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Modernization of Agriculture and Long-Term Growth

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Abstract

This paper develops a two-sector model that illuminates the role played by agricultural modernization in the transition from stagnation to growth. When agriculture relies on traditional technology, industrial development reduces the relative price of industrial products, but has a limited effect on per capita income because most labor has to remain in farming. Growth is not sustainable until this relative price drops below a certain threshold, thus inducing farmers to adopt modern technology that employs industry-supplied inputs. Once agricultural modernization begins, per capita income emerges from stasis and accelerates toward modern growth. Our calibrated model is largely consistent with the set of historical data we have compiled on the English economy, accounting well for the growth experience of England encompassing the Industrial Revolution.

Keywords: long-term growth, transition mechanisms, relative price, agricultural modernization, structural transformation, the Industrial Revolution, England.

JEL classification: O41, O33, N13

"The man who farms as his forefathers did cannot produce much food no matter how rich the land or how hard he works. The farmer who has access to and knows how to use what science knows about soils, plants, animals, and machines can produce abundance of food though the land be poor. Nor need he work nearly so hard and long. He can produce so much that his brothers and some of his neighbors will move to town to earn their living." —T. W. Schultz (1964)

1 Introduction

Sustained growth in living standards is a recent phenomenon. Estimates of per capita GDP around the world indicate dramatic differences in growth in the past two centuries relative to earlier historical periods. Prior to 1820, the world economy was in a Malthusian state with little growth; per capita production in that year was only 50 percent higher than the level estimated for ancient Rome, according to Maddison (2001). Similarly, Clark(2007) shows that the material lifestyle of the average person around 1800 was roughly equivalent to that of a person living in the Stone Age. During the past two centuries, however, the world's per capita output has increased eightfold. Because of its enormous welfare implications, understanding the switch from stasis to progress has become of central concern to economists interested in growth and development.

In a seminal paper, Hansen and Prescott (2002) proposed an explanation for the transition to modern growth that centers on the progress and enhanced choice of technologies.[1] They argue that for a long period in history, the economy was trapped in the Malthusian regime because people employed only land-intensive technology, which is subject to diminishing returns to labor. What triggered sustained growth was the adoption of a less land-intensive production process that, although available throughout history, had not previously been profitable for individual firms to operate. However, the growth of usable knowledge eventually made it profitable to use this technology that is free of diminishing returns, thus

[1] Other explanations for the transition to modern growth have primarily focused on the role played by human capital accumulation and technological change at the aggregate level. Becker, Murphy and Tamura (1990), Lucas (2002) and Doepke (2004) assign a central role to endogenous fertility choice and investment in human capital. Another line of ideas emphasizes the relationship between population growth and endogenous technological progress(e.g., Kremer, 1993; Goodfriend and McDermott, 1995; Jones, 2001). By combining the two foregoing strands of research, Galor and Weil (2000) consider the nexus between human capital investment and technological change as the key to transition. See also Acemoglu and Zilibotti (1997) for a novel explanation that emphasizes the role of financial market development and luck in growth transitions. Galor (2005) provides a comprehensive survey of the literature on the transition from stagnation to growth.

permitting an escape from Malthusian stagnation. Although Hansen and Prescott provide powerful insight into the transition from stagnation to growth, their model is highly stylized. In an aggregate framework with a single final good, the model is abstracted from several key features of long-term development such as structural transformation and the relationship between agricultural and industrial growth.

This paper takes a more disaggregated approach by emphasizing one aspect of technological progress: the transformation of traditional agriculture. Development economists have long stressed the role played by agriculture in long-term growth.[2] Schultz (1964), in particular, argues that subsistence food requirements present a fundamental challenge to poor economies and that the modernization of agriculture is essential for sustained growth. This view is echoed by economic historians. For instance, Wrigley (1990) states: "The economic law of diminishing marginal returns was inescapable. The future was therefore bound to appear gloomy as long as it seemed proper to assume that the productivity of the land conditioned prospects, not merely for the supply of food in particular, but also for economic growth generally. Only if there were radical and continuous technological advances in agricultural technology could this fate be avoided."

Building on these insights from the economic history and development literature, this paper develops and calibrates a two-sector model that highlights the importance of agricultural modernization as a central mechanism of the transition from stagnation to growth. Our model is motivated by three concurrent events that occurred in England between 1700 and 1909, a period encompassing the Industrial Revolution:

(a) the well-known fact that around 1820, per capita GDP for the English economy ended a long flat trend and moved into sustained growth (see Figure 1A);[3]

(b) the less well-known fact that the systematic adoption of farm machinery also began around 1820—the percentage of farms that owned agricultural machines was nearly nil at the beginning of the century, but the adoption of these machines became widespread in the decades thereafter (e.g., Walton, 1979; Overton, 1996; see Figure 2);[4] and

[2] Important contributions from among the vast collection of this literature include those of Johnston and Mellor (1961), Jorgenson (1961), Schultz (1964) and Timmer (1988); Kelley, Williamson and Cheatham (1972) present an early numeric simulation of a two-sector model; Johnson (1997) provides a recent survey.

[3] The statistical information quoted in this paper is obtained from multiple sources. See Section 5 and Appendix B for detailed data descriptions.

[4] For centuries, advancements in agricultural productivity around the world were derived primarily from

(c) perhaps the least known fact, but one that is central to our study, that the price of industrial products relative to agricultural products in England declined persistently for more than a century, hitting a low point in the 1820s and then stabilizing at that level in the following decades (see Figure 1B).

We do not think that the concurrence of the three events is merely a historical coincidence. Instead we argue in this paper that the three events are causally linked. When agriculture relies on traditional technology, industrial development reduces the price of industrial products relative to agricultural products, but has a limited effect on per capita income, because most labor has to remain in farming. Growth is not sustainable until this relative price drops below a certain threshold, thus making it profitable for some farmers to adopt modern technology that uses industry-supplied inputs. Industrial development is a necessary precondition for the modernization of agriculture. Once agricultural modernization begins, per capita income breaks out of stasis and growth starts. During the transition period, when the modern technology is adopted by some but not all farmers, the relative price stabilizes to a threshold level at which farmers are indifferent about which technology to employ.

To illustrate these linkages, we build a model of two sectors, agriculture and industry.[5] Central to our analysis is the choice of two technologies that are potentially available to farmers. The first choice is traditional technology, which uses labor and land, the latter of which is in fixed supply, thus implying diminishing returns to labor. The alternative is modern technology, which also employs an input that is produced by industry. This modern agricultural input could represent both capital, such as manufactured farm implements and machinery, and intermediate input, such as chemical fertilizers and high-yield seed varieties. The cost of the input is determined endogenously, depending in part on the industrial total factor productivity (TFP), which grows exogenously.

In a traditional economy, the cost of industry-supplied input is too high such that farms use traditional technology only. Slow TFP growth in experience-based traditional farming

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the experiences of farm people. However, starting around 1820, in England and in other parts of the world such as the U.S., the application of scientific knowledge and the inputs supplied by industry have become the engine of rapid agricultural productivity growth (Huffamn and Evenson, 1993; Johnson, 1997). This paper defines agricultural modernization as the use of industry-supplied inputs in farming, which primarily refers to the mechanization of the 19th century, but also includes chemical, biological and other agronomic innovations of later periods.

[5] Hence, industry corresponds to the rest of the economy other than agricultural production. We also use "nonagricultural sector" interchangeably with "industry."

requires a high employment share in agriculture to ensure sufficient food supply. Positive shocks to agricultural productivity may lead to temporary structural transformation and per capita income increases. However, high income induces population growth, which in turn reduces the per worker output of agriculture because of the fixed supply of land. TFP growth in industry can generate neither sustained structural transformation nor income growth, because most labor must remain in farming. Therefore, without modernizing agriculture, an economy cannot break away from the Malthusian trap.

In the long-run, however, industrial TFP growth gradually lowers the price of industrial products relative to agricultural products, which eventually leads to agricultural modernization. The transition to modern growth begins when this relative price drops below a critical level, thus inducing farmers to adopt modern technology. During this transition, structural transformation accelerates, and the economy steps onto the path of sustained growth. The critical link is that, as industrial TFP grows, the cost of modern agricultural inputs declines and a larger quantity of these inputs is employed in agricultural production, hence raising agricultural labor productivity. In other words, with agricultural modernization, TFP growth in industry will join forces with TFP growth in agriculture, contributing directly to agricultural labor productivity growth through the use of industry-supplied inputs, and thus facilitating structural change. In contrast to a traditional economy, in which per capita income is constrained by agricultural TFP and population growth, TFP growth in both agriculture and industry contributes to per capita income growth when agriculture is modernized. During the transition period, the relative price settles to a stable level such that farmers are indifferent about which technology to use. Continued industrial growth tends to lower relative price, but the effect is offset by the more widespread use of modern technology and higher demand for industry-supplied inputs. The transition ends with the complete adoption of the new technology. Under modern growth, agriculture's share of labor eventually approaches zero in the limit, and the growth rate of per capita income converges to the growth rate of industry.

