in urban population shares.[16]

[Insert Figure 2 here]

Other regions of the world did not experience sustained, rapid urban growth during this period. For example, the proportion of the Chinese population living in cities reached 3 percent in the mid-T'ang dynasty (762), 3.1 percent in the mid-Sung dynasty (1120), and probably stagnated at the 3-4 percent level thereafter until the 19th century (Maddison, 2001; see the dashed line in figure 2). Eastern Europe had low rates of urbanization overall, and it only saw minor increases after 1500. De Vries (1984) shows gains of 1.5% for the period 1500-1700. Similarly, the Middle East – while highly urbanized on some measures – stagnated in terms of urbanization between 1100 and 1800 (Bosker, Buringh, and van Zanden, 2008).

Urbanization rates reflect agricultural productivity. Townsmen need to be fed, and the greater productivity in agriculture, the higher the proportion of population living in cities that can be sustained (Wrigley, 1985). In many European countries, regulations and the threat of wartime destruction pushed manufacturing activities and market exchange into the cities. Even if some manufacturing activity was performed in the countryside ("proto-industrialization," cf. Ogilvie and Cerman, 1996), urbanization is a useful proxy for non-agricultural output. In China, periodic markets in the countryside served a function monopolized by European cities. This reduced relative urbanization rates (Rozman, 1973). Finally, European cities offered

[16]The period of the so-called 'Commercial Revolution' (Lopez, 2008), from 1000 to 1300, showed some gains in urbanization rates. However, sustained, rapid increases in the percentage of the population living in urban areas only occurred after the Black Death. Urban growth per century was about three times faster in 1300-1700 than in 1000-1300.

a unique benefit not found in other parts of the world – a chance to escape servitude. As a general rule, staying within the city walls for one year and one day made free men out of peasants bound to the land and their lord. In contrast, as one leading historian put it, "Chinese air made nobody free" (Mark Elvin, cited in Bairoch, 1991).

The First Divergence

Adam Smith had no doubt that the "real recompense of labour is higher in Europe than in China" (Smith, 1776). Malthus and many other scholars agreed (Elvin, 1973; Jones, 1981). Recently, the view that output per capita and wages were particularly low in China has been challenged. The "California School" argues that Chinese and European output per capita before 1800 were broadly similar. Pomeranz (2000) compares England with the Yangtze delta, China's most productive area. He concluded that Chinese peasants' incomes were similar or higher in terms of calories than those of English farmers.[17]

Debate about the relative economic positions of China and Europe in the early modern period continues. Data compiled by Broadberry and Gupta (2006) suggests that English wages expressed as units of grain or rice were markedly higher throughout the early modern period (they were higher than Indian wages, too). According to these calculations, Chinese grain-equivalent wages were 87% of English ones by 1550-1649, falling to 38% in 1750-1849. Since foodstuffs were largely non-traded goods, silver wages are arguably a better standard of comparison. They were much higher in Europe than in China. According to Broadberry and Gupta, Chinese silver wages fell from 39% of English ones to a mere 15%. Allen (2009) finds the Yangtze delta to be ahead only in the 17th century, its high point and a relative low point for English wages. According to his figures, Chinese hired farm laborers earned only one third of the wage of their English peers. In contrast, peasant farmers who tilled their own soil may have done better than their English contemporaries in the 17th century. Thereafter, English earnings overtook Chinese ones.[18]

These numbers support the revisionist case only partly. Europe in general, and England in particular saw the share of rent in national income rising as population grew (Allen, 2009). The same did not happen in China, despite massive population pressure. The reasons are essentially political (Brenner and Isett, 2002; Allen, 2009). Thus, even in the most favored area in China, production per head was probably markedly below the English level. This is the variable that matters for our analysis. In late 18th century England, labor was being released on a massive scale to the cities; farm laborers' wages had to be low relative to urban wages to enable this. Chinese agriculture did not release labor; it hoarded it. Allen (2009) shows that output per year and head probably fell by 40% between 1620 and 1820 in Chinese agriculture, as average farm size declined as a result of population pressure. He therefore concludes that "real wage comparisons push the start of the 'great divergence' back from the nineteenth century to the seventeenth." This is the view that underlies our interpretation – Chinese output per capita, while not necessarily below the European norm at the beginning of the early modern period, fell for most of it. In contrast, wages and incomes grew in Europe,

[17] His work has received support from Li (1998), who has presented optimistic conclusions about grain production in Jiangnan.

[18] Taking into account earnings opportunities in textile production, Allen estimates that the family income of an English laborer in the early 19th century was around 5% above that of a Chinese peasant family.

in a way that is difficult to explain in the standard Malthusian model.

The Plague

The plague arrived in Europe from the Crimea in December 1347. Tartar troops besieging the Genoese trading outpost of Caffa suffered from the disease. In an early example of biological warfare, the Tartars used trebuchets to throw disease-infected corpses over the city wall. Soon, the defenders caught the disease. It spread with the fleeing Genoese along the main trading routes, first to Constantinople, to Sicily, then mainland Italy, and finally the rest of Europe. By December 1350, it had reached the North of England and the Baltic (McNeill, 1977).

Mortality rates amongst those infected varied from 30 to 95%. Bubonic and pneumonic forms of the plague both contributed to surging mortality. The bubonic form was transmitted by fleas and rats carrying the plague bacterium (Yersinia pestis). Infected fleas would spread the disease from one host to the next. When rats died, fleas tried to feast on humans, infecting them in the process. In contrast, pneumonic plague spread from person to person, via the tiny droplets transmitted by the coughing of the infected. Transmission and mortality rates were particularly high for the pneumonic form of the plague.[19]

There appear to have been few differences in mortality rates between social classes, age groups, or between rural and urban areas. Some city-dwellers tried to escape the plague, withdrawing to country residences (described in Boccaccio's Decamerone). How successful these efforts were is unclear. Only a handful of areas in the Low Countries, in Southwest France and in Eastern Europe were spared the the Black Death.

We do not have good estimates of aggregate mortality for medieval Europe. The most likely figures are population losses of 15 - 25 mio., out of a total population of roughly 40 mio. people. Approximately half of the English clergy died, and in Florence and Venice, death rates have been estimated as high as 60-75% (Ziegler, 1969; Benedictow, 2004).

The "Great Plague" of 1348-50 was devastating. Less well-known is that a wave of plague outbreaks followed the Black Death. Many of them were linked to warfare or to trade, such as the outbreaks in Germany during the Thirty Years War and the plague in Marseille in 1720. These plague epidemics only peaked during the early modern period. As shown in figure 3, the number of plague epidemics more than quadrupled between the 14th and the 17th century – from about 150 outbreaks per decade after the "Great Plague" to a peak of 705 in 1630-40. The frequency of outbreaks declined only in the late 17th century, before dropping below 50 outbreaks per decade in the 18th century (most of the latter occurred in Eastern Europe).

[Insert Figure 3 here]

Plague was not the only epidemic disease to strike Europe periodically. There were also outbreaks of smallpox, cholera, and typhus. While epidemics were only one factor contributing to the overall mortality

[19] The exact nature of the disease that erupted in 1347 is still debated. For a summary of some of the arguments, cf. Herlihy (1997).

regime, it is clear that life expectancy in the early modern period was trending downwards – even in the most advanced areas of Europe (figure 4).

[Insert Figure 4 here]

Next, we turn to the additional factors that influenced mortality.

City Mortality and Manufacturing

European cities were deadly. Especially children died early: "There certainly seems to be something in great towns, and even moderate towns, peculiarly unfavourable to the very early stages of life" (Malthus, 1973, p. 242). In 1841, life expectancy in Manchester was a mere 25 years. At the same time, the national average was 42, and in rural Surrey, 45 years. While available figures are not as precise, early modern cities were probably just as unhealthy. Life expectancy in London, 1580-1799, fluctuated between 27 and 28 years (Landers, 1993). Nor were provincial towns more fortunate. York had similar rates of infant mortality (Galley, 1998).[20] Clark and Cummins (2009) find that early modern English urban mortality rates may have been up to 1.8 times the level in the countryside. For France, the practice of wet-nursing (sending children from cities for breast-feeding to the countryside) complicates comparisons. A comprehensive survey of rural-urban mortality differences estimates that in early modern Europe, life expectancy was approximately 50 percent higher in the countryside than in cities (Woods, 2003).

No such differential existed in China. Some mortality estimates have been derived from the family trees of clans (Tsui-Jung, 1990), using data from the 15th to the 19th century. Chinese infant mortality rates were lower in cities than in rural areas, and life expectancy was similar or higher. Members of Beijing's elite in the 18th century experienced infant mortality rates that were less than half those in France or England.[21] On average, during the period 1644-1899, men born in Beijing had a life expectancy at birth of 31.8 years. In rural Anhui, the corresponding figure was 31 (Lee and Feng, 1999). While the data is not necessarily representative, other evidence lends indirect support. For example, life expectancy in Beijing in the 1920s and 1930s was higher than in the countryside.

In Japan, where some data for 18th century Nakahara and some rural villages survives, city dwellers lived as long as their cousins in the countryside. Some recent evidence (Hayami, 2001) on adult mortality questions if Far Eastern cities were indeed healthier than the countryside, as some scholars have argued (Hanley, 1997; Macfarlane, 1997). On balance, it seems unlikely that there was a large urban penalty in China and Japan. Principal reasons probably include the transfer of "night soil" (i.e., human excrement) out of the city and onto the surrounding fields for fertilization, relatively high standards of personal hygiene, and a diet rich in vegetarian food. Since the proximity of animals is a major cause of disease, all these factors probably combined to reduce the urban mortality burden in the Far East.

[20] There is not enough data to derive life expectancy. However, infant mortality – a prime determinant of life expectancy – was in the same range in provincial towns and London.

[21] Woods (2003). The average infant mortality rate in the English cities listed before 1800 is 262; for Beijing, it is 104.

High urban mortality in Europe also reflected the way in which cities were built. In the words of one prominent urban historian, in "1600, just as in 1300, Europe was full of cities girded by walls and moats, bristling with the towers of churches" (De Vries, 1976). In China, too, city walls were widely used throughout the early modern period, partly because of their symbolic value for administrative centers of the Empire. However, since the country's unification under the Qin Dynasty in the third century BC, the defensive function of city walls declined. With relative ease, houses and markets spread outside the city walls.[22] Because Far Eastern cities could expand beyond the old fortifications, city growth did not push up population densities in the same way as in Europe.[23] This reduced overcrowding and kept mortality rates low.

Why did Europeans move to unhealthy cities? First, those who moved were not necessarily the ones who died – infant mortality was a major contributor to the urban-rural mortality differential. Second, cities offered other amenities – a wider range of available goods, and freedom from servitude for those who stayed long enough. Third, urban wages were generally higher than rural ones. The wage differential reflected the concentration of manufacturing activities in cities. This was enforced by guilds watching jealously over their monopoly of producing certain goods, in which they were aided by city authorities and princes. While some manufacturing activity gradually moved to rural locations from the 16th and 17th century onwards, the vast majority of non-agricultural goods in early modern Europe was produced in cities and towns (Coleman, 1983).

Wars, Trade and Disease

Early modern armies killed mainly through the germs they spread. The Black Death originally arrived with a besieging Tartar army in the Crimea. As a result of troop movements, isolated communities in the countryside were suddenly exposed to new germs as soldiers foraged or were billeted in farmhouses. The effect could be as deadly as it had been in the New World, where European diseases killed millions (Diamond, 1997). In one famous example, a single army of 6,000 men, dispatched from La Rochelle to deal with the Mantuan Succession, spread plague that may have killed up to one million people (Landers, 2003). As late as the Napoleonic wars, typhus, smallpox and other diseases spread by armies marauding across Europe proved far deadlier than guns and swords. Battlefield casualties were generally low, compared to aggregate death rates.[24] While individual campaigns could be deadly, armies were too small for military deaths to boost aggregate mortality rates directly.[25]

[22] In some cases, the new suburbs would also be enclosed by city walls (Chang, 1970).

[23] Barcelona is one extreme example. After the 1713 uprising, the Bourbon kings did not allow the city to expand beyond its existing walls until 1854. As industrial growth led to an inflow of migrants, living conditions deteriorated considerably (Hughes, 1992).

[24] Data on deaths caused by military operations in the early modern period are sketchy. Landers (2003) offers an overview of battlefield deaths. Lindegren (2000) finds that military deaths only raised Sweden's death rates by 2-3/1000 in most decades between 1620 and 1719, a rise of no more than 5%. Castilian military deaths were 1.3/1000, equivalent to 10 percent of adult male deaths but no more than 3-4% of overall deaths.

[25] Since infant mortality was high, by the time men could join the army, many male children had died already. This makes it less likely for military deaths to matter in the aggregate.

Civilian population losses in wartime could be heavy. The Holy Roman Empire lost 5-6 mio. out of 15 mio. inhabitants during the Thirty Years War; France lost 20% of its population in the late 16th century as a result of civil war. The figures for early 17th century Germany and 16th century France imply that aggregate mortality rates rose by 50 to 100%, and that these rates were sustained for decades. For the early and mid-nineteenth century, we have additional data on the indirect, country-wide rise in mortality from warfare. In the Swedish-Russian war of 1808-09, mortality rates in all of Sweden doubled, almost exclusively through disease. In isolated islands, the presence of Russian troops – without any fighting – led to a tripling of death rates. During the Franco-Prussian and the Austro-Prussian wars later in the 19th century, non-violent death rates increased countrywide by 40-50% (Landers, 2003). These numbers are a lower bound for the impact of warfare on aggregate death rates before 1700. In the 19th century, warfare was less likely to spread new germs, since areas touched by troop movements were now integrated by extensive road, canal, and railway networks. In our calibrations, we are going to work with conservative assumptions – a rise in death rates by between 40% and 100% during wartime.