To examine empirically the model's predictions about the structural breaks and coordinated movements in several macroeconomic variables through different stages of long-term growth, we turn to the Industrial Revolution in England. This focus reflects not only the fact that England was the first nation to emerge from Malthusian stagnation, but also the availability of exceptionally rich historical data. We compile data on decennial time series of real per capita GDP, prices for agricultural and principal industrial products, agricultural mechanization, employment share in agriculture, real average wages of adult farm workers, and land rent from multiple sources. We also rely on historical studies of the English economy to infer the exogenous TFP growth in agricultural and nonagricultural production. We then calibrate our model to the English economy, simulate the time paths for the six key aggregate economic variables through the periods of stagnation, transition and growth, and compare them with their counterparts in the data. Our quantitative analysis accounts well for the observed English experience of growth in the period between 1700 and 1909. The empirical findings, which also take into account the role of food trade, support a coherent view of the importance of agricultural modernization in making the transition from stagnation to growth possible.

Hence, the contributions of this paper are twofold. First, we contribute to the literature on long-term growth with a quantitative model of growth transitions that emphasizes the central roles played by agricultural modernization and structural transformation. Second, drawing on historical statistics, we assess the empirical validity of the model and show that it can account quantitatively for the growth experience of England encompassing the period of the Industrial Revolution. The data we have compiled reveal some novel features of the English economy that may also be conducive to future research.

Our central idea lies in technological change within agriculture. This emphasis is closely related to Hansen and Prescott's study (2002), which investigates the growth implications of switching from traditional to modern technology in an aggregate model. However, Hansen and Prescott's framework is essentially a one-sector model with two production technologies that produce a single good. Therefore, their model leaves no room to explore the implications of the role of food constraint on structural transformation, the interactions between industrial and agricultural development, and the relative price changes as keys to agricultural modernization, which are the emphasizes of our paper. In addition, by showing how industrial development leads to agricultural modernization through the choice of nonagricultural inputs by optimizing farmers, we endogenize part of the productivity growth of the modern technology, which was taken as exogenous in their study.

This paper also belongs to a burgeoning body of literature on structural transformation and growth.[6] By stressing the importance of agriculture in a dual-economy model, our paper is most closely related to Gollin, Parente and Rogerson (2007), who examine the effects of using alternative agricultural technologies on the evolution of international income

[6] See, for instance, Matsuyama (1992), Echevarria (1997), Laitner (2000), Caselli and Coleman (2001), Kogel and Prskawetz (2001), Kongsamut, Rebelo and Xie (2001), Gollin, Parente and Rogerson (2002), Ngai (2004), Wang and Xie (2004), Ngai and Pissarides (2007), Hayashi and Prescott (2008), Acemoglu and Guerrieri (2008) and Lucas (2009).

differences.[7] Similar to us, Gollin, Parente and Rogerson also emphasize the importance of food constraint and modern agricultural technology in long-run growth. However, Our paper differs from their study in several ways. First, they do not consider population growth and its Malthusian implication of stagnation. In their model, stagnation is possible only if there is zero TFP growth in agriculture; the transition from stagnation to growth starts whenever agricultural TFP growth becomes positive; and, growth can be sustained in the long run even without switching to modern agricultural technology that uses industry-supplied inputs. In contrast, we model the population growth as in Hansen and Prescott and show that, even with positive TFP growth both in and outside agriculture, the economy cannot escape from the Malthusian trap in the long run unless there is a switch from traditional agricultural technology to a modern one that uses industry-supplied inputs. Second, we derive more analytical results on the timing and mechanisms of the transition process by relating them to the changes in the relative price of industrial good. Unique to our model is the emphasis on industrial development as a necessary precondition for the modernization of agriculture. We document the adoption of farm machinery based on unique historical data and incorporate these data into our quantitative analysis. Finally, by allowing for food trade, we calibrate our model to the English economy and show that the transition mechanisms we identify are quantitatively consistent with the England's growth experience.

As we do in this paper, Stokey (2001) also calibrates a model of the British Industrial Revolution for the period 1780-1850. However, her focus is on quantifying the contributions made by growing foreign trade and TFP growth in individual sectors to overall growth, rather than on investigating the transition from stagnation to growth.

The rest of the paper is organized as follows. Section 2 presents the basic structures of the two-sector model. In Section 3, we analyze the equilibrium properties for a traditional economy without the use of modern agricultural technology. Section 4 explores the features of the transition to modern growth. In Section 5, we document the stylized patterns of the English economy using data for the 1700-1909 period and present findings on how the predictions of our calibrated model match the main features of the British Industrial Revolution. Section 6 presents our concluding remarks.

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[7] A related paper is Restuccia, Yang and Zhu (2008), which examines the role of the barriers to using modern agricultural technology in accounting for cross-country income gaps.

2 The Two-Sector Model

A. Preferences and Endowments

Consider an economy in discrete time. There is a fixed amount of land, $\overline{Z}$, and N_t identical individuals in period t. Each individual owns $z_t = N_t^{-1}\overline{Z}$ amount of land and one unit of time, which is supplied inelastically to work in the labor market.[8] Let w_t be the wage rate and r_t be the rental rate of land. Then, an individual's income is $y_t = w_t + r_t z_t$.

There are two consumption goods, agricultural and nonagricultural (or industrial). Let the agricultural good be the numeraire and p_t be the price of the industrial good. Each individual household consumes a constant amount $\overline{c}$ of the agricultural good (c_{at}) and spends its remaining income on the consumption of the industrial good (c_{nt}). Therefore, we have

$$c_{at} = \overline{c}; \quad c_{nt} = p_t^{-1}(y_t - \overline{c}). \tag{1}$$

Each individual lives for one period, and, at the end of period t, gives birth to g_t children. The land owned by the parent will be divided equally among the children. We assume that the population growth rate is a function of per capita income, $g_t = g(y_t)$. Thus,

$$N_{t+1} = g(y_t)N_t. \tag{2}$$

Because the agricultural good is used as the numeraire, per capita income y_t is not the same as the usual measure of national per capita income, which is deflated by a GDP deflator. Rather, y_t is a measure of the household's capacity to purchase agricultural goods. This corresponds well to the living standard measures used for the early stages of development in the economic history literature, where they are often calculated as the ratio of nominal income to the price of commonly consumed food products.

B. Production Technologies

The nonagricultural good is produced with a linear production technology: $Y_{nt} = A_{nt}L_{nt}$, where A_{nt} represents TFP in the industrial sector.[9]

[8] We prohibit trading in land ownership. As households are identical in this economy, this assumption is not substantial.

[9] The choice of this simple production function responds primarily to the limitation that no data on capital investment is available for England during the 1700-1910 period. Therefore, we cannot conduct quantitative analysis treating capital as a key variable. Although we can add capital into the model, which will complicate the analytical results, all our qualitative results on structural transformations will stay the

Two technologies are potentially available for farm production. The traditional technology uses only land and labor as inputs:

$$Y_{at}^{T} = Z_t^{1-\sigma} \left(A_{at} L_{at}\right)^{\sigma}, \quad 0 < \sigma < 1.$$

Here, Z_t and L_{at} are land and labor inputs, respectively, where A_{at} denotes the TFP in traditional agriculture[10], σ is the labor share, and superscript T denotes traditional technology. The modern agricultural technology (with superscript M) uses an industry-supplied input, X_t, as well as the traditional inputs, i.e., land and labor:

$$Y_{at}^{M} = \left[Z_t^{1-\sigma} \left(A_{at} L_{at}\right)^{\sigma}\right]^{1-\alpha} X_t^{\alpha}, \quad 0 < \alpha < 1.$$

This modern input is produced outside of agriculture and has a factor share of α. We think of this modern agricultural input as consisting of both manufactured capital goods, such as farm implements, processing machinery and transportation equipment, and intermediate inputs, such as chemical fertilizer, pesticide and high-yield seed varieties. We assume full depreciation of the industry-supplied input at the end of the period, which corresponds to a decade in later quantitative analysis. The production of one unit of the input requires π units of industrial output; hence, its price is πp_t. For simplicity, we assume that $\pi = 1$ for the rest of the paper.

Because the production technologies have constant returns to scale, we assume, without loss of generality, that there is one stand-in firm in each of the two sectors. Both firms behave competitively, taking the output and factor prices as given and choosing the factor inputs to maximize profits. Hence, the profit maximization problem of the industrial firm is: $\max_{L_{nt}} \left\{p_t A_{nt} L_{nt} - w_t L_{nt}\right\}$.

The stand-in firm (or farm) in agriculture has the following profit maximization problem.

$$\max_{Z_t^T, Z_t^M, L_{at}^T, L_{at}^M, X_t} \left\{ \begin{array}{c} (Z_t^T)^{1-\sigma} (A_{at} L_{at}^T)^{\sigma} + \left[(Z_t^M)^{1-\sigma} \left(A_{at} L_{at}^M\right)^{\sigma}\right]^{1-\alpha} X_t^{\alpha} \\ -p_t X_t - r_t Z_t - w_t L_{at} \end{array} \right\}, \tag{3}$$

subject to quantity constraints: $Z_t^T + Z_t^M = Z_t$, and $L_{at}^T + L_{at}^M = L_{at}$.

same in this paper. We should acknowledge that an extension of the model incorporating capital can be productively applied to study structural transformation in developing countries during modern times, when capital information is available.

[10] According to the production specification, the TFP in agiculture should be A_{at}^{σ} instead of A_{at}. For exposition simplicity, however, we simply call A_{at} the agricultural TFP.

C. Technology Adoption in Agriculture

If a farm adopts the modern technology and allocates $Z_t^M (> 0)$ amount of land and $L_{at}^M (> 0)$ amount of labor to production using that technology, then, from (3), the optimal quantity of the industrial input it uses is given by $X_t = (\alpha/p_t)^{1/(1-\alpha)} (Z_t^M)^{1-\sigma} \left(A_{at} L_{at}^M\right)^{\sigma}$,and the value-added produced by the modern agricultural technology is

$$\widehat{Y}_{at}^M = Y_{at}^M - p_t X_t = (1-\alpha)(\alpha/p_t)^{\alpha/(1-\alpha)} (Z_t^M)^{1-\sigma} \left(A_{at} L_{at}^M\right)^{\sigma}.$$

In comparison, if the farm uses the same amounts of land and labor for production using the traditional technology, then its output is $(Z_t^M)^{1-\sigma} \left(A_{at} L_{at}^M\right)^{\sigma}$. Clearly, the farm will adopt modern technology only if

$$(1-\alpha)\left(\frac{\alpha}{p_t}\right)^{\alpha/(1-\alpha)} \geq 1. \quad (4)$$

When the equality in (4) holds, the farm is indifferent about which of the two technologies to choose; one or both may be used. This condition implies that the farm will adopt the modern agricultural technology only when the relative price of the industry-supplied input (p_t) falls below a certain threshold. Because the modern input is produced in the nonagricultural sector, the decline in its price is ultimately determined by the productivity growth in that sector. Therefore, in our model, technological change in agriculture is a result of (or is induced by) technological progress outside agriculture, as emphasized by Hayami and Ruttan (1971).

Our model adopts a general equilibrium approach in which the relative price p_t influences the farmer's choice of technologies, and the equilibrium value of p_t depends on the use of technologies in agriculture. To pin down the exact conditions for technology adoption, we need to solve the equilibrium price p_t as a fixed point. Before doing that, however, we first define the competitive equilibrium.

D. Market Equilibrium

Definition 1 *A competitive equilibrium consists of sequences of prices $\{w_t, r_t, p_t\}_{t\geq 0}$, firm allocations $\{L_{at}^T, L_{at}^M, L_{nt}, Z_t^T, Z_t^M, X_t\}_{t\geq 0}$, consumption allocations $\{c_{at}, c_{nt}\}_{t\geq 0}$, and the size of the population $\{N_t\}$, such that the following are true: (1) Given the sequence of prices, the firm allocations solve their profit maximization problems; (2) The consumption allocations are given by (1); (c) All markets clear: $Y_{at} = N_t \bar{c}$, $Y_{nt} = N_t c_{nt} + X_t$, $N_t = L_{at}^T + L_{at}^M + L_{nt}$, and $\overline{Z} = Z_t^T + Z_t^M$; and (4) The population growth rate is given by equation (2).*

The following proposition holds for the competitive equilibrium.

Proposition 1 *Let* $\Phi_l \equiv (1-\alpha)^{\frac{\alpha-1}{\alpha}}\sigma\alpha^{-1}\overline{c}^{\frac{\sigma-1}{\sigma}}$, $\Phi_h = (1-\alpha)^{-\frac{1-\sigma}{\sigma}}\Phi_l$, *and* $\widetilde{A}_{at} = A_{at}\left(\overline{Z}/N_t\right)^{\frac{1-\sigma}{\sigma}}$, *which can be interpreted as the measure of labor productivity in traditional agriculture that increases with agricultural TFP* A_{at} *and land-to-population ratio* $\overline{Z}/N_t$*. In agricultural production, the farm uses only traditional technology if* $A_{nt}/\widetilde{A}_{at} \leq \Phi_l$*; uses only modern technology if* $A_{nt}/\widetilde{A}_{at} \geq \Phi_h$*; and uses both technologies if* $\Phi_l < A_{nt}/\widetilde{A}_{at} < \Phi_h$*.*

The proofs of the propositions are provided in Appendix A. This proposition identifies several factors that directly influence the use of modern agricultural technology. First, TFP parameter A_{at} and land-to-population ratio $\overline{Z}/N_t$ are negatively related to the adoption of modern technology. Second, the industrial TFP (A_{nt}) has a positive effect on the adoption of the modern farm technology. As we shall shortly elaborate on further, this is because a high level of industrial productivity lowers the price of the nonagricultural good, thus reducing the cost of using the industry-supplied input.[11]

3 Traditional Economy

We define a traditional economy as one in which farmers use only traditional technology. Proposition 1 suggests that if the initial land-to-population ratio $\overline{Z}/N_0$ is sufficiently high and/or the initial relative TFP A_{n0}/A_{a0} is sufficiently low, then the economy starts out as a traditional one. The following proposition states the determination of the key variables in this economy.

Proposition 2 *In a traditional economy, we have*

$$p_t = \sigma\overline{c}^{\frac{\sigma-1}{\sigma}}\frac{\widetilde{A}_{at}}{A_{nt}},\; w_t = \sigma\overline{c}^{\frac{\sigma-1}{\sigma}}\widetilde{A}_{at},\; r_t = (1-\sigma)\overline{c}\frac{N_t}{\overline{Z}}, \tag{5}$$

$$y_t = \left[1-\sigma+\sigma\overline{c}^{-\frac{1}{\sigma}}\widetilde{A}_{at}\right]\overline{c}, \tag{6}$$

$$\frac{L_{at}}{N_t} = \overline{c}^{\frac{1}{\sigma}}\widetilde{A}_{at}^{-1}. \tag{7}$$

In period t, both per capita income (y_t) and the employment share of agriculture (L_{at}/N_t) are determined by variable $\widetilde{A}_{at}$. This is an intuitive result. Since $\widetilde{A}_{at} = A_{at}\left(\overline{Z}/N_t\right)^{\frac{1-\sigma}{\sigma}}$,

[11] In the context of tractor adoption by farmers in the U.S., Manuelli and Seshadri (2003) recently argued that wage growth is a key factor in the diffusion of modern technology. In our model, as we show below, the diffusion of modern agricultural technology is indeed associated with a rising wage rate. Both, however, are the result of productivity growth in the nonagricultural sector.

a higher level of agricultural TFP and land endowment imply greater agricultural labor productivity, which, in turn, lead to higher per capita income and a lower employment share in agriculture. Moreover, in period t, rental prices rise with population size; the wage depends on agricultural labor productivity; and the relative price (p_t) is determined by the relative productivity of agriculture and industry ($\widetilde{A}_{at}/A_{nt}$).

The steady-state properties of the key variables can also be derived as follows. Equations (6) and (7) suggest that a traditional economy can achieve sustained structural change (i.e., persistent decline in the employment share of agriculture) and per capita income growth only if there is sustained growth in $\widetilde{A}_{at}$. By definition, we have

$$\begin{aligned}\frac{\widetilde{A}_{at+1}}{\widetilde{A}_{at}} &= \frac{A_{at+1}}{A_{at}}\left(\frac{N_{t+1}}{N_t}\right)^{-\frac{1-\sigma}{\sigma}} = \frac{A_{at+1}}{A_{at}}\left[g(y_t)\right]^{-\frac{1-\sigma}{\sigma}} \\ &= \frac{A_{at+1}}{A_{at}}\left[g\left((1-\sigma+\sigma\overline{c}^{-\frac{1}{\sigma}}\widetilde{A}_{at})\overline{c}\right)\right]^{-\frac{1-\sigma}{\sigma}}.\end{aligned}$$

If A_{at} grows at a constant rate $\gamma_a \geq 1$, then, the foregoing equation becomes

$$\widetilde{A}_{at+1} = \gamma_a\left[g\left((1-\sigma+\sigma\overline{c}^{-\frac{1}{\sigma}}\widetilde{A}_{at})\overline{c}\right)\right]^{-\frac{1-\sigma}{\sigma}}\widetilde{A}_{at}. \tag{8}$$

We make the following assumption about function $g(.)$.

Assumption 1 *(i) $g(\overline{c}) < 1$; (ii) there is a $\widehat{y} > \overline{c}$, such that $g(\widehat{y}) > \gamma_a^{\frac{\sigma}{1-\sigma}}$; and (iii) $g(.)$ is continuous and strictly increasing over the interval $[0, \widehat{y})$, decreasing over the interval $[\widehat{y}, \infty)$, and $\lim_{y\longrightarrow\infty} g(y) = 1$.*

Under this assumption, the population growth rate increases with income when starting at an initially low income level. This growth rate then increases to its peak at a certain income level, after which it declines with income and eventually converges to one. This hump-shaped function for the population growth rate is consistent with typical patterns of demographic transition.