Warfare is expensive. It became ever more so during the early modern period (Brewer, 1991; Landers, 2003; Tilly, 1992). The "military revolution" produced a need for professional, drilled troops, Italian-style fortifications, ships, muskets, and cannons. To make war, princes needed access to liquid wealth. After the plague, incomes per capita were higher – and there was more surplus above subsistence that could be expropriated. Following the so-called 'commercial revolution' of the late Middle Ages, the economy had already become more urban, monetized and commercialized (Lopez, 2008). Surpluses could be taxed more easily, providing the means for fighting more, and fighting longer. The development of credit markets reinforced these trends. Many early modern wars were fought with the funds provided by Genoese banking families, Amsterdam financiers, the Fuggers, and the Medici.

Trade in early modern Europe was also a frequent cause of disease. The Black Death in the 14th century spread along trade routes (Herlihy, 1997). The last outbreak in Europe occurred in Marseille in 1720, and is also linked to long-distance trade. A plague ship from the Levant, with sufferers on board, was first quarantined, only to have the restriction lifted as a result of pressure by merchants. It is estimated that 50,000 out of 90,000 inhabitants died in the subsequent outbreak (Mullett, 1936). As transport infrastructures improved and incomes grew, more goods were traded over longer distances. Trade increased massively between the medieval period and the eighteenth century. Canals and better coastal shipping made it possible to trade bulky commodities. Since trade increases with per capita incomes, the positive effect of the Black Death on wages created knock-on effects. These raised mortality rates yet further. Finally, there were interaction effects between the channels we have highlighted. The effectiveness of quarantine measures, for example, often declined when wars disrupted administrative procedure (Slack, 1981). All these factors in combination ensured that, after the Black Death, European death rates increased, and stayed high, in a way that is unlikely to have occurred in other parts of the world.

China in the early modern period saw markedly less warfare than Europe (Pomeranz, 2000). Even on the most generous definition, wars and armed uprisings only occurred in one year out of five, no more than a quarter of the European frequency. Why did Europe see much more inter-state conflict than other parts of the globe? Tilly (1992) emphasizes the fragmented nature of the European political system in the late medieval period. In addition, after the Reformation, religious strife contributed to frequent warfare (Jones, 1981). Compared to that, politically unified states like China had many fewer "flash points" leading to military conflict.

Not only were wars fewer in China during the early modern period. They also produced less of a spike in epidemics. Europe is geographically subdivided by rugged mountain ranges and large rivers, with considerable variation in climatic conditions. China's main population areas were more homogenous in geographical terms than Europe's. The history of epidemics in China suggests that by 1000 AD, disease pools had become largely integrated (McNeill, 1977). Since linking semi-independent disease pools through migratory movements pushes up death rates in a particularly effective way, troop movements produced less of a surge in Chinese death rates than in Europe.[26]

While the period after 1300 saw relatively few wars in China, this was not true of earlier years. The Mongol invasion in the 13th century led to massive loss of life – perhaps as much as half of the population perished. Whether income increased, as standard Malthusian models predict, is not well-known. What is clear is that in areas with sophisticated, centrally-maintained irrigation systems such as the Yangtze Delta, political turmoil could reduce output markedly.[27] In this way, the nature of agriculture – and the importance of political stability to maintain agricultural infrastructure – also distinguished China from Europe. While land-labor ratios improved in both as a result of war shocks, infrequent, devastating ones like the Mongol invasions were much less likely to be a net positive than the constant, low- to medium-intensity warfare that Europe saw between 1500 and 1800.

The Destructiveness of War

Early modern war could be deadly (mostly because of disease), and it could destroy farms, livestock, and infrastructure. The siege and sack of a city, for example, could inflict major damage to civilian property. Since many houses before the 18th century were constructed out of wood, they burnt easily. In the countryside, cattle and horses were regularly stolen by the raiding parties of advancing armies. Where seed grain was taken, famine in the following year became likely. Murder and rape were common. Long-distance trade became hazardous, and often declined markedly. Mercenary armies, often undisciplined, were particularly feared. Where fighting continued for prolonged periods – such as along the river Rhine in Germany during the Thirty Years War, and in Northern Italy – large population losses could coincide with severe economic dislocation (Landers, 2003).

Despite all this, De Vries (1976) concluded in *The Economy of Europe in an Age of Crisis* that "it is hard to prove that military action checked the growth of the European economy's aggregate output." As Jones (1981) emphasized, pre-modern wars were much more destructive for labor than for capital. For all

[26]We are indebted to David Weil for this point. Weil (2004) shows the marked similarity of agricultural conditions in large parts of modern-day China.

[27]The same is true of the Mongol invasion in the Middle East, where it wrought havoc on another "hydraulic empire" (in Wittfogel's phrase). Jones (1981) emphasizes how difficult economic recovery after wars was in many non-European areas that had massive irrigation systems.

its horrors, the economic losses induced by early modern warfare were often limited, and they did not last long. Malthus himself, in his *Essay on Population*, noted the remarkable ability of early modern economies to bounce back from war-induced destruction (Malthus, 1798):

> "The fertile province of Flanders, which has been so often the seat of the most destructive wars, after a respite of a few years, has appeared always as fruitful and as populous as ever. Even the Palatinate lifted up its head again after the execrable ravages of Louis the Fourteenth."

A variety of compensating factors mitigated economic losses. In areas of frequent troop movement, peasants developed sophisticated early warning systems. By 1645, a Franconian official informed the prince that all of his subjects had fled to towns in the area, taking every moveable good with them (Parker, 1987). Since advancing troops relied on food and fodder from the countryside, in areas with regular troop movement, plunder and extortion was quickly transformed into a system of tax-like contributions. Destruction of capital mattered less where it could be rebuilt quickly. Wooden houses were easy to reconstruct. After the Turkish siege of Vienna in 1683, the Venetian ambassador marvelled at the fact that "the suburbs...as well as the neighbouring countryside...have been completely rebuilt in a short space of time" (Tallett, 1992). A detailed study of the military conflict and rural life in the war-torn Basse-Meuse region in France found that local adaptation mitigated negative effects to a large extent (Gutmann, 1980).

Where fields went untended, fertility subsequently increased – a form of involuntary fallowing facilitated nitrogen fixation in the soil. Farm animals have high fertility rates, and losses of livestock can be made up quickly. Where food production fell, prices soared. This provided a windfall for surviving farmers. Well-disciplined troops also spent funds. Supplying them represented a business opportunity. While the taxes and debts that supported wartime expenditure may have been distortionary, it is not clear how much of it was 'wasted.' Pay constituted the single largest expenditure item, and was recycled in the local economy. Armies were generally small, recruiting no more than 0.5-1.5 percent of total population until the end of the 18th century. Moreover, men serving in the field were rarely drawn from the productive segments of society. Finally, war-induced mortality, where it resulted from poor nutrition, was probably concentrated amongst the more vulnerable groups – the young and the elderly (Tallett, 1992). Thus, war reduced the dependency burden.

Early modern states tried to limit the destructiveness of wars. The Thirty Years War was devastating, but it was not the norm. Italian condottieri leading mercenary armies often avoided pitched battles, reducing the loss of valuable fighting men. As armies grew in size after 1500, they became more disciplined. Articles of war became more common, and were enforced more rigorously. The use of mercenaries declined. Where the armies of Wallenstein and Tilly during the Thirty Years War had often plundered and killed indiscriminately, the well-trained troops of the eighteenth century mainly lived on food supplies from strategically positioned magazines (Parker, 1988). Attrition became less important as a way to subdue the enemy; manoeuvre warfare gained in relative importance.

None of this is to say that war had lost its destructiveness by the end of the early modern period. Yet its impact cannot be compared with that of modern-day conflict. Military technology was too primitive to cause widespread destruction of capital stock. Where conflict was frequent, local economic structures adapted. Negative effects were thus primarily short-run, reflecting the local destruction of livestock, capital, and the disruption of communications. Once hostilities ceased, compensating factors – such as the boost to land productivity from fallowing – made good many of the losses. In our baseline modeling, we will assume that war shifted the mortality schedule, but that it did not affect productivity. In addition, we explicitly model negative productivity effects of warfare in appendix A.3. While this changes the short-term dynamics, we show that our long-run results are unaffected.

Engel's Law

For our interpretation, it is important that consumers grown rich(er) after the Black Death spent relatively less on food, and more on luxury goods produced in cities. Evidence on consumption patterns in medieval England suggests that Engel's Law held. Dyer (1988) shows how the proportion of income spent on food falls from very high percentages for peasants to somewhat above half for a clerical household earning £20; a little less than half for esquires earning £50, and less than a quarter for earls earning thousands of pounds sterling per year. Over time, following the shock of the Black Death, the pattern is also clear. Spending by peasants on dwellings, clothing, cooking utensils, ceramics, and furniture all appear to have increased (as reflected in probate inventories). Dyer (1988) also notes that the quality of goods improved:

> "Pewter tableware and metal ewers replaced some wood and pottery vessels for more substantial peasants, and ceramic cisterns supplanted wooden casks. Potters began to supply cups, which had all previously been made of wood... The dice, cards, chessmen, footballs, musical instruments and 'nine-men's morris' boards show that resources could be spared..."

For England in the early modern period, Horrell (1996) found an income elasticity of food expenditure of 0.76. This is very similar to recent estimates for present-day India (0.7, as estimated in Subramanian and Deaton, 1996). In combination, there is ample evidence – both in the cross-section, and over time – that Engel's law operated in the late middle ages.

Chinese vs. European demography

Chinese and European demography were radically different. Since our model explains divergent incomes via the demographic channel, it is important to summarize the key differences. Chinese demographic growth was much more rapid than in Europe: Population in China grew by 170% between 1500 and 1820; in Europe only by 38%.[28] A long tradition of scholarship emphasized differences in fertility – Europeans practiced fertility limitation, by postponing marriage and having a high percentage of women that never married. In China, marriage occurred early and was universal. Recent research instead argues that fertility rates were not too different overall, with infanticide and low fertility within marriage reducing Chinese birth rates (Lee

[28] Maddison (2007); Lee and Feng (1999) also show China accounting for a rising percentage of the world's population.

and Feng, 1999). Because population growth was so much faster in China, mortality rates overall there must have been lower than in Europe.

Since incomes per capita were lower than in Europe, fertility rates *controlling for income* were markedly higher in China, while mortality was lower. In other words, given how rich Europeans were, they should have lived longer and had more children if Europe and China had shared a demographic regime. Instead, Europeans died early and had few children despite their riches. This paper explains why this does not constitute a paradox, by arguing that specific European factors driving up mortality rates pushed up per capita incomes.

3 The Model

In this section, we describe the two-sector Malthusian model summarized in the introduction (see figure 1). The economy is composed of N identical individuals who work, consume, and procreate. N_A individuals work in agriculture (A) and live in the countryside, while N_M agents live in cities producing manufacturing output (M), both under perfect competition. For simplicity, we assume that wages are the only source of income. Mobility of the workforce ensures that rural and urban wages equalize. Agricultural output is produced using labor and a fixed land area. This implies decreasing returns in food production. Manufacturing uses labor only and is subject to constant returns to scale. Preferences over the two goods are non-homothetic and reflect Engel's law: The share of manufacturing expenditures (and thus the urbanization rate N_M/N) grows with p.c. income. Technology parameters in both sectors, A_A and A_M, are fixed throughout the main part of our analysis. We introduce exogenous technological change below in section 4.4, where we analyze its contribution to the 'Rise of Europe.'

3.1 Consumption

Each individual supplies one unit of labor inelastically in every period. There is no investment – all income is spent on agricultural goods (c_A) and manufactured goods (c_M). Agents choose their workplace in order to maximize income. When migration is unconstrained, this equalizes urban and rural wages: $w_A = w_M = w$.[29] The resulting budget constraint is $c_A + p_M c_M \leq w$, where p_M is the price of the manufactured good. The agricultural good serves as the numeraire. Before individuals buy manufactured goods, they need to consume a minimum quantity of food, $\underline{c}$. We refer to $\underline{c}$ as the subsistence level. Below it, individuals suffer from hunger, but do not necessarily die – mortality increases continuously as c_A falls below $\underline{c}$. While the wage rate is below $\underline{c}$, any increase in income is spent on food. Preferences take the Stone-Geary form and

[29]In the following, the subscripts A and M not only represent agricultural and manufacturing goods, but also the locations of production, i.e., countryside and cities, respectively. Higher city mortality arguably lowers the utility of urban workers. In the working paper version (Voigtländer and Voth, 2008) we take this fact into account for endogenous individual workplace decisions. As a result, urban wages are above their rural counterparts, compensating for higher city mortality. While adding historical realism, this more complicated setup does not affect our main results.

imply the composite consumption index:

$$u(c_A, c_M) = \begin{cases} (c_A - \underline{c})^{\alpha} c_M^{1-\alpha}, & \text{if } w > \underline{c} \\ \phi(c_A - \underline{c}), & \text{if } w \le \underline{c} \end{cases} \tag{1}$$

where $\phi > 0$ is a constant. Given w, consumers maximize (1) subject to their budget constraint. In a poor economy, where income is not enough to ensure subsistence consumption $\underline{c}$, the starving peasants are unwilling to trade food for manufactured goods at any price. Thus, the demand for urban labor is zero, and there are no cities. All individuals work in the countryside: $N_A = N$, while $(c_A = w_A < \underline{c}$.

When agricultural output per capita is high enough to provide above-subsistence consumption ($w_A > \underline{c}$), expenditure shares on agricultural and manufacturing products are:

$$\begin{aligned} \frac{c_A}{w} &= \alpha + (1-\alpha)\left(\frac{\underline{c}}{w}\right) \\ \frac{p_M c_M}{w} &= (1-\alpha) - (1-\alpha)\left(\frac{\underline{c}}{w}\right) \end{aligned} \tag{2}$$

Once consumption passes the subsistence level, peasants start to spend on manufacturing goods. These are produced in cities, which grow as a result. If income increases further, the share of spending on manufactured goods grows in line with Engel's law, and cities expand. The relationship between income and urbanization is governed by the parameter α. A higher α implies more food expenditures and thus less urbanization at any given income level.