Proposition 3 *Under Assumption 1, there exists a unique steady-state solution to the difference equation (8) such that the corresponding income per capita $y^* \in (\overline{c}, \widehat{y})$.*

Therefore, without the adoption of modern agricultural technology, the economy always settles down at a Malthusian steady state with per capita income constant at y^* and no sustained growth in living standards. From equation (6), we know that the steady-state value of $\widetilde{A}_{at}$, $\widetilde{A}_a^*$, is determined by the equation $y^* = \left[1-\sigma+\sigma\overline{c}^{-\frac{1}{\sigma}}\widetilde{A}_a^*\right]\overline{c}$. Because $y^* > \overline{c}$, $\widetilde{A}_a^* > 0$.

Thus, in the steady state, the population size is given by the equation $\widetilde{A}_a^* = A_{at}\left(\overline{Z}/N_t\right)^{\frac{1-\sigma}{\sigma}}$ or $N_t = \left(A_{at}/\widetilde{A}_a^*\right)^{\frac{\sigma}{1-\sigma}}\overline{Z}$.Consequently, in a traditional economy, the effects of temporary agricultural TFP growth and any initial advantage in land endowment on agricultural labor productivity are completely offset by the adjustment in population size in the long run. As a result, labor productivity in agriculture is independent of both the agricultural TFP and land endowment. At the Malthusian steady state, as equations (5) to (7) show, per capita income, wages, and the employment share of agriculture remain at constant levels; land rental rises with population; and relative price declines with industrial TFP growth.

4 Transition to Modern Growth

A. What Triggers the Transition?

We have shown that, without the use of modern agricultural technology, an economy remains trapped in Malthusian stagnation. However, will the farmers in such an economy eventually find it profitable to adopt the new technology?

Proposition 1 suggests that farmers will choose the modern input if $A_{nt}/\widetilde{A}_{at} > \Phi_l$.Suppose the economy starts out with a steady-state equilibrium, where $\widetilde{A}_{at}$ settles at a constant level $\widetilde{A}_a^*$. Then, as long as A_{nt} grows without bounds, a time will eventually come at which this inequality holds. The same point can be made based on the behavior of the relative price of the nonagricultural good. From (5), $p_t = \sigma\overline{c}^{\frac{\sigma-1}{\sigma}}\widetilde{A}_{at}/A_{nt}$. In the Malthusian steady state, we have

$$p_t = \sigma\overline{c}^{\frac{\sigma-1}{\sigma}}\widetilde{A}_a^*/A_{nt}, \tag{9}$$

which declines monotonically with the growth of industrial TFP. Hence, at some point in time, the price of the nonagricultural good will reach a low threshold level $p^M = \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}}$ such that the adoption condition (4) holds with equality. At that point, farmers will begin to use the industry-supplied input for agricultural production. Thus, continued industrial TFP growth, or a persistent decline in the relative price, eventually triggers the transition from traditional agricultural technology to modern agricultural technology. Initially, when relative productivity $A_{nt}/\widetilde{A}_{at}$ only just surpasses threshold level Φ_l, but still remains below Φ_h, the industrial TFP is not sufficiently large to meet the demand for modern inputs by all farmers at a price that would make it profitable for them to adopt the modern technology. Under this scenario, the economy is at an equilibrium at which some but not all farmers will use the new technology and the relative price p_t stays at a level at which farmers remain indifferent about the choice of technologies. We define the transition period—the period during which farmers use both technologies—as a mixed economy.

B. Mixed Economy

Proposition 4 *In a mixed economy,*

$$p_t = p^M \equiv \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}},\ w_t = p^M A_{nt},\ r_t = (1-\sigma)\left(\frac{\sigma}{p^M}\frac{\widetilde{A}_{at}}{A_{nt}}\right)^{\frac{\sigma}{1-\sigma}}\frac{N_t}{\overline{Z}}, \tag{10}$$

$$y_t = p^M A_{nt} + (1-\sigma)\left(\frac{\sigma}{p^M}\frac{\widetilde{A}_{at}}{A_{nt}}\right)^{\frac{\sigma}{1-\sigma}}, \tag{11}$$

$$\frac{L_{at}}{N_t} = \left(\frac{\sigma}{p^M}\frac{\widetilde{A}_{at}}{A_{nt}}\right)^{\frac{1}{1-\sigma}}\widetilde{A}_{at}^{-1},\ \frac{Z_t^M}{\overline{Z}} = \frac{1-\alpha}{\alpha}\left[\left(\frac{A_{nt}}{\widetilde{A}_{at}}\Phi_l^{-1}\right)^{\frac{\sigma}{1-\sigma}} - 1\right]. \tag{12}$$

The time paths of the macroeconomic variables in this mixed economy differ significantly from those of the variables in a traditional economy. More specifically, note the following structural breaks that occur in each of the variables.

The price of industrial products relative to agricultural products (p_t): In the traditional steady state, p_t declines with the growth of A_{nt} because $\widetilde{A}_{at}$ is a constant (see equation 5). Once agricultural modernization begins, p_t settles to a constant level at which farmers are indifferent about the adoption of either technology. Industrial TFP growth tends to lower the relative price, but this induces the more widespread use of modern technology, which helps to keep the relative price at a stable level.

Per capita income (y_t): At the Malthusian equilibrium, per capita income y_t is trapped at a low level because the slow growth of A_{at} is fully offset by population adjustment (see equation 6). During the transition, however, when the two sectors are integrated through the use of industry-supplied modern inputs, A_{nt} contributes directly to per capita income, thus creating a clear structural break in the growth path of y_t. The modernization of agriculture helps an economy to escape the Malthusian trap.

The use of modern inputs in agriculture ($Z_t^M/\overline{Z}$): The ratio of the land devoted to new technology over the total land area measures the extent of modern technology adoption. In an agrarian economy, the old technology prevails. Once the transition begins, however, if the TFP in nonagriculture A_{nt} grows sufficiently fast, then $A_{nt}/\widetilde{A}_{at}$ increases over time, and the proportion of land (and labor) allocated to modern agricultural production increases from zero to one, as $A_{nt}/\widetilde{A}_{at}$ moves from Φ_l to Φ_h (see equation 12).

Agriculture's employment share (L_{at}/N_t): In a traditional economy, the employment share is a decreasing function of $\widetilde{A}_{at}$, which depends positively on A_{at} and $\overline{Z}/N_t$ (see equation 7). Because $\widetilde{A}_{at}$ tends to settle at a steady-state level, there can be no sustained structural change in such as an economy. With mixed technologies, the share of employment in agriculture is also a decreasing function of A_{nt}, because TFP growth in industry reduces the cost of modern input X_t, thus inducing farmers to use more X_t and less labor. Agricultural modernization thus makes sustained economic structural change possible.

Wage rate (w_t): This is a constant at the Malthusian steady state. As the economy enters the transition, the wage rate grows with industrial TFP A_{nt}.

Land rent (r_t): During the transition, the land rental price is no longer a simple increasing function of the population size, as in a traditional economy. The price of land is also affected by the relative TFP levels in the two sectors $(\widetilde{A}_{at}/A_{nt})$ because the modern input has become a substitutable factor for land in agricultural production.

C. Modern Growth

When A_{nt} grows sufficiently fast, the relative productivity $A_{nt}/\widetilde{A}_{at}$ will continue to rise such that it eventually reaches threshold Φ_h. Thereafter, the economy enters into an era of modern growth with the complete adoption of modern technology.

Proposition 5 *Let* $\widetilde{A}_{at}^M = \left(\widetilde{A}_{at}\right)^{\frac{\sigma(1-\alpha)}{\alpha+\sigma(1-\alpha)}} A_{nt}^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}}$. *Then, in a modern economy, we have*

$$p_t = \sigma(1-\alpha)\left(\frac{\alpha}{\sigma(1-\alpha)}\right)^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}} \overline{c}^{-\frac{(1-\sigma)(1-\alpha)}{\alpha+\sigma(1-\alpha)}} \frac{\widetilde{A}_{at}^M}{A_{nt}}, \tag{13}$$

$$w_t = \sigma(1-\alpha)\left(\frac{\alpha}{\sigma(1-\alpha)}\right)^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}} \overline{c}^{-\frac{(1-\sigma)(1-\alpha)}{\alpha+\sigma(1-\alpha)}} \widetilde{A}_{at}^M, \tag{14}$$

$$r_t = (1-\alpha)(1-\sigma)\overline{c}\frac{N_t}{\overline{Z}}, \tag{15}$$

$$y_t = (1-\alpha)\left[1-\sigma+\sigma\overline{c}^{-\frac{1}{\alpha+\sigma(1-\alpha)}}\left(\frac{\alpha}{\sigma(1-\alpha)}\right)^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}} \widetilde{A}_{at}^M\right]\overline{c}, \tag{16}$$

$$\frac{L_{at}}{N_t} = \overline{c}^{\frac{1}{\alpha+\sigma(1-\alpha)}}\left(\frac{\sigma(1-\alpha)}{\alpha}\right)^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}} \widetilde{A}_{at}^{M-1}. \tag{17}$$

In this modern economy, the wage rate is a linear function of $\widetilde{A}_{at}^M = \left(\widetilde{A}_{at}^T\right)^{\frac{\sigma(1-\alpha)}{\alpha+\sigma(1-\alpha)}} A_{nt}^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}}$, which is a geometric average of the TFP levels in the two sectors. Therefore, TFP growth in both sectors contributes to the growth of per capita income. The growth rate of $\widetilde{A}_{at}^{M}$ is given by

$$\begin{aligned}
\frac{\widetilde{A}_{at+1}^{M}}{\widetilde{A}_{at}^{M}} &= \left(\frac{\widetilde{A}_{at+1}^{T}}{\widetilde{A}_{at}^{T}}\right)^{\frac{\sigma(1-\alpha)}{\alpha+\sigma(1-\alpha)}} \left(\frac{A_{nt+1}}{A_{nt}}\right)^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}} \\
&= \left(\frac{A_{at+1}}{A_{at}}\right)^{\frac{\sigma(1-\alpha)}{\alpha+\sigma(1-\alpha)}} \left(\frac{A_{nt+1}}{A_{nt}}\right)^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}} [g(y_t)]^{-\frac{(1-\sigma)(1-\alpha)}{\alpha+\sigma(1-\alpha)}}.
\end{aligned}$$

Suppose that A_{at} and A_{nt} grow at constant rates, γ_a and γ_n. Then, the growth rate of $\widetilde{A}_{at}^{M}$ becomes $\widetilde{A}_{at+1}^{M}/\widetilde{A}_{at}^{M} = (\gamma_a)^{\frac{\sigma(1-\alpha)}{\alpha+\sigma(1-\alpha)}} (\gamma_n)^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}} [g(y_t)]^{-\frac{(1-\sigma)(1-\alpha)}{\alpha+\sigma(1-\alpha)}}$.Therefore, as long as $(\gamma_a)^{\sigma(1-\alpha)} (\gamma_n)^{\alpha} > [g(\widehat{y})]^{(1-\sigma)(1-\alpha)}$, $\widetilde{A}_{at}^{M}$ will grow without bounds, as will per capita income.

Summarizing all of the foregoing results, we have the following.

Proposition 6 *Under Assumption 1 and the assumption that* $(\gamma_a)^{\sigma(1-\alpha)} (\gamma_n)^{\alpha} > [g(\widehat{y})]^{(1-\sigma)(1-\alpha)}$, *an economy that starts out in a Malthusian steady state will at some point move into a mixed economy and, eventually, into a modern economy with sustained growth in per capita income. During this process, the relative price of nonagricultural goods declines in a traditional economy, remains constant in a mixed economy, and then declines further in a modern economy. The employment share of agriculture starts to decline in the mixed economy period and converges to zero in the modern economy. Land rent increases with population growth in both the traditional and modern economy, and it also depends on the relative productivity growth during the transition period. Finally, the real wage remains flat in a Malthusian regime, but begins to grow at the onset of the transition and indefinitely into the future.*

5 Quantitative Analysis of the English Economy, 1700-1909

In this section, we examine whether our calibrated model can quantitatively account for the growth experience of England from 1700 to 1909. We focus on long-term trends, structural breaks, and coordinated movements across the six key macroeconomic variables—per capita GDP, relative price, agricultural mechanization, farm employment share, real wage of agricultural workers, and land rent. We first describe our data sources and characterize the major trends in the English economy, followed by model calibration and a discussion of our findings.

A. Data Compilation

Our quantitative analysis employs data on the aggregate economic performance of the English economy for the 1700 to 1909 period. The selection of this country is significant, not only because the Industrial Revolution first occurred in England, but also because of the availability of exceptionally rich historical data. We use England rather than the United Kingdom as the unit of analysis because data for Wales, Scotland, and Northern Ireland are incomplete for early historical periods. We choose 1700 as our starting year, as several data series—including by-sector employment share and industrial output—are unavailable for earlier historical periods. Our coverage ends in 1909, the year that concludes the first decade of the twentieth century, as World War I is considered to have opened another historical era. The 1700-1909 period is long enough to span across the essential stages of the transition from stagnation to growth in England, encompassing the Industrial Revolution.

We construct the data series on a decennial basis, emphasizing long-term trends with no attempt to account for short-term fluctuations. A decade consists of 10 years starting with a rounded year of 10, i.e., 1700-1709; by this principle, 1909 marks the ending year of analysis. Although data for 1910 to 1912 are available, we do not use three-year data to represent decennial trends. The data series consists of constructed indices of real per capita GDP, population, employment share in agriculture, indices of agricultural mechanization, prices of agricultural products, prices of principal industrial products, real average day wages of adult farm workers, land rent, and food imports as a percentage of domestic production. Moreover, we rely on historical studies of the English economy to obtain estimates for exogenous improvements in total factor productivity in both agricultural and nonagricultural production.

Our data compilation is based on an extensive review of statistical sources, as well as historical studies of the British economy. Completeness and reliability are two important criteria. Hence, our data are drawn heavily from two authoritative volumes of British historical statistics complied by B. R. Mitchell (1962, 1988), who assembled the best available data from government sources, censuses, historical studies, economists, statisticians, and independent scholarly publications. When certain data series are not available in Mitchell's volumes, or cannot be traced back to 1700, we have explored other historical studies. For example, we have relied on the works of Clark (2001, 2002, 2004), Crafts and Harley (1992), Deane and Cole (1967), and Wrigley and Schofield (1981), among those of other scholars. Our sources and the construction of all of the key variables are described in greater detail in Appendix B.

B. The English Economy, 1700-1909

Table 1 presents historical statistics on the English economy, encompassing the entire course of the Industrial Revolution. In the period up to 1820, real per capita GDP fluctuated around a constant level, exhibiting typical features of a Malthusian regime. The employment share in agriculture declined gradually, which is consistent with slow increases in agricultural productivity. Starting in the early 1800s, however, the growth of per capita GDP and the pace of structural transformation began to accelerate. Then, in the decades between 1820-9 and 1900-9, per capita GDP increased by a factor of 1.88, and the employment share of agriculture dropped from 33 percent to 10 percent. By 1909, England was far ahead of other countries in the extent of its structural transformation, and had clearly left behind the stagnation of the Malthusian regime.

The escape from Malthusian stagnation occurred concurrently with the modernization of agriculture as revealed by the adoption and diffusion of farm mechanization in England in the early 1800s. Despite the sparsity of historical data, John Walton creatively used farm sale advertisements to quantify the adoption of farm machines for selective regions of England and Wales for the years from 1753 to 1880 (see Walton, 1979; Overton, 1996; also see the details provided in Appendix B). Figure 2 reports the percentage of the dispersal sales of farm stocks containing eight specific types of farm machinery. The use of threshing, haymaking, and chaff machines began around 1810, and the adoption of turnip cutters steadily continued from around 1820. The diffusion of these machines, except for threshing machines, continued in an uptrend until 1880. Columns (6) and (7) of Table 1 present the computed probabilities of a farm's adoption of at least one and at least two agricultural machines, respectively, during individual decades. In the case of two machines, the rate of their possession by a typical farm was only 2 percent in 1810-9, but had zoomed to 85 percent by 1880-9.[12]

A central implication of our model is that the price of industrial goods relative to agricultural goods falls continuously in the Malthusian steady state as a result of industrial TFP growth [see equation (9)]. Then, during the transition to modern growth, the relative price should settle at a constant level, as equation (10) demonstrates. The observed English experience shows exactly this pattern (see Figure 1B). More specifically, as column (2) of Table 1 reveals, the relative price index declined rather persistently from 2.14 in 1700-9 to 1 in 1820-9, and then fluctuated at around that level thereafter. Note that the constructed rela-

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The timing of farm mechanization suggested by these historical data appears to be several decades behind the schedule assumed in the study by Gollin, Parente and Rogerson (2007). They assume that the process of mechanization in England finished by 1805.

tive price is based on price indices of agricultural outputs and principle industrial products, where the latter comprise of both intermediate inputs for industrial production as well as final goods. Admittedly, more direct measures for the price of industrial machinery or capital goods would be better indictors for the costs of agricultural machinery, which influence their adoption in farming. However, such historical prices on industrial machinery are not available until much later years, as explained in the data appendix. Given that the prices of principle industrial products are closely correlated with the prices of industrial machinery or capital goods, we compare the constructed relative price with model-predicted price in quantitative analysis. Because of this data caveat, caution is needed to interpret the fitting of these two price series.

Table 1 also shows the systematic patterns for real land rents and the real wage of agricultural workers. The real wage remained flat for more than a century, but began to rise persistently after 1820. Throughout the period, real land rents exhibited an upward pattern, although the extent of the rise appears to have been more pronounced in the first rather than the second period.

C. Incorporating Food Trade

We have so far presented a closed economy model without any discussion of international trade. It is well known, however, that England was a net food exporter in the first half of the 18th century, and then turned into a net importer towards the end of that century (see Overton, 1996; Deane and Cole, 1967). Table 1 suggests that food exports began to decline around 1740-9, followed by an initially gradual growth in food imports—net imports relative to domestic production were merely 1 percent in 1780-9, but the ratio increased steadily to 17 percent in 1850-9. However, soon after the repeal of the English Corn Law, food imports exploded, finally reaching 76 percent of domestic production by 1900-9. Such changes in food trade would clearly affect the pace of structural transformation and possibly the time paths of the other macroeconomic variables for the English economy. Therefore, it is necessary to incorporate food trade into the benchmark model before moving on to carry out quantitative analysis.