3.2 Production

Both agricultural and manufactured goods are homogenous and are produced under perfect competition. In the countryside, peasants use labor N_A and land L to produce food. The agricultural production function is

$$Y_A = A_A N_A^{\beta} L^{1-\beta} \tag{3}$$

where β is the labor income share in agriculture. Suppose that there are no property rights over land. Thus, the return to land is zero, and agricultural wages are equal to the output per rural worker:

$$w_A = A_A \left(\frac{L}{N_A}\right)^{1-\beta} = A_A \left(\frac{l}{n_A}\right)^{1-\beta} \tag{4}$$

where $l = L/N$ is the land-labor ratio and $n_A = N_A/N$ is the labor share in agriculture, or rural population share. Since land supply is fixed, increases in population reduce the land-labor ratio and curtail agricultural wages. Manufacturing goods are produced in cities using the technology

$$Y_M = A_M N_M \ . \tag{5}$$

Manufacturing firms maximize profits and pay wages $w_M = p_M A_M$. The manufacturing labor share n_M is identical to the urban population share.

Figure 5 illustrates the basic income-demand-urbanization mechanism of our model. If the rural wage (horizontal axis) is below subsistence (normalized to $\underline{c} = 1$), the starving population does not consume any manufacturing goods. Cities do not exist (zero urbanization, left axis), and there are no workers employed in manufacturing (zero urban wages, right axis). Cities emerge once peasants' productivity is high enough for consumption to rise above subsistence; manufacturing production starts. Without constraints on migration, urban and rural wages equalize. As productivity increases further, urbanization and wages grow in tandem.

[Insert Figure 5 here]

3.3 Population Dynamics

Birth and death rates depend on nutrition, measured by food consumption c_A.[30] Individuals procreate at the rate

$$b = b_{\underline{c}} \cdot (c_A/\underline{c})^{\varphi_b} \tag{6}$$

where $\varphi_b > 0$ is the elasticity of the birth rate with respect to nutrition, and $b_{\underline{c}}$ represents the birth rate at subsistence consumption. In the absence of the 'Horsemen effect,' the aggregate death rate falls with income and is given by

$$d = \min\{1,\ d_{\underline{c}} \cdot (c_A/\underline{c})^{\varphi_d}\} \tag{7}$$

where $\varphi_d < 0$ is the elasticity of mortality with respect to food consumption and $d_{\underline{c}}$ is the death rate at subsistence income.

Next, we introduce the Horsemen in our model. Higher urbanization raises aggregate death rates. The corresponding impact on aggregate death rates is given by $n_M \triangle d_M$, where $\triangle d_M$ represents city excess mortality. In addition, growing incomes and urbanization also indirectly increased mortality – by fostering wars and trade, which spread diseases. A poor economy with little urbanization has few funds for warfare, nor demand for goods traded over long distances; germ pools remain largely isolated. Higher p.c. incomes after the plague simultaneously spur trade and wars. Liquid wealth in cities funds armies and attracts traders. Military casualties mount. Armies as well as merchants continuously spread pathogenic germs to cities and countryside. These factors raise background mortality. In combination with $\triangle d_M$, the 'Horsemen effect,' h pushes up death rates. We use the urbanization rate n_M as a proxy for its strength.[31] To capture the positive

[30] In the working paper (Voigtländer and Voth, 2008) we present an alternative modeling strategy, where fertility and mortality depend on a measure of real income. The results are very similar to the ones presented here.

[31] All results are very similar if instead we use income to proxy for the strength of the 'Horsemen effect.' We focus on urbanization because the corresponding historical data are more reliable, which is crucial when taking the model to the data. In this, we take the lead that is common in this literature, i.e. to use urbanization rates as proxies of economic development (Wrigley, 1985; Acemoglu et al., 2005).

relationship between urbanization and the 'Horsemen effect,' we calculate h as:

$$h(n_M) = \triangle d_M n_M \ + \begin{cases} 0, & \text{if } n_M \leq \underline{n}_M \\ \min\{\delta\,(n_M - \underline{n}_M)\,,\,\overline{h}\}, & \text{if } n_M > \underline{n}_M \end{cases} \tag{8}$$

The first term is the direct impact of urbanization on aggregate death rates, while the second term reflects the spreading of disease through warfare and trade. The latter two factors add a maximum of $\overline{h}$; $\delta > 0$ is a slope parameter, and $\underline{n}_M$ is the threshold urbanization rate where the indirect effect sets in.[32] The role of the plague in our model is to introduce germs and to push p.c. income to levels where $n_M > \underline{n}_M$.

In the presence of the 'Horsemen effect,' aggregate mortality is given by

$$d^h = d + h(n_M) \tag{9}$$

When the Horsemen ride, increasing income has an ambiguous effect on mortality. On the one hand, greater food consumption translates into lower death rates in (7). On the other hand, the Horsemen raise background mortality. The aggregate impact of income on mortality depends on the model parameters. Our calibration in section 4.1 shows that death rates increase in income over some range, which implies a shape of the mortality schedule as shown in the right-hand panel of figure 1.

Population growth equals the difference between the average birth and death rate, $\gamma_N = b - d^{(h)}$, where the latter can include the 'Horsemen effect,' as indicated by the superscript (h). The law of motion for aggregate population N is thus

$$N' = (1 + b - d^{(h)})N\ , \tag{10}$$

where N' denotes next period's population. Births and deaths occur at the end of a period, such that all individuals N enter the workforce in the current period.

3.4 Solving the Model and Steady States

A steady state in our model is characterized by constant output per worker, labor shares, wages, prices, and consumption expenditure shares. We begin by analyzing the economy without technological progress; in this case, population is also constant in steady state.[33] The level of steady state variables depends on the position of the birth and death schedules, and on how they respond to income. Figure 1 visualizes the shape of the schedules, as given by (6) and (9).[34]

Points E_0 and E_H in figure 1 are stable steady states with endogenous population size. During the transition to steady state, population dynamics influence the land-labor ratio and thus output per worker.

[32] A more detailed justification for $\underline{n}_M > 0$ is that it indicates a minimum income level that cannot be expropriated, containing food for elementary nutrition as well as basic cloth and tools produced in city manufacturing. Once this threshold is passed, taxation yields the means for warfare and arouses the Horsemen.

[33] In the presence of ongoing technological progress, population grows at a constant rate (see section 4.4).

[34] Figure 1 refers to a simple one-sector setup. Because food consumption c_A is proportional to wages (see equation (2)), we can use the same figure to illustrate the intuition in our two-sector model.

Consequently, wages, expenditure shares, prices, and labor shares all change along the transition. In the following, we analyze these dynamics, following a two-step procedure: First, we take population as given and derive all other variables, including net population growth. We then use the latter in (10) to calculate the next period's income and population. We repeat this procedure until the economy reaches a steady state with zero population growth. Initial conditions and the size of the plague shock determine whether the economy converges to E_0 or E_H.

The Economy with Below-Subsistence Consumption

To check if food productivity (determined by A_A and the land-labor ratio) is sufficient to ensure above-subsistence consumption, we construct the indicator $\widehat{w}$, assuming that all individuals work in agriculture. Equation (3) with $N_A = N$ gives the corresponding per-capita income:

$$\widehat{w} \equiv \frac{Y_A(N)}{N} = A_A \left(\frac{L}{N}\right)^{1-\beta} \tag{11}$$

If $\widehat{w} \leq \underline{c}$, all individuals work in agriculture and spend their entire income on food. Since there is no demand for manufacturing goods ($c_M = 0$), the manufacturing price is zero. This implies zero urban wages and zero city population ($w_M = 0$ and $n_M = 0$). In addition, $w_A = c_A = \widehat{w}$, which can be used in (6) and (7) to derive population growth.[35] These equations characterize the economy with below-subsistence consumption. In principle, our model can have a steady state with below-subsistence consumption, such that the economy is completely agrarian. This is the case if death rates are generally low. However, urbanization rates were not zero in Europe even before the Black Death, so that our calibration below features both E_0 and E_H with above-subsistence consumption.

Above-Subsistence Consumption

If $\widehat{w} > \underline{c}$, agricultural productivity is high enough for consumption levels to rise above subsistence. Following (2), well-nourished individuals spend part of their income on manufacturing goods. To produce them, a share n_M of the population lives and works in cities. In each period, individuals choose where to live and work. Wage increases (e.g., driven by shocks to population) lead to more manufacturing demand and spur migration to cities, which occurs until $w_M = w_A$. For small income changes, migration responses are minor and cities can absorb enough migrants to establish this equality immediately. We refer to this case as unconstrained city growth. Goods market clearing together with equations (2), (3), and (5) implies

$$A_A N_A^{\beta} L^{1-\beta} = [\alpha w + (1-\alpha)\underline{c}]\, N \tag{12}$$

$$p_M A_M N_M = [(1-\alpha)(w - \underline{c})]\, N, \text{ if } \widehat{w} > \underline{c} \tag{13}$$

[35]Note that the 'Horsemen effect' is zero because $n_M = 0$.

Substituting $w_M = p_M A_M$ into (13) and using $(1 - n_A) = N_M/N$ yields the employment share in agriculture:

$$n_A = \alpha + \frac{(1-\alpha)\underline{c}}{w}, \quad \text{if } \widehat{w} > \underline{c} \tag{14}$$

The share of agricultural employment decreases in wages, while urbanization $n_M = 1 - n_A$ increases. The responsiveness of urbanization to wages is the stronger the smaller α – a result that we use to calibrate this parameter. To solve the model we also need the wage rate. Dividing (12) by N yields

$$\alpha w + (1-\alpha)\underline{c} = A_A \left[n_A(w)\right]^{\beta} \left(\frac{L}{N}\right)^{1-\beta}, \tag{15}$$

which says that per-capita food demand (LHS) equals per-capita production in agriculture (RHS), with the rural employment share n_A depending on wages as given in (14). This equation implicitly determines the wage rate for a given population size N. It has a unique solution, and w increases in A_A and L/N. Given w and $p_M = w/A_M$, food and manufacturing consumption follow from (2), labor shares from (14), and demographic variables from (6)-(8).

All calculations up to now have been for a given N. For small initial population, births outweigh deaths and N grows until diminishing returns bring down p.c. income enough for $b = d$ to hold. The opposite is true for large initial N. To find the steady state, we derive b and d for given N. We then iterate the above system of equations, deriving N_{i+1} in each iteration i from (10), until the birth and death schedules intersect. The steady state level of population depends on the productivity parameters A_A and A_M, and on the available arable surface, L. Wages in a given steady state, however, depend only on the intersection of the b and d schedules (see figure 1), and are independent of the levels of A_A, A_M, or L.

4 Calibration and Discussion of Results

Are the Horsemen powerful enough to explain an important part of the rise in European incomes, and of the divergence between Europe and China? To obtain multiple steady states in our model, death rates must rise substantially with income. In this section, we examine the magnitude of the 'Horsemen effect.' We calibrate our model with and without the additional mortality that comes from urbanization, trade, and war. This provides a dynamic path of two economies – one a stylized version of Europe, the other of China. Parameters are chosen to match historically observed fertility, mortality, and urbanization rates. We then simulate the impact of the plague and derive the steady state levels of p.c. income and urbanization in the centuries following the Black Death. We also discuss the context and robustness of our results, as well as the implications of our key mechanism for relative prices.

4.1 Calibration

We proceed in four steps. First, we calibrate the relationship between wages and urbanization. Wages above subsistence are proportional to the share of urban population in our model (see figure 5), and historical data on the latter are generally more reliable than income estimates. Thus, we use urbanization throughout the calibration, which reflects wage rates. Second, we set initial parameters to match the pre-plague characteristics in Europe. Intuitively, this step locates the fertility and mortality schedule such that point E_0 in figure 1 reflects pre-plague birth rates, death rates, and wages (w_0, corresponding to information on 14$^{\text{th}}$ century urbanization $n_{M,0}$). The second step involves calibrating the slopes of the fertility and mortality schedule, TFP in the two sectors, as well as initial population, the relative price of manufacturing, and land size. In the third step, we derive historical estimates for the size of the 'Horsemen effect.' We also calibrate the threshold urbanization rate at which the effect sets in, and the point where it reaches its maximum scope. Finally, we set the parameter that constrains the speed of city growth – a dimension that adds historical realism to our model during the transition from E_0 to E_H, but does not influence the steady state outcome.

We begin by calibrating the relationship between the wage rate and urbanization. For low wage levels ($w < \underline{c}$), all expenditure goes to agriculture. With higher p.c. income, the manufacturing expenditure share and urbanization grow in parallel. To derive this relationship, we pair income data from Maddison (2007) with urbanization rates from De Vries (1984). In the model, the responsiveness of urbanization to wages is governed by the parameter α. Figure 6 plots urbanization rates in Europe and England in the early modern period against per capita income. The latter is normalized to unity for the pre-plague period.[36] Our calibration, derived with a model parameter of $\alpha = 0.68$, traces out the pattern in the data.[37] Recall that the urbanization-income mechanism is driven by the relative demand for food vs. manufacturing products. Our choice of $\alpha = 0.68$ implies an income elasticity of food expenditure between 0.7 and 0.8 over the relevant income range in our model, which is almost identical with contemporary figures from India and 18$^{\text{th}}$ century England (Subramanian and Deaton, 1996; Horrell, 1996).