Following the approach adopted by Stokey (2001), who observes that England already imported significant amounts of food in the 1820s, and exported roughly equal amounts of manufactured goods in terms of value-added, we take food imports as exogenous and assume balanced trade, such that the value of exports in nonagricultural goods is determined by the need to import food. Denote i_t as the percentage of food imports relative to domestic food production for year t. The market clearing conditions for agricultural and nonagricultural goods become

$$(1+i_t)Y_{at} = N_t\overline{c} \text{ and } Y_{nt} = N_t c_{nt} + X_t + E_t, \tag{18}$$

where E_t is the amount of exports in nonagricultural goods. We assume balanced trade, i.e., $p_t^w E_t = i_t Y_{at}$,where p_t^w is the relative price of nonagricultural goods in the world market. As in Stokey (2001), we take p_t^w as an exogenous variable and assume that it remains at a level such that trade is welfare-enhancing for domestic households at the margin. In Appendix A, we show that this requires p_t^w to be greater than or equal to the relative price of nonagricultural goods under autarky. The solutions to this model with trade are identical to that of the benchmark model with one exception: the subsistence consumption requirement changes to $\overline{c}/(1+i_t)$. With food trade now specified in the framework, we can proceed to examine whether our model can quantitatively account for the growth experience of the English economy.

D. Model Calibration

For this quantitative exercise, each period in the model consists of 10 years, with the initial period starting in 1700-9. We assume that the model economy is initially a traditional one with no modern technology used in agriculture; then, in the 1820-9 period, it begins agricultural modernization, or the transition to modern growth. The technology parameters, subsistence consumption, initial TFP levels, and population growth profiles are calibrated. We then feed the TFP growth rates estimated from the historical data into the model to generate time series predictions for six key variables—per capita GDP, relative price, agricultural mechanization, farm employment share, real wage of agricultural workers, and land rents—and compare them to their counterparts in the data. The details are as follows.

Technology parameters. We set the labor share in traditional agriculture σ at 0.6, consistent with Hansen and Prescott (2002) and Ngai (2004). Following Restuccia, Yang and Zhu (2008), we set the share of intermediate input in modern agriculture α at 0.4.[13] The value of land endowment $\overline{Z}$ is normalized to one.

Initial values. We normalize the initial value of income y_0 to 1 and set N_0 as the population level of England in 1700. From equations (6) and (7), $y_t = \left[1-\sigma+\sigma\left(L_{at}/N_t\right)^{-1}\right]\overline{c}$

[13] As such, we use farm mechanization as a proxy for agricultural modernization as formulated in the model. We consider 10 years to be a reasonable life span for farm machinery in 19th century England. In modern agriculture, most equipment and machines retain 20-50% of their initial value after 10 years of normal usage (Cross and Perry, 1995). Given that the durability of machines in the early stage of farm mechanization are likely to be shorter than that of modern machines, full depreciation of machinery in 10 years appears broadly consistent with facts.

holds in a traditional economy. In the case with food imports, this equation becomes $y_t = \left[1 - \sigma + \sigma \left(L_{at}/N_t\right)^{-1}\right] \left[\bar{c}/(1+i_t)\right]$ .Clark (2002) states that the fraction of labor in agriculture in England in 1700-9 was 0.55. Hence, we can use the foregoing equation to pin down the value of $\bar{c}$ such that the implied initial income level y_0 in the model is 1. Given N_0 and the calibrated value of $\bar{c}$, we can then use equation (7) adjusted for food imports to pin down the value of A_{a0} such that the implied value of L_{a0}/N_0 in the model is 0.55. Because agricultural mechanization emerged in England in the early nineteenth century, or around 1820-9 to be more precise (Walton, 1979; Overton, 1996), we choose the initial value of A_{n0}, such that, in our model, the use of modern agricultural technology begins in that decade.

Population growth profile. We assume that population growth follows the same functional form as that in Hansen and Prescott (2002), and we use England's observed decennial population growth rates and per capita income levels to estimate the parameters of the function. Similar to their schedule, this estimated population growth function increases linearly at low income levels and then starts declining at a slower rate through a linear scheme.

Total factor productivity growth. It is important to differentiate between gross-output and value-added production functions in calibrating TFP growth rate (Ngai and Samaniego, 2009). In the appendix, we show that the real agricultural value-added is always $(A_{at}L_{at})^{\sigma}\,\overline{Z}^{1-\sigma}$ whether our model economy is in traditional or mixed regimes. Therefore, the growth rate of agricultural TFP A_{at} is simply

$$\frac{1}{\sigma}\text{(growth rate of agricultural value-added) - growth rate of labor force in agriculture.}$$

Clark (2002) provides historical estimates for England of both agricultural value-added (net output) and labor force in agriculture by decades. We use those two data series and the formula above to calculate the decennial TFP growth rate for the 1700-1910 period. As Clark points out, agricultural TFP grew at a slow rate prior to 1860 and shifted to a faster growth period thereafter. Accordingly, we assume that A_{at} grows at a decennial constant rate of γ_{a1} for the 1700-1860 period and then grows at a constant rate of γ_{a2} for the subsequent period. For each of the two periods, $i = \{1, 2\}$, we regress $log(TFP)$ on a time trend to obtain slope coefficient ξ_i, which is the decennial exponential growth rate. We then calculate γ_{ai} according to the formula $\gamma_{ai} = \exp(\xi_i)$.

With regard to TFP growth in nonagriculture, the pioneering work of Deane and Cole (1967) presents estimates of the aggregate economic performance of the British economy for the 1688-1959 period. However, as most economic historians agree, net output (or value-added) growth during the Industrial Revolution was much slower than Deane and Cole's original estimates indicate. To obtain an estimate of A_{nt} for England, we thus rely on the revised estimates of British industrial value-added made by Crafts and Harley (1992) as the primary data source, assuming that nonagricultural TFP growth were the same across regions in Great Britain. Their results are widely accepted among economic historians, and have been used in recent quantitative studies of the aggregate performance of the British economy (e.g., Stokey, 2001).

We use estimates of the net output growth per worker in British industrial production to approximate exogenous improvements in TFP for the nonagricultural sector, i.e. $\triangle A_n/A_n = \triangle Y_n/Y_n - \triangle L_n/L_n$, an approach that is consistent with our model specification of linear production technology $Y_{nt} = A_{nt}L_{nt}$. More specifically, we first use the indices of British industrial production for the 1700-1909 period, as covered in Crafts and Harley (1992), to compute the rate of industrial net output growth ($\triangle Y_n/Y_n$). Crafts and Harley estimated the annual growth rate of British industrial labor ($\triangle L_n/L_n$) as 0.8 percent for the 1760-1801 period and 1.4 percent for the 1801-1831 period; therefore, the decennial growth rate of A_{nt} for the 1760-1831 period can be inferred. For 1831-1909, we compute the decennial growth of the industrial labor force based on the British population census reported in Mitchell (1962). For the earlier period, 1700-1760, Clark (2002) reports both the share of the adult male labor force in agriculture (s_a) and estimates of that labor force (L_a) by decade; therefore, we can compute the decennial nonagricultural labor force, i.e., $L_n = L_a(1-s_a)/s_a$. By assuming that the labor force in the nonagricultural sector grew at a similar rate as that in the industrial sector, we can obtain nonagricultural TFP growth for the 1700-1760 period.

E. Simulation Results

The primary objective of our model is to illuminate the transition mechanisms of stagnation to growth, highlighting the causal linkages among several macroeconomic variables over the very long run. Although it is not our intention to provide a detailed model of the English growth experience, the success of our calibration certainly helps to validate the model's relevance. In this vein, we compare the model's predictions for the six major variables with data for the English economy over the 1700-1909 period.

Figure 3 presents the time paths of the variables—actual data series versus model simulations with and without food trade. Figure 3C, which reports the computed probabilities of adopting at least one (data 1) and at least two (data 2) agricultural machines on a farm during the individual decades, reveals the transition paths from traditional to mixed and modern economies.[14] In the traditional economy that existed before 1800-19, farms used only the old technology, as the model implies. Agricultural mechanization began around 1800-19, and the transition to modern growth took about eight periods (or decades), ending in 1890-9 with the complete adoption of the new technology.

Overall, the time paths of the variables predicted by the model track the structural breaks and systematic trends that occurred in the English economy over more than two centuries well. In the periods before 1820-9, the economy was settled in the Malthusian steady state, where per capita GDP (Figure 3A) and the real wage (Figure 3E) both remained constant. The growth in industrial TFP led to a persistent decline in the relative price (Figure 3B), but before this price reached a low threshold level, farmers did not find it profitable to use modern productive inputs, which resulted in no adoption of farm machinery (Figure 3C). Therefore, agricultural productivity remained at a low level because of diminishing returns to labor due to the fixed supply of land. The closed economy model implies that there was no structural transformation during this period because the low level of agricultural productivity limited the release of labor to industry (Figure 3D). For England, however, the switch in its trade position from exporting to importing food facilitated structural transformation. Indeed, along with increases in net food imports, the employment share in agriculture began a steady decline in the middle of the 18th century, although the economy remained trapped in the Malthusian regime (Figure 3D).