[Insert Figure 6 here]

Next, we calibrate the parameters for the pre-plague steady state E_0. The intersection of birth and death schedule determines per-capita income and urbanization rates in steady state. Urbanization rates in Europe before the 14$^{\text{th}}$ century were approximately 2-3% (data from De Vries (1984) and Bairoch et al. (1988); see figure 2 and appendix A.1). We choose $n_{M,0} = 2.5\%$. For cities to exist in E_0, wages have to be above subsistence, i.e., $w_0 > \underline{c}$. This requires the intersection of b and d to lie to the right of $\underline{c}$. Thus, death rates must be higher than birth rates *at* the subsistence level, $d_{\underline{c}} > b_{\underline{c}}$. The exact parameter values depend on the slope of the birth and death schedules. Kelly and Ó Grada (2008) estimate the elasticity of death rates with respect to income before the Black Death (1263-1348). We use the average of their results, $\varphi_d = -0.55$. This is very similar to the figures estimated by Kelly (2005) for the period 1541-1700.[38] For the elasticity of birth rates with respect to real income, we use the estimate in Kelly (2005) of $\varphi_b = 1.41$.[39] Both φ_d

[36]Note that at this point $n_M = 2.5\%$ in the model, which follows from our calibration of initial conditions in step 2.

[37]The simulation consistently shows slightly higher urbanization rates for a given income level. This is deliberate – urbanization likely underestimates the production of non-agricultural goods, as many authors have emphasized (cf. Wrigley, 1985).

[38]Kelly and Ó Grada (2008) find $\varphi_d = -0.59$ for 20 large manors and -0.49 for the full sample of 66 manors. These numbers coincide with the one estimated by Kelly (2005), who finds $\varphi_d = -0.55$ using weather shocks as a source of exogenous variation.

[39]These elasticities are bigger than the estimates in, say, Crafts and Mills (2008), or in Anderson and Lee (2002). Because

and φ_b rely on estimates for England as a best-guess for Europe. This is a conservative assumption for our purposes, since the Poor Law is likely to have softened Malthus' "positive check" in England. Without the buffer of income support, death rates elsewhere are likely to have spiked more quickly in response to nutritional deficiencies. Regarding the level of birth and death rates in the pre-plague steady state, we use $b_0 = d_0 = 3.0\%$, which is in line with the rates reported by Anderson and Lee (2002). This, together with the elasticities and the pre-plague urbanization rate of $n_{M,0} = 2.5\%$, implies $d_{\underline{c}} = 3.04\%$ and $b_{\underline{c}} = 2.75\%$.

In agricultural production, we use a labor income share $\beta = 0.6$. This is similar to the value implied by Crafts (1985), and is almost identical with the average in Stokey's (2001) calibrations. For any steady state wage level derived from the intersection of b and d, we can calculate the corresponding population N.[40] We normalize $L = 1$ and choose parameters such that initial population is unity ($N_0 = 1$). This involves the initial productivity parameters $A_{A,0} = 1.076$, $A_{M,0} = 1.087$. Our calibration also implies a price of manufacturing goods that is equal to the price of agricultural products, i.e., $p_{M,0} = 1$.[41] Since our baseline calibration refers to Europe, we take city excess mortality into account when deriving aggregate death rates in the pre-plague steady state.

We now turn to the calibration of the mortality regime in Europe, where the 'Horsemen effect' raises death rates. The first Horseman, urbanization, comes into play as soon as people dwell in cities, where death rates are higher. As discussed in the historical overview section, death rates in European cities were approximately 50% higher than in the countryside. This implies a value of $\triangle d_M = 1.5\%$. The first term in equation (8) captures the direct effect of urbanization on background mortality. On average, European urbanization grew from approximately 3 to 9 percent between 1300 and 1700 (see figure 2).[42] This boosts average death rates by approximately 0.05% in 1300 and 0.15% in 1700. City mortality is, however, not the biggest contributor to higher average death rates.

After the Black Death, this direct effect is reinforced by rising mobility and the spreading of diseases. Warfare and trade grow with p.c. income, and greater mobility leads to an ongoing dispersion of germs. According to equation (8), these indirect Horsemen are at work when the urbanization rate n_M is larger than the threshold level $\underline{n}_M$. We choose $\underline{n}_M = 3\%$, which is above the pre-plague urbanization rate and corresponds to wages that are approximately 10% above subsistence. The indirect 'Horsemen effect' begins to play a role only if wealth becomes large enough to support the cost of warfare. Below $\underline{n}_M$, income is too low to be taxed or expropriated, serving merely to provide elementary nutrition and basic manufacturing

of endogeneity issues in deriving a slope coefficient in a Malthusian setup, the IV-approach by Kelly is more likely to pin down the magnitude of the coefficients, compared to identification through VARs or through Kalman filtering techniques. For the same reason, we are not convinced that Malthusian forces weakened substantially in the early modern period, as argued by Nicolini (2007), Crafts and Mills (2008), and Galloway (1988).

[40] For example, rural population is implicitly given by (4), and is the larger (for a given wage) the more land is available and the larger is A_A. We calculate the steady state by solving for birth and death rates for given N, and then iterate over population until $b = d$. This procedure gives the long-run stable population as a function of fertility and mortality parameters, productivity, and land area.

[41] Other values of the relative price, resulting from different $A_{M,0}$ relative to $A_{A,0}$, do not change our results.

[42] We use De Vries' cutoff level of 10,000 inhabitants to define a city. Evidence from England suggests that York (12,000 inhabitants) had similar life expectancy as London in the 16th and 17th century. Note that our choice is a conservative one – a cutoff of 5,000 would deliver higher urbanization rates and thus a larger direct city mortality effect.

goods. This implies an important non-linearity – even in the face of massive population losses, expropriable surplus may rise considerably. This will be especially true if starting levels are close to subsistence, as they probably were in Europe before the plague.[43] Effectively, war is a "luxury good" for rulers, as a function of per capita income of their subjects. The threshold $\underline{n}_M$ that we chose is approximately in line with the income/urbanization level beyond which warfare in early modern Europe intensified dramatically. Once wealth, and thus urbanization, is above the threshold, the 'Horsemen effect' in (8) increases steadily in the urbanization rate until it reaches its maximum.[44]

In order to derive the maximum impact of warfare on mortality, we use data on war-related deaths and epidemics from Levy (1983). His data show that, in a typical year, more than one European war was in progress – there were 443 war years during the period 1500-1800, normally involving three or more powers. Since it is the movement of armies, and not just military engagements that caused death, we count the territories of combatant nations as affected if they were the locus of troop movements. Combined with demographic data in Maddison (2007), we obtain the percentage of European population affected by war between 1500 and 1700. Since European borders changed substantially over time, we use figures on population, urbanization, wars, and income, for the territory of states as they exist today. While anachronistic, this method has the advantage that it is not affected by border changes. Put another way, France's incorporation of Alsace-Lorraine in the early modern period does not lead to a larger percentage of the European population being affected by war every time France fights; we simply use France in its present borders from the start.[45] Figure 7 shows that this measure grows from about 12% in 1500 to roughly 50% around 1700, and decreases in the 18$^{\text{th}}$ century. The population share affected by wars mirrors the trend in the number of plague outbreaks shown in figure 3, as it should if wars were one of the main factors spreading disease in early modern Europe. In times of war, death rates *nationwide* could rise by 40 to 100% (see section 2). The impact of war was local, but we focus on nationwide effects to match the construction of the war frequency variable, which also uses nations as the unit of analysis. Given steady state death rates of 3%, this implies an additional 1.2-3 percent under warfare. Throughout the second half of the 17$^{\text{th}}$ century – the 50-year period with the largest war frequency in early modern times – on average 38% of the European population were affected by wars. Based on this period, we derive the maximum war-related mortality increase:

$$\text{Excess death under warfare} \times \text{max. share of population affected} = [0.46 - 1.14\%]$$

In the baseline calibration, we use a point estimate close to the center of this interval – a maximum war-related 'Horsemen effect' of 0.75%.

To this we add an estimate of 0.25% for epidemics spread via trade. We do not know with certainty how many extra deaths were caused by the increase in trade resulting from higher per capita incomes. Modern data can help to gauge the broad effects. Oster (2009) argues that in the case of HIV in Africa, a doubling

[43] Kelly and Ó Grada (2008) offer evidence on how close to the minimum large parts of the English population were before 1350.

[44] Our long-run results would be the same if the 'Horsemen effect' reached its full strength immediately after the plague. However, our modeling choice provides more historical realism during the transition – warfare and death rates increased only gradually with urbanization in early modern Europe.

[45] Linear interpolation is used for the years where no population data are available. We count all countries at war as affected because troop movements also occur within countries even when there is no fighting on their own soil.

of trade leads to between a doubling and a quadrupling of infections. If infectious disease in the pre-plague steady state accounted for only one death out of eight, an increase in the death rate by 0.25% is plausible.[46] This probably constitutes a lower bound on death by diseases spread via trade routes – plague, typhoid, smallpox and influenza are more infectious than HIV. Overall, our best guess for the sum of the two indirect 'Horsemen effects' – due to warfare and trade – is $\overline{h} = 1\%$. This value is reached during the 17th century, which saw particularly savage warfare, with troop movements over a very wide area, and for extended periods (Levy, 1983). Urbanization rates reached 8% in the mid-17th century (De Vries, 1984). The implied slope parameter of the indirect 'Horsemen effect' is therefore $\delta = \overline{h}/(0.08 - \underline{n}_M) = 0.2$.

[Insert Figure 7 here]

Migration from the countryside to cities was not immediate. Cities could not absorb migrants overnight. In the case of larger inflows, new dwellings and infrastructure had to be provided. Building new houses and enlarging cities was one of the costliest undertakings in the early modern economy. The arrival of numerous migrants caused over-crowding, making further migration to the cities less attractive. To capture these difficulties during the transition phase, we assume that city growth was constrained. We explain this extension to the baseline model in appendix A.2. While none of the long-run results depend on this assumption, we gain historical realism and can compare predicted transitional dynamics to the data. We set maximum urban growth to the highest growth rate observed over the period 1300-1800, equivalent to $\overline{\nu} = 0.8\%$.[47] Finally, we will use exogenous sector-neutral technological progress in our dynamic simulations. We assume that A_A and A_M grew at a rate $\gamma_A = 0.1\%$ in the centuries before 1700. This is in line with the estimates by Galor (2005) of roughly 0.05-0.15% per year. Table 1 summarizes the calibrated parameters.

[Insert Table 1 here]

4.2 Plague and Steady State without 'Horsemen Effect'

The left panel of figure 8 shows the pre-plague steady state without 'Horsemen effect.' This reflects conditions in China, where urbanization did not raise background mortality. Our simulation for China thus sets $h(n_M) = 0, \forall n_M$ in (9). The economy is trapped in Malthusian stagnation in the unique steady state C.[48]

[46] Our estimate is derived as follows: Trade grows with elasticities of 0.8 and 0.65 with respect to income of country A and B, as in the gravity model estimated by Bergstrand (1985, table 1, column 1). This implies that as overall income doubles, trade rises by 145%. We focus on the period 1500-1700, where income data are available. In order to provide a conservative estimate, we consider only the per capita component of overall income growth. That is, we do not take into account the contribution of population growth to aggregate income increases, because growing population might reflect the convergence back to long-run levels after the Black Death. Using Bergstrand's elasticity, combined with the fact that p.c. incomes grew by approximately 30%, suggests that trade may have increased by 44% during our period. Using the average elasticity of 1.5 from Oster (2009), infectious disease should have been 65% higher. For the aggregate death rate to increase by 0.25% as a result of more trade in 1700, an annual 0.38% (= 0.25% / 0.65) of the population must have fallen victim to infectious diseases before the plague. This corresponds to approximately one out of every 8 deaths in the pre-plague steady state.

[47] This was observed during the 14th century, according to our data in figure 2.

[48] Note that the urbanization rate in steady state C is below the pre-plague level of 2.5% for Europe. The reason is that the direct 'Horsemen effect' – excess city mortality – is not at work in China, so that average mortality is slightly lower than in Europe, implying lower steady state urbanization. This difference becomes apparent when comparing C and E_0 in figure 9.

The fertility and mortality schedules intersect at a rate of approximately 3% for each, while 2.2% of the population live in cities. The latter corresponds to wages that exceed subsistence by 8 percent.[49]

[Insert Figure 8 here]

The right panel of figure 8 shows the effect of the Black Death in an economy without 'Horsemen effect.' Before the plague, population and urbanization stagnate. The Black Death in our calibration reduces population by 40%. As an immediate consequence, wages and p.c. consumption rise. Urbanization rates increase more slowly because cities cannot immediately grow to their new steady state size. In the aftermath of the plague, population grows because the economy is now situated to the right of the steady state in point C, with fertility higher than mortality. The falling land-labor ratio eventually drives the economy back to C, with all variables returning to their pre-plague values. We argue that this describes the Chinese experience. Things look different in the presence of the 'Horsemen effect,' which is unique to Europe.

4.3 Steady States with 'Horsemen Effect'

Using the calibrated parameters for Europe, the left panel of figure 9 shows two stable steady states, E_0 and E_H, and an unstable one, E_U. Initially, the European economy is in E_0, and all variables remain unchanged in the absence of technological progress. In order to initiate the transition from E_0 to E_H, a shock to population (or productivity) must be large enough to push the economy beyond E_U, where Horsemen-augmented death rates exceed birth rates.[50] We argue that early modern Europe underwent such a transition.

Following the Black Death, p.c. incomes surged. Surviving individuals and their descendants were substantially better off than their ancestors before the plague. This is in line with historical evidence: It took until the 19$^{\text{th}}$ century for wages to recover their post-plague peak (Clark, 2005). The demand for urban goods made cities grow, fostering trade and providing the means for warfare. Enhanced mobility constantly spread epidemics and therefore raised mortality. The size of this 'Horsemen effect' grew together with urbanization until the 17$^{\text{th}}$ century, as shown in figures 3 and 7, and captured by equation (8) in our model. The economy converges to the 'Horsemen steady state' (point E_H in figure 9) in the aftermath of the Great Plague. This steady state is characterized by higher birth and death rates (about 3.8%) and higher urbanization (9%). The corresponding dynamics are shown in the right panel of figure 9.