Starting in 1820-9, when continuous industrial development pushed the relative price down to a low enough critical level, profit-maximizing farmers began to adopt the modern input produced by the industrial sector. This agricultural modernization then triggered a virtuous cycle. As farmers substituted modern agricultural inputs for labor, structural transformation accelerated. As a result, per capita income emerged from stasis and began its high rate of growth. This is because once agricultural modernization begins, the TFP growth in industry joins forces with it, thus contributing to aggregate growth [see equation (11)]. During the transition, the model's predicted relative price settles to a constant, which is consistent with the data. By and large, the predicted wage (Figure 3E) and land rent (Figure 3F) also track the data well. Although the rent displays an upward pattern,[15] the

[14] We use the estimated probability of adopting agricultural machinery as our measure of agricultural modernization because historical data on the percentage of land and labor allocated to modern technology are not readily available. This variable is closely matched with the measure of modern technology adoption specified in the model, which is the fraction of productive inputs (land and labor) devoted to the new technology.

[15] The model tracks the data well in the period before 1820, as a larger popuation has a direct and positive

real wage remains flat for more than a century, but then rises persistently.

Despite the success of model simulations in matching the general time paths of all six macroeconomic variables, two noticeable discrepancies remain. The first is that the observed relative price declines more significantly than the predicted changes in the model in the first century, although the downward trends are very similar. This disparity could be the result of imperfect data measurement: the composition of modern agricultural inputs modeled in the paper may not match perfectly with the principle industrial products comprised in the data. Because remarkable innovations in the early stage of the Industrial Revolution involved the substitution of energy for human power and technological advances in metallic and textile industries, efficiency gains in major components of principle industrial products could outpace technological advances in capital goods and intermediate inputs in farming. This view is consistent with the evidence that the decline in the relative price in the data accelerated between 1760 and 1820, a period which accounts for a large portion of the disparity of fitting the model to the data.

The second inconsistency relates to the land rent: whereas the data indicates a continuous increase throughout the period under study, the predicted land rent exhibits several decades of significant declines after 1820. Two factors may have contributed to this mismatch. To focus on the role of agriculture in growth, we have only modeled the use of land in farming and ignored the demand for land from residential, industrial and urban development. Therefore, when agricultural modernization begins with the adoption of industry-supplied inputs, the demand for land, and thus its price, falls in the model. In reality, however, the increased demand for land stemming from household income growth and industrial development could more than compensate for the reduced demand for farm land, resulting in a rise in land rent. Another factor relates to policies and institutions. In the decades surrounding the repeal of the English Corn Law, national food imports as a fraction of domestic production jumped by double-digit percentage points (see Table 1). In our model with trade, large increases in food imports would substitute for domestic food production, which in turn would reduce the demand for agricultural inputs. This theoretical result is unlikely to be fully revealed in the data because farmers would continue to farm the land at least in the short run, despite the reduced demand for domestic food production. We should stress that, after short periods of decline, land rents eventually return to their upward trend, thus conforming with the patterns revealed in the data. Overall, the simulation results support a coherent and unified view of

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effect on land rent [see equation (5)]. During the transition, however, the determination of land rent becomes more complex, as equation (10) suggests.

the importance of agricultural modernization in making the transition from stagnation to growth.

6 Concluding Remarks

History has witnessed persistent technological advances.[16] Long before the Industrial Revolution, the Greeks and Romans discovered cement masonry, developed sophisticated hydraulic systems, and made great strides in advancing civil engineering and architecture. The inventions developed in China, including paper, printing, the magnetic compass and gun powder, raised production efficiency through diverse channels. In the Middle Ages, dramatic improvements in energy utilization through the use of windmills, waterwheels, and horse technologies effectively expanded the frontiers of production, and the creation of the mechanical clock marks the entry of a key machine of the modern industrial age. Turning to the Renaissance, in addition to its remarkable scientific achievements, innovations in shipbuilding, mining techniques, spinning wheels for textile production, and the use of blast furnaces raised the capacity of industrial production to new levels. Why then did these major technological advances fail to generate sustained improvement in living standards?

We have argued in this paper that productivity growth in industry during early development is not enough to pull an economy out of a stagnant equilibrium. This is because the low level of labor productivity associated with traditional agriculture requires much of the labor force to produce food, thus imposing a constraint on per capita income growth. The decline in the relative price of industrial output not only reflects technological progress in industry, but also acts as an agent—when it falls below a critical level—inducing farmers to adopt modern technology that relies on industry-supplied inputs. Agricultural modernization ignites the transition to modern growth. Our analysis compliments the existing explanations for this transition that focus on the role played by technological change and human capital accumulation. For instance, when structural transformation accelerates along with the modernization of agriculture, the rate of return to human capital is likely to rise because the dynamic environment of industry provides higher rewards for skill. Consequently, families will invest more in human capital and have fewer children. The average fertility rate will drop further because of a declining percentage of rural families. The emphasis on agricultural technology also provides specific content for long-term technological progress, thus allowing

[16] See Mokyr (1990) for a summary of technological progress from the classical antiquities to the modern era of the later nineteenth century.

us to explore the timing and coordinated movements in macroeconomic variables through the transition from stagnation to growth.

Farm mechanization in England was only the beginning of agricultural modernization. In the past two centuries, the development of farm technology has been integrated into the rapidly expanding and increasingly complex systems of industrial and scientific advancements. The application of chemical and biological science has led to numerous inventions and has reduced the costs of fertilizers and new seeds, which have vastly improved agricultural productivity. In the United States, for instance, the labor employed on farms to produce a ton of wheat or corn in the 1980s was about 1-2 percent of the labor needed in 1800, and for a bale of cotton, only 1 percent (Johnson, 1997). In the twentieth century, labor productivity growth in agriculture has generally outpaced that in other sectors of industrialized economies. The modernization of agriculture has been a crucial force driving sustained growth. In contrast, agricultural labor productivity in less developed countries, where there is little use of modern inputs, is very low. As Restuccia, Yang and Zhu (2008) show, agricultural GDP per worker in the richest 5 percent of countries in 1985 was 78 times that of the poorest 5 percent, whereas their GDP per worker in nonagricultural sectors differed only by a factor of 5. Therefore, as our theory suggests, the provision and implementation of locally productive modern technologies in agriculture may contribute a great deal in helping the poorest countries escape from economic stagnation. The modernization of agriculture should be a central component of any development policy.

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Table 1: Historical Statistics of England: 1700-1909

Year	Real per capita GDP (1)	Relative price (Pn/Pa) (2)	Employment share in agriculture (3)	Real wage agricultural labor (4)	Real land rent (5)	Farm machines n≥1 (6)	Farm machines n≥2 (7)	Food imports as fraction of domestic production (%) (8)
1700-9	0.80	2.14	0.55	1.01	0.62	0.00	0.00	-0.02
1710-9	0.79	1.89	0.54	0.95	0.64	0.00	0.00	-0.03
1720-9	0.83	1.83	0.53	0.97	0.69	0.00	0.00	-0.04
1730-9	0.93	1.91	0.52	1.13	0.73	0.00	0.00	-0.05
1740-9	0.85	1.95	0.52	1.10	0.67	0.00	0.00	-0.07
1750-9	0.86	1.77	0.53	1.01	0.77	0.00	0.00	-0.06
1760-9	0.84	1.83	0.49	0.98	0.75	0.00	0.00	-0.03
1770-9	0.85	1.59	0.47	0.92	0.75	0.00	0.00	-0.01
1780-9	0.82	1.71	0.44	0.97	0.74	0.00	0.00	0.01
1790-9	0.82	1.54	0.40	0.89	0.75	0.04	0.00	0.04
1800-9	0.84	1.29	0.37	0.81	0.75	0.07	0.00	0.06
1810-9	0.91	1.13	0.35	0.87	0.87	0.23	0.02	0.09
1820-9	1.00	1.00	0.33	1.00	1.00	0.42	0.07	0.11
1830-9	1.02	0.97	0.30	1.05	1.01	0.49	0.09	0.13
1840-9	1.06	0.96	0.26	1.11	1.08	0.75	0.29	0.15
1850-9	1.07	1.08	0.24	1.18	1.08	0.85	0.48	0.17
1860-9	1.08	1.03	0.21	1.18	1.11	0.91	0.62	0.24
1870-9	1.23	0.94	0.17	1.44	1.19	0.95	0.77	0.46
1880-9	1.40	0.90	0.15	1.69	1.24	0.98	0.85	0.56
1890-9	1.61	0.91	0.12	2.02	1.26	N.A.	N.A.	0.66
1900-9	1.88	1.04	0.10	2.08	1.13	N.A.	N.A.	0.76

Note: the figures in columns (1), (2), (4) and (5) are indices of the corresponding variables with their 1820-09 values normalized to one. Columns (6) and (7) report the computed probabilities of a farm adopting at least one and at least two agricultural machines, respectively, during individual decades. See Appendix B for details on how these time series were constructed.