[Insert Figure 9 here]

Following our argument, urbanization, trade, and war increased per capita incomes in early modern Europe. As by our calibration, their individual contributions to aggregate death rates in E_H are approximately 0.15%, 0.25%, and 0.75%, respectively. This corresponds to the 17$^{\text{th}}$ century, when the 'Horsemen effect' reached its maximum. Given the slope of the birth schedule, we can translate the increasing death rates into

[49] When wages are *at* the subsistence level $\underline{c}$, cities do not exist.

[50] With ongoing technological progress the argument is similar. Continuous technological progress implies rising population at stagnant p.c. income. We analyze this case below.

the corresponding changes in urbanization. City mortality alone would have raised urbanization by over one percent. Trade's effect is similar, but slightly larger. The single biggest contributor, according to our baseline calibration, is war. It alone raises urbanization rates by approximately 4%. In combination, our 'Three Horsemen' can account for an increase in the percentage of Europeans living in towns and cities from 2.2% in C to approximately 9% in E_H. Using the relationship depicted in figure 5, we can translate those urbanization rates into p.c. income levels. The 2.2% in C correspond to a p.c. income of 1.08 (where 1.0 is subsistence), which grows to 1.37 in E_H. The resulting increase in p.c. income of approximately 30% matches the number provided by Maddison (2007) for Western European growth between 1500 and 1700.[51]

Our story can explain rising urbanization and individual income in early modern Europe in the absence of technological change. However, in this reduced form our model predicts falling population, which contradicts the observed trend. Next, we allow for slowly growing productivity. We find that technological progress can explain rising population, but cannot account for increasing urbanization. The latter is explained largely by the 'Horsemen effect.'

4.4 The Role of Technological Progress

Technological progress in pre-modern times alone is not enough to escape from the Malthusian trap. While a growing population eventually reverses the benefits of one-time inventions, *ongoing* progress implies higher, but still stagnating, steady state p.c. income. Its effects are thus similar to a permanent outward shift of the death schedule. The new steady state can be derived from equation (3). Constant p.c. income (and thus a constant agricultural labor share) implies $\gamma_N = \gamma_A/(1-\beta)$, with γ_A representing TFP growth. Thus, in the steady state population growth is proportional to the rate of technological progress, and this relationship is the stronger the larger the labor share β in agricultural production. Intuitively, if β is small the fixed factor land is important – when technology pushes p.c. income up and N responds, decreasing returns quickly offset any technological gains and keep population in check.

The setup with ongoing technological progress corresponds to a steady state in point T in the left panel of figure 10, where the birth rate exceeds the death rate and technological progress is exactly offset by the falling land-labor ratio. The right panel of figure 10 illustrates the orders of magnitude involved. The rate of technological change before the Industrial Revolution was low, approximately 0.1% (Galor, 2005). For purposes of illustration, we begin in 1300. Progress is assumed to set in after 50 years of stagnating technology. As the figure shows, this raises the urbanization rate by less than 2%. Note that this is an extreme scenario where the economy jumps from complete stagnation to continuous inventions. The corresponding increase of urbanization is thus an upper bound for the impact of technology on individual income. Our calibrated model therefore suggests that the effect of technological progress in early modern Europe was markedly smaller than the impact of rising death rates.

[Insert Figure 10 here]

[51] Maddison does not report income figures for 1300. Interpolating the estimates for 1000 and 1500 to obtain a proxy for 1300 implies p.c. income growth of approximately 50% between 1300 and 1700.

How fast would technology have to improve to explain the rise of early modern Europe? Based on Maddison's (2007) figures we derive a lower bound, focusing on the period 1500-1700. Over these two centuries, European p.c. income increased by 30%. If technological improvements were the sole cause for this rise, the rate of population growth in 1700 would be at least 1.7%.[52] To sustain per capita incomes at 30% above the 1500 level, technological progress would have to offset the rapid population growth, which implies TFP growth rates of $\gamma_A = (1-\beta)\gamma_N \simeq 0.7\%$. TFP increases of this magnitude were not observed before the second half of the 19th century (Crafts and Harley, 1992; Antràs and Voth, 2003). If we assessed the strength of Malthusian responses accurately, technological progress cannot be a candidate to explain the 'Rise of Europe' in the early modern period.

4.5 Model Fit

How well does the model fit the data? We begin simulations in 1000 AD in order to show both the pre- and post-plague fit of the model.[53] While the 'Horsemen effect' alone can account for almost all the observed increase in European urbanization (see figure 9), technological progress is responsible for the growth in population. In other words, technological progress alone, without the Horsemen, translates into rapid population increases, while per capita income stagnates. On the other hand, the Horsemen alone, without TFP growth, deliver higher *per capita* income (figure 9), but *aggregate* income decreases because of the substantial population decline. Both mechanisms together deliver growing population and per capita income, and therefore also rising aggregate income.[54] A simple calculation sheds light on the relative importance of the two components. Using Maddison's (2007) numbers for Europe in 1500 and 1700, we find that rising per capita income accounts for 42 percent of aggregate GDP increases over this period, and population growth explains the remaining 58 percent.[55] Finally, figure 11 shows our simulation results together with the data. Our model performs well in reproducing both population growth and urbanization.

[Insert Figure 11 here]

Implications for Relative Prices

Our model has implications for the relative price of urban vs. rural goods. First, as the plague raises wages, the price of goods produced in cities should rise relative to those produced in the countryside. The reason

[52] To derive this number, we normalize p.c. income to unity in 1500, $y^{1500} = 1$, and set $b_0 = d_0 = 3\%$. Together with (6) and (7) this setup implies $\gamma_N^{1500} = 0$. We then use a linear approximation to derive the population growth rate, γ_N^{1700}, corresponding to the higher level of p.c. income in 1700. This yields $\gamma_N^{1700} = (\varphi_b - \varphi_d)b_0(y^{1700} - y^{1500}) = (1.41 + 0.5) \cdot 3\% \cdot 0.3$ = 1.72%.

[53] We allow technology to grow at $\gamma_A = 0.1\%$ throughout the simulation. The model is calibrated to yield the same pre-plague (1350) values as above for population, urbanization, fertility, mortality, and relative prices (as given in the lower part of table 1). Intuitively, this technology-progress adjusted calibration corresponds to shifting the death schedule downwards by $\gamma_A/(1-\beta)$ in figure 10. The new steady state with ongoing technological progress (but lower mortality) then involves the same urbanization rate as the previous C in the figure.

[54] In our calibration, the rate of TFP growth $\gamma_A = 0.1\%$ is sufficiently large for productivity-driven population increases to overcompensate population losses due to the Horsemen.

[55] Aggregate European GDP grew at rate of 0.31% p.a. between 1500 and 1700, with p.c. income and population growing at 0.13% and 0.18%, respectively.

is that richer consumers want to buy more of the highly income-elastic goods produced in towns. Cities cannot grow at infinite speed because of the need to build urban infrastructure (reflected by the parameter $\overline{\nu}$ in our model). This bottleneck means that higher demand translates into higher relative prices after the plague. As migration to cities continues, growing supply of urban goods leads to declining relative prices. This effect is reinforced by declining demand: With population slowly recovering, p.c. income falls. Our model thus predicts a hump-shaped pattern for the relative price of urban goods during the aftermath of the Black Death.

We investigate this prediction by analyzing the price data collected by Clark (2005) for his project on the cost of living in England.[56] His database contains retail prices for numerous manufactured goods, most of which were typical 'urban' products. Figure 12 plots the price of four manufactured goods, relative to the price of wheat, for the period 1300-1750. All four goods – bricks, manufactured goods made of iron, nails, and linen – show strong price increases immediately after the Black Death. Relative prices peaked 50-80 years after the plague. This seems a sensible time horizon over which the immediate disruptions of production (which we do not model) could dissipate. Eventually, during the 15th century, urban infrastructure could catch up with demand, and migration into the towns raised the supply of urban goods. This explains the falling relative price of urban goods after 1400. What is crucial for testing our model is that in the medium run – following the impact of the Black Death, the relative price of manufactured goods increases. This confirms our use of Engel curves to predict higher demand for urban products after the plague.

[Insert Figure 12 here]

4.6 Robustness of Calibration Results

Next, we examine the robustness of our calibration results when alternative parameter values are used. The size of the 'Horsemen effect' is of central to our results. To shed light on the margin of error of the overall effect, we discuss the contribution of individual components. Data on excess city mortality are relatively reliable. Table 2 shows the corresponding magnitudes in 1300 and 1700 for various countries and two different city mortality penalties – one corresponding to our baseline calibration and the other representing an upper bound, 80%. The upper bound is derived from the ratio of Northern town mortality and the rural Sussex death rate in 1841 (Szreter and Mooney, 1998). Clark and Cummins (2009) find a similar differential between the offspring of urban and rural testators in early modern England.[57] From one country to the next, the magnitude of the direct 'Horsemen effect' varies substantially depending on overall urbanization rates. In England it is initially close to zero. As urban centers grow, it increases to 0.2-0.32 percent. In the most urbanized countries in Europe, such as the Netherlands, the direct effect reaches 0.5-0.8%. On average in Europe, city mortality contributed 0.05 to 0.22% to overall death rates. With the value from our baseline calibration, 0.14%, this factor alone can account for 1.2% higher urbanization rates, or one fifth of the total.

[56] We thank Gregory Clark for sharing this data with us.

[57] The life expectancy at birth on farms in his sample is 41.8; in cities and towns, it falls from 32 to 29. The latter is derived from the weighted average of London mortality and that in other urban centers.

[Insert Table 2 here]

Next, we turn to the indirect 'Horsemen effect' due to warfare and trade. In section 4.1 we argued that war-related deaths added 0.5-1.0%, based on the war frequency in the second half of the 17^{th} century. For trade we based our estimate of 0.25 percent on an analogy with the trade and HIV in modern-day Africa (Oster, 2009). Even if we use the lower bound of the warfare effect (0.5%), and assume zero for trade, the 'Horsemen' play a substantial role. Under these conservative assumptions, the two remaining effects (city death and warfare) raise urbanization rates to about 7 percent.

The responsiveness of population growth to p.c. income changes is also important for our findings. This variable is governed by the elasticity of birth and death rates to nutrition, based on Kelly's (2005) estimates for early modern Britain. More recent work by Kelly and Ó Grada (2008) confirms the orders of magnitude involved. If the b and d schedules are flatter than in our baseline calibration, population growth reacts more slowly to income increases. Consequently, there is more scope for technological progress to improve living standards. On the other hand, the model also becomes more sensitive to an increase in background mortality, which increases the power of the Horsemen. More precisely, if both b and d have only half the slope that we used in the baseline calibration, technological progress at 0.1% p.a. delivers a 4% increase in urbanization (corresponding to roughly 9% increase in p.c. income).[58] This leaves ample scope for the 'Horsemen of Riches' to contribute to the 'Rise of Europe.'

Our calibration implicitly determines the minimum size of the 'Horsemen effect' that is required to generate multiple steady states, i.e., to have a long-run effect. For this to be the case, the birth and death schedule must cross more than once. In figure 9, the 'Horsemen effect' has to account for at least the mortality differential between E_U and C – approximately 0.25%. Our lower-bound estimate for the war-related 'Horsemen' alone is almost double in size (see section 4.1). Mortality changes were thus large enough for our model to capture important aspects of the historical experience in early modern Europe.

Finally, we include two extensions of our model in the appendix. First, in A.3 we allow for negative effects of warfare on productivity, reflecting the destruction of physical capital, slaughter of livestock, and the disruption of communications during early modern military campaigns. While dynamics in the short run change, our long-run results are robust to this extension. Second, appendix A.4 introduces the effect of the European Marriage Pattern (EMP) into our setup with multiple Malthusian steady states. EMP alleviated population pressure by reducing birth rates – an effect that was particularly strong in North-Western Europe. Elsewhere, we argue that EMP contributed importantly to intra-European divergence (Voigtländer and Voth, 2010). In the case of England, where income surged ahead of other European countries after 1500, the 'Horsemen effect' alone accounts for approximately one half of the rise in wages and urbanization. EMP can explain much of the remainder.

[58] To derive this result, we follow the approximation shown in footnote 52, using the fact that population must grow at $\gamma_N = \gamma_A/(1-\beta)$ in steady state.

5 Conclusion

Europe saw almost continuous warfare during the early modern period. It also suffered numerous disease outbreaks. Its cities were major death traps. Far from undermining the strength of the European economy, we argue that death and disease spelled riches and power, contributing to Europe's economic ascendancy. We use a simple two-sector Malthusian model in which higher population causes lower incomes because of declining marginal returns to labor. The Black Death marked a turning point for economic fortunes in early modern Europe. It killed between a third and half of the European population. In a Malthusian setting, a boost to incomes after an epidemic should be transitory. Yet the plague shock was so big that it took several generations for population growth to reverse the substantial wage gains. In the meantime, political and structural changes effectively produced a ratchet effect. Europe's "golden age of labor" after 1350 saw a richer population buying more manufactured goods, produced to a large extent in urban centers. Because early modern European cities were "graveyards" (Bairoch, 1991), this boost to urbanization rates reduced pressure on land-labor ratios, and thus helped to stabilize incomes. The plague shock also perpetuated higher incomes through two other channels. Higher incomes meant that there was more money available for taxation and borrowing. Thus princes fought more often, and for longer. Higher incomes also stimulated trade, which spread disease. We call the repercussions of the Black Death the 'Horsemen of Riches' because they jointly increased mortality, thus helping to preserve post-plague wage gains.

We demonstrate that permanently higher mortality rates, indirectly caused by the Black Death, were empirically important. In our calibrations, the mortality channel alone can account for at least half of the increase in per capita incomes in early modern Europe. Of this increase, the largest component came from more frequent warfare. Diseases spread by trade and excess city mortality made smaller contributions.

Non-reproducible factors of production, such as land, probably still play a role in production in today's Third World (Weil and Wilde, 2009). That is why deadly epidemics such as AIDS may raise per capita incomes (Young, 2005). Oster (2009) shows that HIV in Africa spreads along trade routes. Since trade is linked to incomes, a similar feedback mechanism to the one we identified in early modern Europe may operate in developing countries. Urbanization and war, on the other hand, are unlikely to have similar effects. Military technology has become markedly more destructive. This limits the benign effects of rising land-labor ratios as a result of war. In addition, cities are no longer notably less healthy than rural areas.

Why did war, disease, and urbanization not yield similar results outside Europe in pre-modern times? Neither plagues, war, nor cities were unique to Europe. However, European cities were remarkably unhealthy, for a variety of cultural reasons. A highly fragmented political environment gave rise to frequent wars. The absence of these factors limited the operation of the 'ratchet effect' elsewhere. The plague in China could not produce a similar, self-reinforcing cycle of higher incomes and rising mortality. There, a one-off increase in wages did not produce a lasting rise in death rates via higher urbanization and more war. Similarly, the Justinian Plague that hit Imperial Rome – possibly just as devastating at its 14$^{\text{th}}$ century counterpart – occurred at a time when Roman cities were amply provided with clean water. They were also not as overcrowded as early modern European cities. The latter kept concentrating ever larger numbers of people in the same area, protected by massive fortifications. In both 14th century China and in Justinian Rome, another crucial 'Horseman of Riches' – war – was also not available. Both regions were politically unified, and a rise in city wealth did not translate into more frequent warfare.[59]

Economic fortunes diverged markedly within Europe during the early modern period. North-Western Europe pulled decisively ahead of other areas which had been pre-eminent in the medieval period, such as the Mediterranean (Acemoglu et al., 2005). While we do not explore this aspect in detail, the differential impact of the plague also appears to be a good predictor of changes in urbanization. Figure 13 plots the increase in the share of urban population against the population losses as a result of the Black Death. Where the plague shock was largest, subsequent gains in urbanization were strongest. Also, there is some evidence that areas that were affected the most by war saw the biggest increases in the share of the population living in cities.

[Insert Figure 13 here]

Our paper has emphasized the paradoxical increase of incomes in early modern Europe. Europe's political fragmentation and geographical heterogeneity interacted with the negative shock of the Black Death in a unique way. In combination, urbanization, warfare, and trade produced a mortality regime that was different from the one prevailing in other parts of the world. As a result, death and disease contributed importantly to the 'Rise of Europe.'

[59] Political fragmentation was also much lower in the Middle East, which was hard-hit by the 14th century plague. Much of it was quickly unified under first the Mamluks, then the Ottomans. This limited the potential for death rates to be driven up by continued fighting. In addition, the destruction of irrigation systems in the Middle East by the Mongols did much to undermine production. Europe did not have similarly centralized, vulnerable infrastructure.

Online Appendix – Not for Publication

A.1 Urbanization Data

We use two data series for urbanization rates. De Vries' (1984) figures are often considered the most reliable dataset for historical European urbanization. De Vries reports the share of population living in cities larger than 10,000 inhabitants. His data is available after 1500. Second, we derive urban population from Bairoch et al. (1988), who report the size of 2,191 European cities over the period 800-1850. As Bairoch et al. (1988) emphasize, estimates before 1300 are rough and less reliable. For many cities, observations are missing in at least some years. For example, Douai in France is reported to have 10,000 inhabitants in 1500 and 13,000 in 1700; no observation is given for 1600. We use linear interpolation to fill these gaps. When numbers are missing in 1400, we extrapolate the 1300 value with the country-specific population loss between 1300 and 1400, in order to approximate the impact of the Black Death in the mid-14th century.[60] For Cordoba (Spain) in 1000, we use population from Glick (1979), as proposed by Buringh and van Zanden (2009), correcting the unrealistically large number in Bairoch et al. (1988). These steps result in a comprehensive measure of urban population in Europe, which we divide by the population estimates of McEvedy and Jones (1978) to calculate urbanization rates at the country level, as used in figure 13.[61] Finally, in order to provide comparability with our first data series for European averages, we restrict the Bairoch et al. sample to countries covered by De Vries (which means excluding Russia and the Balkans). All urbanization rates that we report reflect weighted averages (by country population).

A.2 Congestion and Constrained City Growth

Income increases raise the demand for urban goods and thus manufacturing wages, attracting migration to cities. However, in the short-run migration is constrained because new dwellings and infrastructure must be provided. Too many migrants therefore lead to over-crowding, making further migration to urban centers unattractive. In the interest of simplicity, we capture congestion effects with an upper limit to the growth rate of cities, $\overline{\nu}$. When shocks are large, and urban-rural wage differentials are substantial, this constraint becomes binding. It then takes time until population shares reach their steady state levels n_M^{LR} and n_A^{LR}, as given by the equation for unconstrained migration, (14).

Let $N_A^\star$ and $N_M^\star$ be the number of individuals living in the countryside and cities, respectively, at the beginning of a period. $N_M^{LR} = n_M^{LR} N$ denotes steady state urban population, i.e., the number of city inhabitants that would be established under unconstrained city growth if overall population is N. Next, we derive the growth of city population that occurs when migration is unconstrained, reaching the steady state

[60]The underlying country-level population data are from McEvedy and Jones (1978). For a number of countries where hard data is not available, McEvedy and Jones give estimates of population. We use the descriptive evidence in Benedictow (2004) to augment the data in McEvedy and Jones. For example, for the case of Norway, McEvedy and Jones do not give an estimate for population in 1400. Benedictow emphasizes the similarity of the plague's impact in Norway and England. Hence, we assume that the same percentage decline in population that occurred in England also affected Norway.

[61]Acemoglu, Johnson, and Robinson (2002) use the same approach to calculate European urbanization rates. However, they do not correct the raw data of Bairoch et al. (1988).

instantly.[62]

$$\nu \equiv \frac{N_M^{LR} - N_M^\star}{N_M^\star} = \frac{n_M^{LR} - n_M^\star}{n_M^\star} \tag{A.1}$$

The likelihood that congestion constrains migration is the larger the more the steady state population distribution deviates from actual values. If ν exceeds the upper bound for the growth rate of urban centers, the constraint $\overline{\nu}$ becomes binding. In this case, replacing ν with $\overline{\nu}$ in (A.1) gives the law of motion for city population:

$$N_M = (1 + \overline{\nu})N_M^\star \tag{A.2}$$

The remainder of the population works in agriculture: $N_A = N - N_M$. Wages, production, and relative prices under constrained city growth can be derived from the known location-specific employment. Note that urban and rural wages differ in this case. Agricultural wages are given by (4). The manufacturing wage depends on the relative demand for urban goods. Introducing location-specific wages in (2) together with market clearing yields an explicit solution for urban wages:[63]

$$w_M = \frac{1}{n_M}\frac{1-\alpha}{\alpha}\left[w_A n_A - \underline{c}\right] \tag{A.3}$$

Manufacturing products are sold at $p_M = w_M/A_M$. Workplace-specific food consumption follows from the corresponding wages and (2). Accordingly, fertility and mortality also vary by location, following from (6) and (7), respectively. Aggregate birth and death rates are weighted averages of the rural and urban rates. The 'Horsemen effect' is calculated as in the unrestricted case. While none of the long-run (or qualitative) results in this paper depend on the assumption of congestion and limited city growth, it is important for historical realism in the transitional dynamics.

A.3 Negative Impact of Warfare on Productivity

As discussed in section 2, early modern warfare was destructive, but on a limited scale. Productivity suffered in the short-run, as a result of the destruction of physical capital, slaughter of livestock, and the disruption of communications. These adverse effects normally disappeared quickly once armies moved on.[64] We now incorporate this negative impact into our model. In the modified setup, each country will be at war for four consecutive years in each decade. This is equivalent to the highest average observed for a fifty-year period in early modern Europe (see figure 7). Under warfare, TFP decreases by 1% (5%), and returns to the baseline level when hostilities cease. Death rates increase by $\triangle d$. To isolate effects, we assume that neither city

[62] More precisely, this is the growth rate of city population due to migration only. We implicitly assume that urban offspring do not contribute to congestion because they live with their parents, at least in the short run. In this specification, the growth rate of ν is equal to the growth of the urbanization rate – a fact that we use to calibrate $\overline{\nu}$.

[63] A detailed solution of the model with location-specific wages and demand is provided in the working paper Voigtländer and Voth (2008).

[64] Even if warfare had a negative long-run impact on productivity, our main result would not change. Following the Malthusian logic, with permanently lower productivity levels, population would be lower in equilibrium. But p.c. incomes would still rise with mortality.

mortality nor trade add to background mortality in this exercise. The remainder of the decade is peaceful, and death rates are at their baseline level. During wars, we use conservative values, $\triangle d = 1\%$ and 2%, and simulate the model without migration constraints and without technological progress.[65] Figure 14 shows the results.

[Insert Figure 14 here]

Initially, the economy is in equilibrium C (see e.g. figure 9). Periodic warfare sets in after 50 years. The left panel shows the effect of negative TFP shocks of 1% during wars; the right one, 5%. In both cases, p.c. income rises and population falls in the long-run. Per capita income fluctuates more strongly when warfare is assumed to have a large negative effect on TFP, but overall development patterns are unaffected. With $\triangle d = 1\%$, p.c. income fluctuates around 1.23, which corresponds to an urbanization rate of 6%. For the case of larger mortality rates due to warfare ($\triangle d = 2\%$), it fluctuates around 1.37, which implies urbanization rates of 8.5%. The latter value is very similar to the main result in the baseline calibration.

This modified analysis shows that our results are robust to relaxing two implicit assumptions. First, even with lower productivity under warfare, long-term p.c. income and urbanization rise. This is explained by the quick return of TFP to its pre-war level in early modern times, while population growth takes time to replace the deceased. Second, periodic warfare (with a large mortality increase during wars and zero additional mortality otherwise) delivers similar results as continuous warfare (with a constant average impact on mortality).

A.4 The European Marriage Pattern

Europeans curtailed fertility in an important way – by delaying marriage for most women, and ensuring that a high proportion never married. This pattern is known as the European Marriage Pattern (EMP), and it was particularly pronounced in North-Western Europe (Kussmaul, 1981; Voigtländer and Voth, 2009, 2010). Lower birth rates for a given income have a similar effect as higher background mortality: Both alleviate population pressure and reduce the land-labor ratio in steady state. If EMP emerged as a consequence of the plague, as some authors argue (de Moor and van Zanden, 2005; Voigtländer and Voth, 2010), then some of the increase in North-Western European incomes after 1350 has to be attributed to the plague's impact on fertility.

In the following, we investigate EMP's contribution to city growth in our model. We focus on England, where births were unusually responsive to economic conditions (Lee, 1981; Wrigley and Schofield, 1981) in early modern times.[66] We also make the extreme assumption that birth rates were not responsive to income before the Black Death, so that $\varphi_b^{\text{before}} = 0$. This stacks the odds in favor of finding a larger impact of EMP,

[65] These figures compare to the previous calibration as follows: With a maximum 38% of the European population affected by wars, 1 and 2 percent excess mortality during warfare translate into a 0.38 and 0.76 percent maximum war-related 'Horsemen effect,' respectively. The second value is therefore similar in magnitude to our baseline calibration.

[66] England was also ahead of the European average in terms of incomes and city growth: P.c. income grew by 75% between 1500 and 1700, and urbanization rates more than quadrupled from 3% to over 13% (and 20% in 1800) (Maddison, 2007; de Vries, 1984).

as to ensure that we do not exaggerate the role of the 'Horsemen effect.' The steady state before the plague is given by point S_0 in figure 15. When EMP emerges after the plague, it shifts the birth schedule downwards by 1%. This corresponds to a 30% drop relative to the pre-plague steady state for a given p.c. income (or correspondingly, urbanization) level (Clark, 2007). EMP also makes birth rates responsive to income such that $\varphi_b^{\text{after}} = 1.4$, as in the baseline calibration.[67]

[Insert Figure 15 here]

In the absence of the 'Horsemen effect,' the shift and tilt of the birth schedule move the economy from the pre-plague steady state S_0 to the S_{EMP} steady state; urbanization grows from 2.5% to 8.5%. The 'Horsemen effect' creates an additional rise in urbanization (steady state S_{H+EMP}) – from 8.5 to 14 percent. Both effects appear to be equally important, and together they match the observed increase in England's urbanization rate. This underlines the importance of the 'Horsemen effect' for increasing wages in early modern Europe – in continental Europe, where EMP was weaker, the Horsemen contribution was possibly even more significant.

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[67]The corresponding parameter values are $b_0^{\text{before}} = 0.03$ and $b_0^{\text{after}} = 0.02$. With all other parameters unchanged, this implies again a steady state urbanization rate of 2.5% before the plague.

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Figure 1: Steady states in the standard Malthusian model and with ’Horsemen effect’

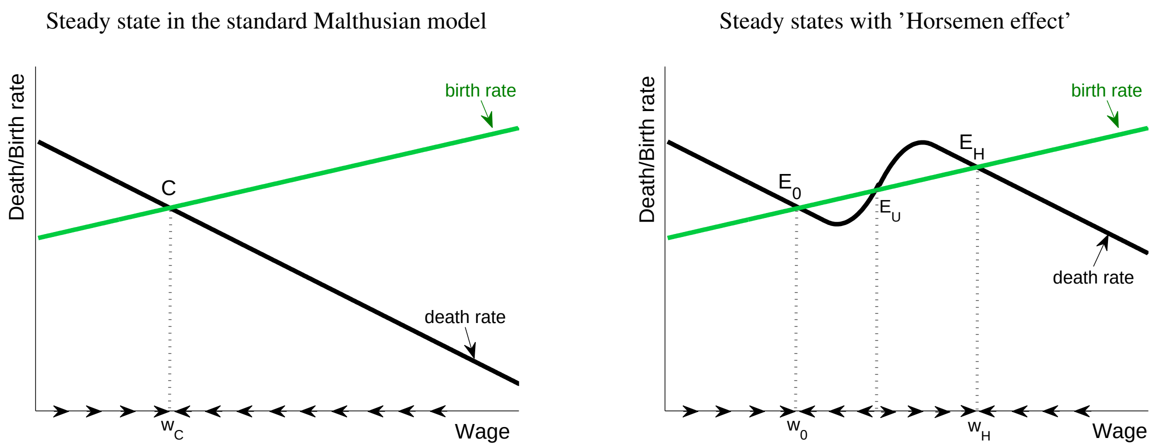

Figure 2: Urbanization rates in Europe and China, 1000-1800.

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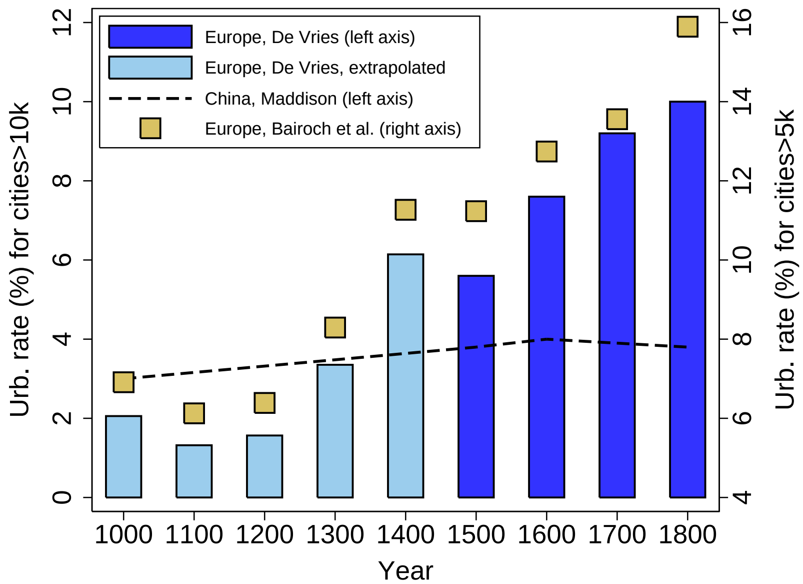
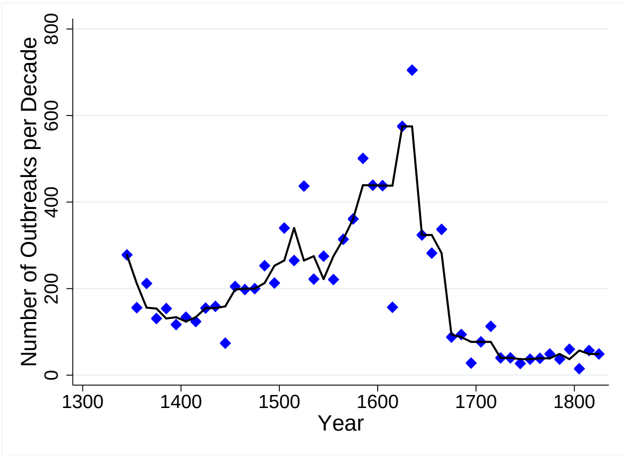


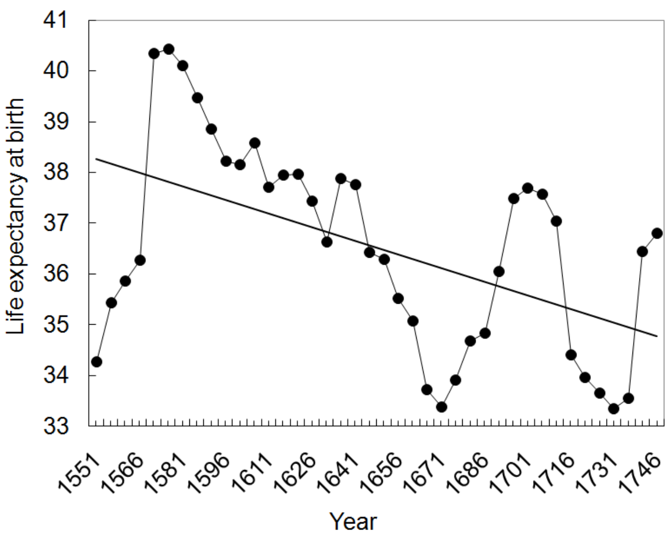
Sources: De Vries (1984) for European urbanization rates 1500-1800, corresponding to cities with more than 10,000 inhabitants. Bairoch et al. (1988) for population in cities larger than 5,000 inhabitants between 1000 and 1800, divided by country-level population from McEvedy and Jones (1978) to obtain urbanization rates; see appendix A.1 for details. A regression-based technique in the spirit of Chow and Lin (1971) is used to extrapolate De Vries' figures based on Bairoch et al.'s numbers. China: Maddison (2001), tables 1-8c and B-14; the line interpolates in 1100-1400 and 1700.

Figure 3: Plague outbreaks in Europe



Data source: Biraben (1975). Data points represent the number of outbreaks over 10 year periods. The solid line is the median of each data point and the two adjacent ones.

Figure 4: Life expectancy in early modern England



Source: Wrigley and Schofield (1981); 20-year moving average.

Figure 5: Wages and urbanization

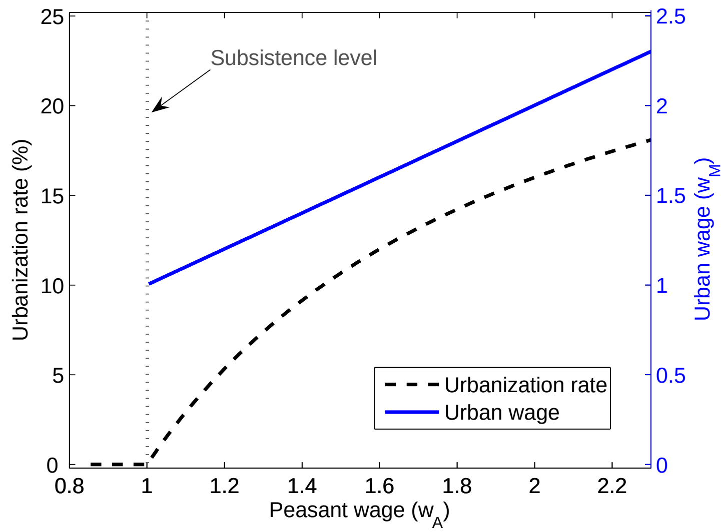
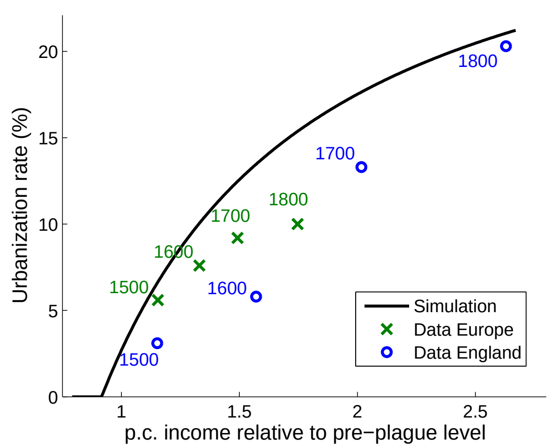
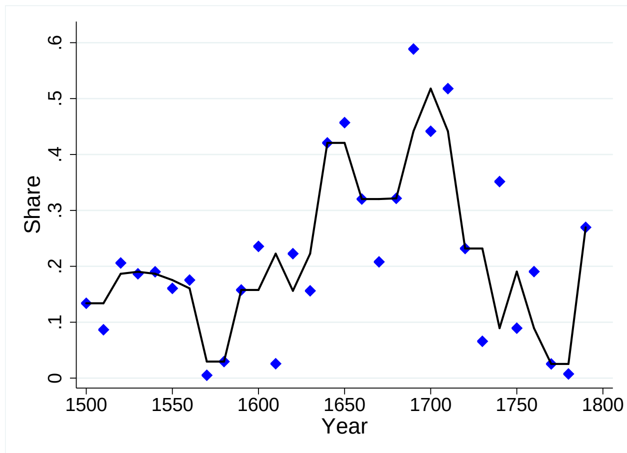


Figure 6: Urbanization and p.c. income – model vs. data



Data sources: Per capita income from Maddison (2007) is relative to the 1350 level (obtained with linear interpolation between 1000 and 1500). Urbanization rates from De Vries (1984).

Figure 7: Percentage of European population affected by war



Data sources: War data from Levy (1983); population from Maddison (2007). Data points represent 10-year averages. The solid line is the median of each data point and the two adjacent ones.

Figure 8: Long-run impact of the plague without 'Horsemen effect' – The case of China

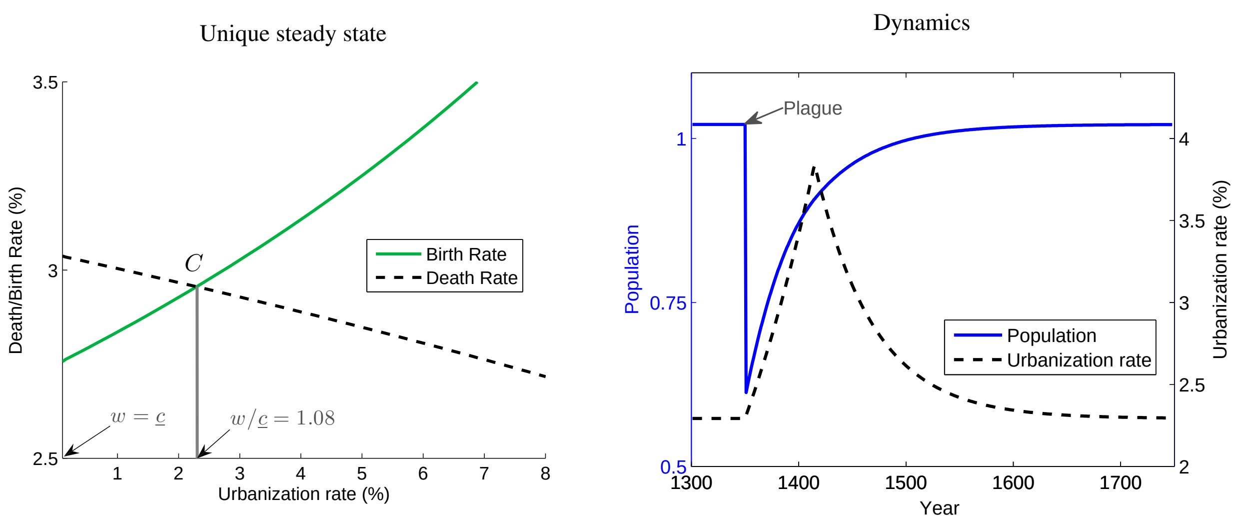


Figure 9: Long-run impact of the plague with 'Horsemen effect' – The case of Europe

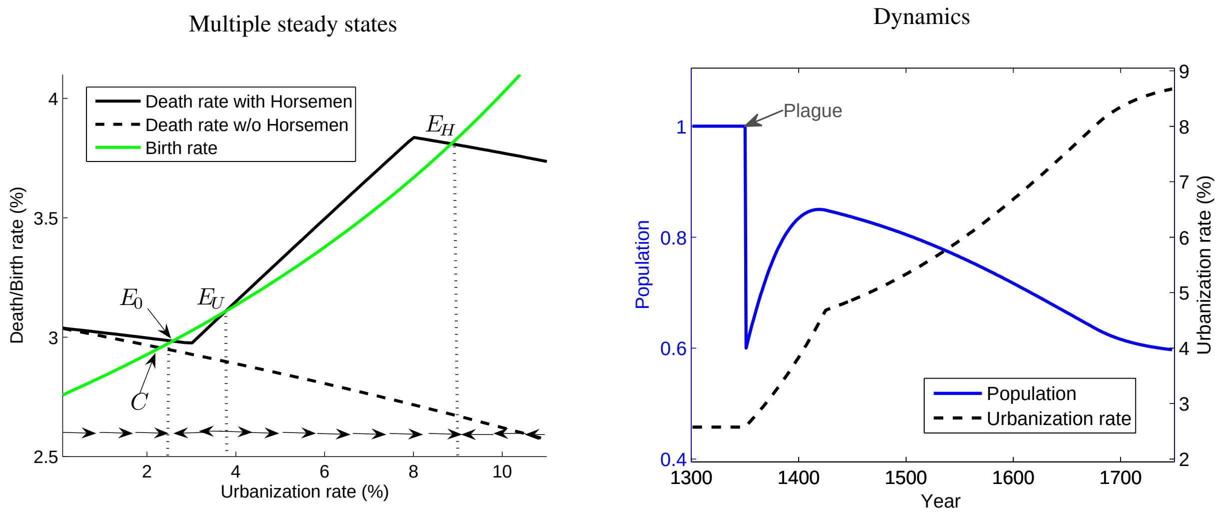


Figure 10: Effect of ongoing technological progress

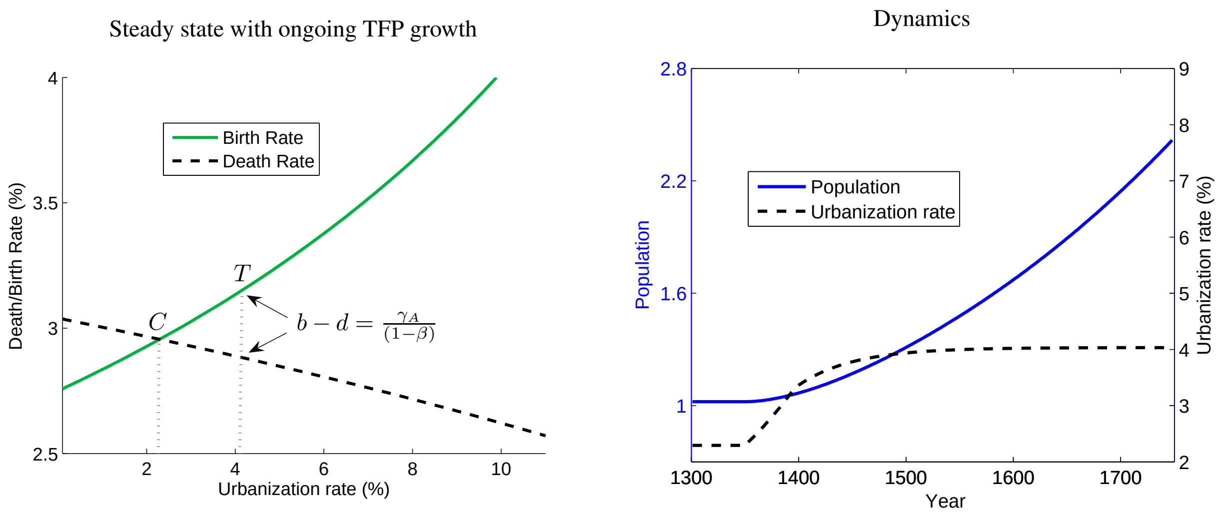
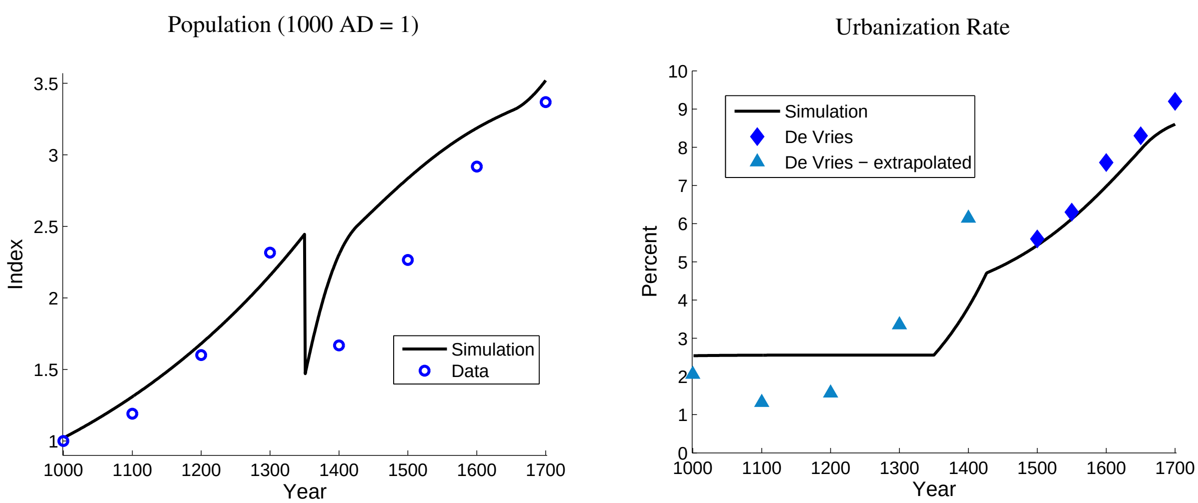
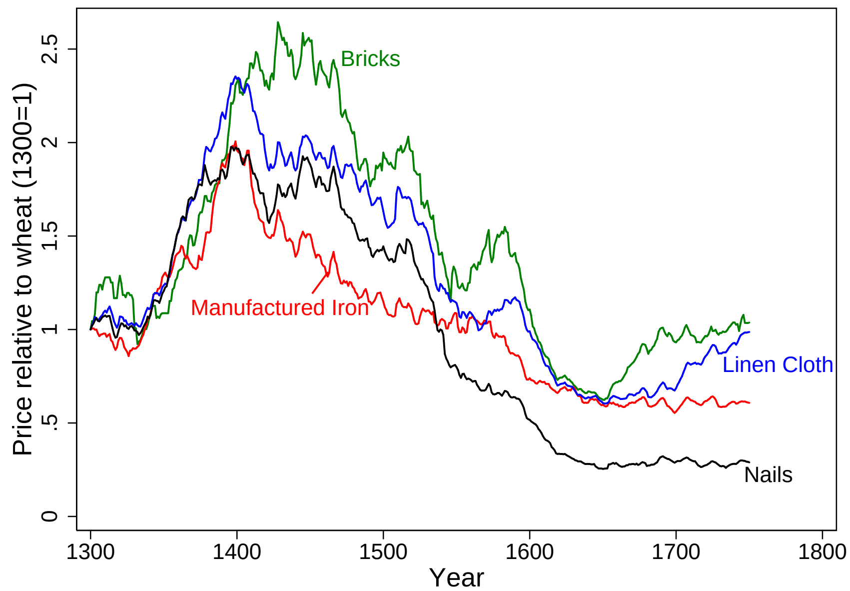


Figure 11: Europe: Simulation results vs. data



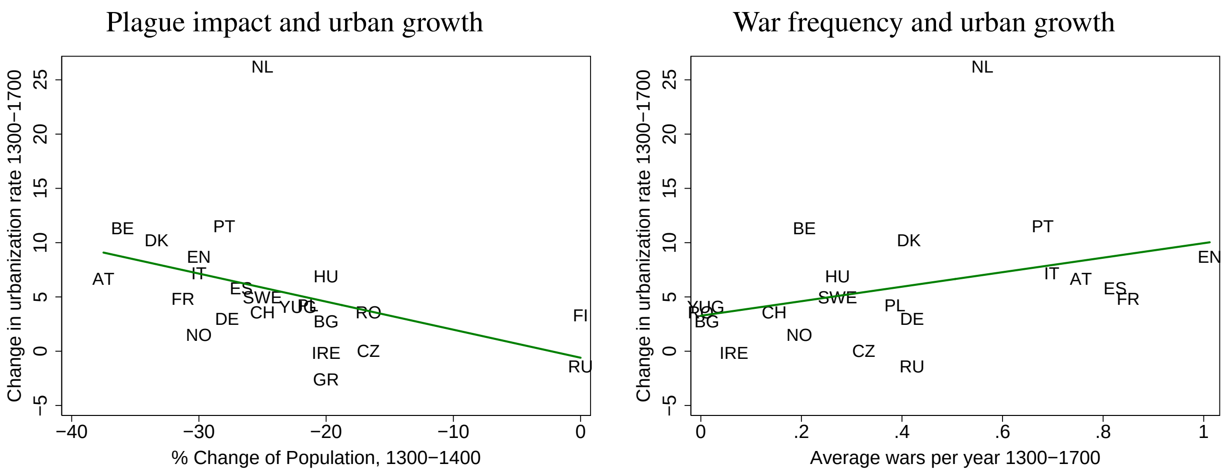
Data sources: Population for Europe (exclusive of the Balkans and Russia) from McEvedy and Jones (1978). Urbanization rates: For 1500-1700 from de Vries (1984); 1000-1400: De Vries (1984), extrapolated using data from Bairoch et al. (1988). See the notes below figure 2 and appendix A.1 for details.

Figure 12: Prices of manufactured goods relative to wheat for England, 1300-1750



Notes: Price data from Clark (2005). All prices are relative to the price of wheat; the 25-year moving average is depicted.

Figure 13: Population losses during the Great Plague, warfare, and early modern urbanization

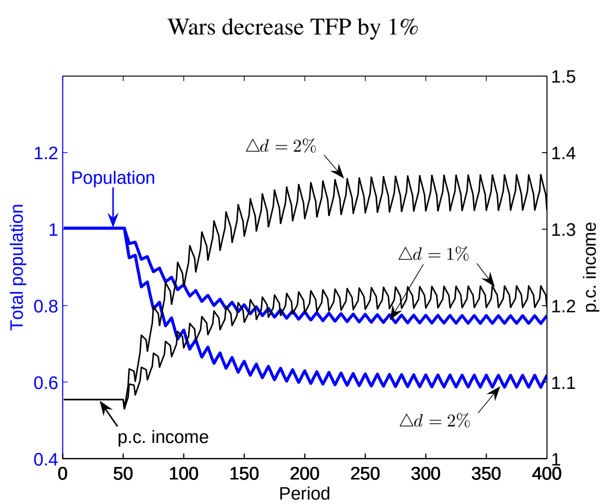


Notes: Population change 1300-1400 from McEvedy and Jones (1978), combined with information on the impact of the plague in Benedictow (2004). Change in urbanization from Bairoch et al. (1988), as explained in appendix A.1. Average wars per year are derived from the dataset used in Acemoglu et al. (2005).

Left panel: The regression line has a slope parameter of -.258 with a t-statistic of -3.71 (robust standard errors) and an R^2 of .17. When excluding the outlier Netherlands, the slope becomes -.243 (t-statistic -3.33), while the fit improves (R^2 of .37). Finally, when we additionally exclude the zero-population change observations Finland and Russia, both fit and significance increase (slope -.394, t-statistic -3.72, R^2 .42).

Right panel: The regression line has a slope of 6.68 with a t-statistic of 2.59 (robust standard errors) and an R^2 of .12. When excluding the outlier Netherlands, the slope parameter is 4.96 (t-statistic 3.04 and R^2 .17).

Figure 14: Robustness of Results: Negative impact of warfare on TFP



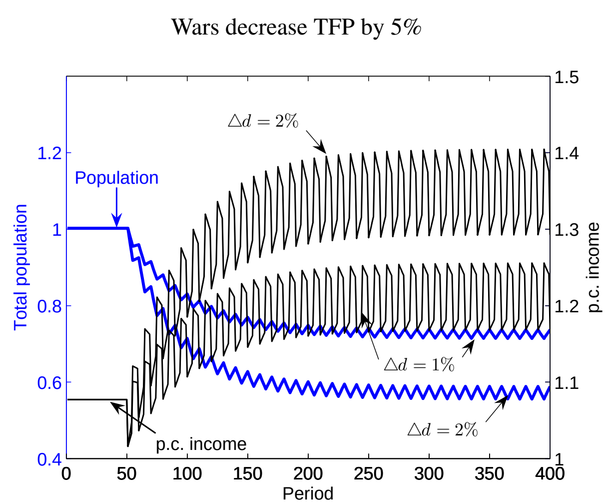


Figure 15: Pre-and post-plague steady states with EMP and Horsemen

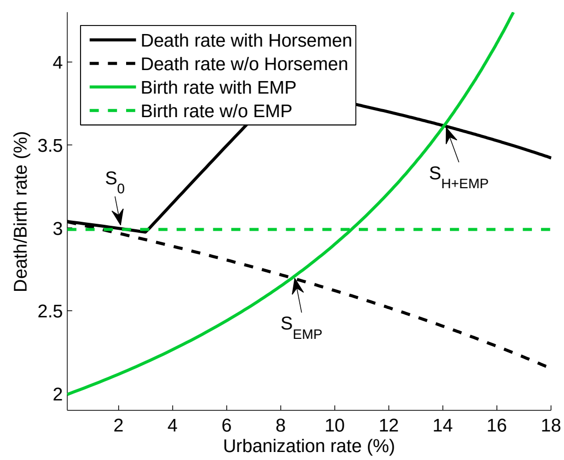


Table 1: Baseline Calibration

Symbol	Interpretation	Value
Parameters		
α	Responsiveness of urbanization to income	0.68
β	Labor share in agriculture	0.6
$\underline{c}$	Subsistence food consumption	1
L	Land	1
$A_{A,0}$	Initial TFP in agriculture	1.076
$A_{M,0}$	Initial TFP in manufacturing	1.087
γ_A	Rate of technological progress	0.1%
$b_{\underline{c}}$	Birth rate at $w = \underline{c}$	2.75%
$d_{\underline{c}}$	Death rate at $w = \underline{c}$	3.04%
φ_b	Elasticity of birth rates wrt. income	1.41
φ_d	Elasticity of death rates wrt. income	-0.55
$\triangle d_M$	City excess mortality	1.5%
$\overline{h}$	Maximum trade and war effect	0.01
$\underline{n}_M$	Threshold for trade and war effect	0.03
δ	Slope parameter for trade and war effect	0.20
$\overline{\nu}$	Upper bound on city growth due to congestion	0.8%
Resulting values in the pre-plague steady state E_0		
N_0	Population	1.0
$n_{M,0}$	Urbanization rate	2.5%
$b_0 = d_0$	Economy-average birth and death rate	3.0%
$p_{M,0}$	Relative price of manufacturing goods	1.0

Table 2: Urbanization and its contribution to average mortality

		Europe	NL	Italy	England
Year		*Urbanization rate (n_M)*			
1300		3.4	6.4	10.6	2.2
1700		9.2	33.6	13.2	13.3
	City penalty	*Mortality due to n_M (%)*			
1300	$\triangle d_M = 50\%$	0.05	0.10	0.16	0.03
1300	$\triangle d_M = 80\%$	0.08	0.15	0.25	0.05
1700	$\triangle d_M = 50\%$	0.14	0.50	0.20	0.20
1700	$\triangle d_M = 80\%$	0.22	0.81	0.32	0.32

Sources: Urbanization rates in 1700 from De Vries (1984); in 1300 extrapolating de Vries' figures backwards with the country-specific trend based on Bairoch et al. (1988). See appendix A.1 for details. The table shows the country-wide additional mortality due to city excess mortality ($\triangle d_M$), calculated as $\triangle d_M \cdot n_M$.