Figure 1. Real Per Capita GDP and the Relative Price
of Industrial and Agricultural Products in England, 1700-1909

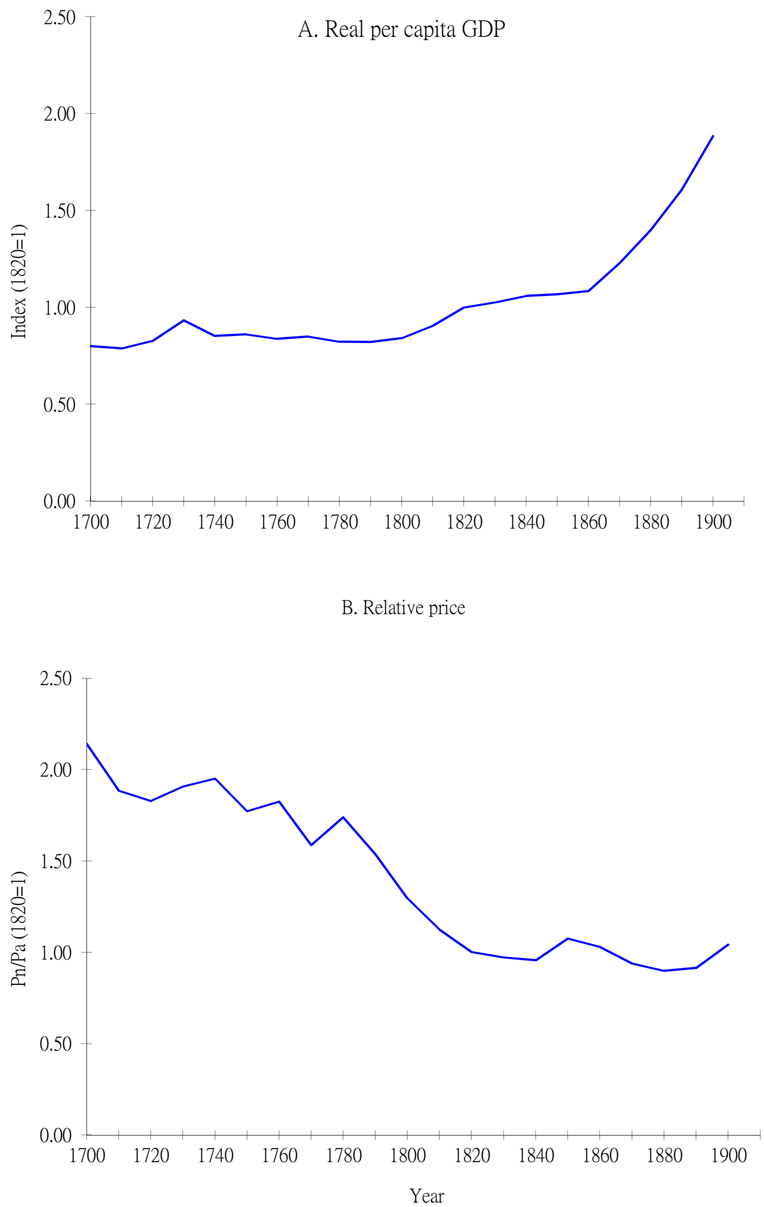
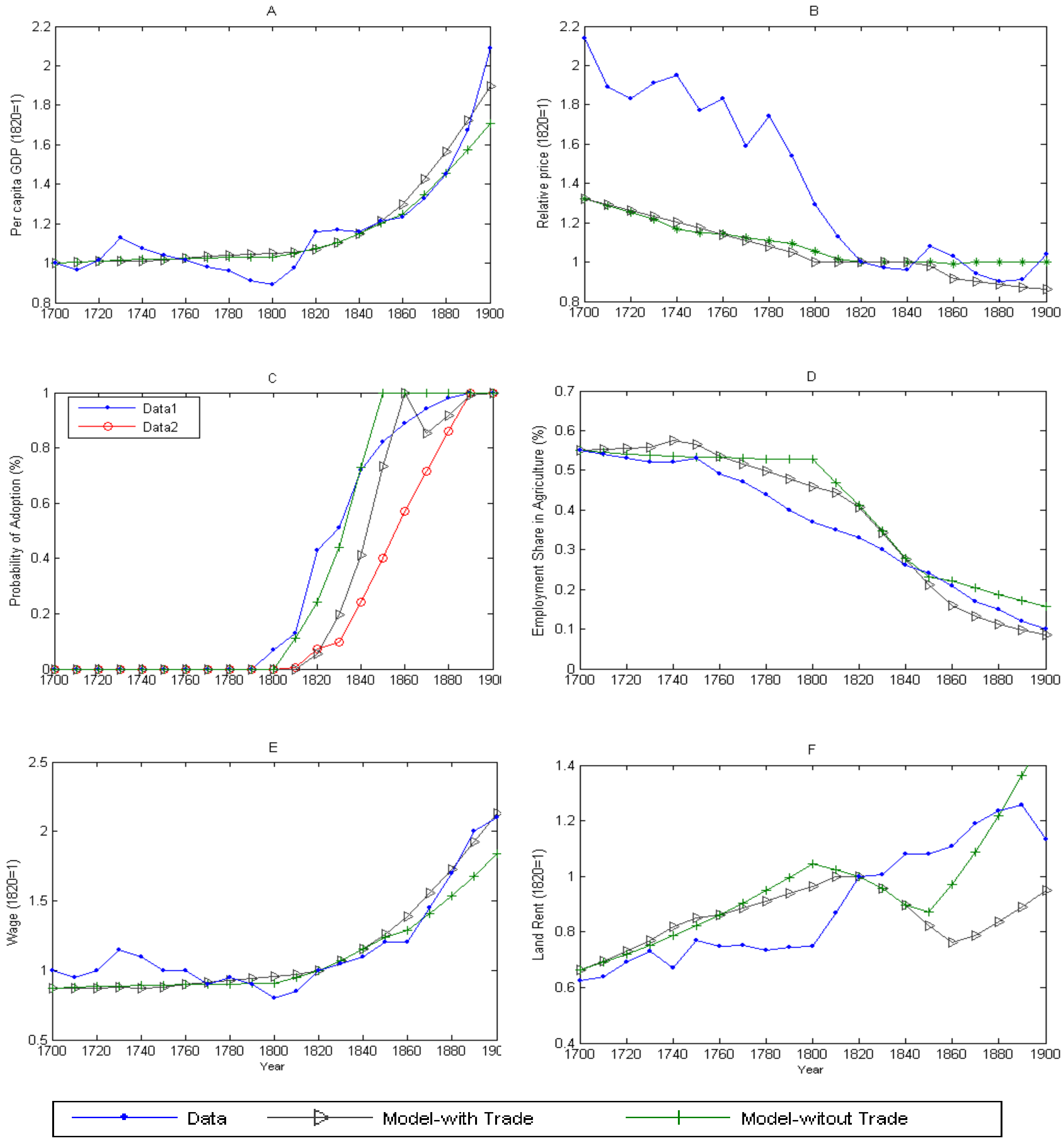


Figure 2. Percentage of Farms Adopted Agricultural Machinery for Oxfordshire Regions in England: 5-year Moving Means

Source: Walton (1979).

Figure 3. Trends in Major Macroeconomic Variables in England:
Data and Simulations with and without Trade, 1700-1909



Note: Data 1 and 2 in the left middle panel are the computed probabilities of a farm adopting at least one and at least two agricultural machines, respectively, in individual decades.

Appendix: Not for Publication

A. Proofs of the Propositions

Proof of Proposition 1

Let $\widetilde{A}_{at} = A_{at}(\overline{Z}/N_t)^{\frac{1-\sigma}{\sigma}}$. We first solve for the equilibrium prices in the three possible cases.

(1) Traditional technology only: $Y_{at}^T = \overline{Z}^{1-\sigma}(A_{at}L_{at})^\sigma$. From the market clearing conditions, we have $N_t\overline{c} = \overline{Z}^{1-\sigma}(A_{at}L_{at})^\sigma$, which implies that

$$\begin{aligned}
\frac{L_{at}}{N_t} &= \overline{c}^{\frac{1}{\sigma}}\widetilde{A}_{at}^{-1}, \\
w_t &= \sigma\frac{Y_{at}}{L_{at}} = \sigma\frac{Y_{at}}{N_t}\left(\frac{L_{at}}{N_t}\right)^{-1} = \sigma\overline{c}^{\frac{\sigma-1}{\sigma}}\widetilde{A}_{at}, \\
p_t^T &= \frac{w_t^T}{A_{nt}} = \sigma\overline{c}^{\frac{\sigma-1}{\sigma}}\frac{\widetilde{A}_{at}}{A_{nt}}.
\end{aligned}$$

(2) Modern technology only: $Y_{at} = \left(\frac{\alpha}{p_t}\right)^{\alpha/(1-\alpha)}\overline{Z}^{1-\sigma}(A_{at}L_{at})^\sigma$. Again, from the market clearing conditions, we have $N_t\overline{c} = (\alpha/p_t)^{\alpha/(1-\alpha)}\,\overline{Z}^{1-\sigma}(A_{at}L_{at})^\sigma$, which implies that

$$\frac{L_{at}}{N_t} = \overline{c}^{\frac{1}{\sigma}}\widetilde{A}_{at}^{-1}\left(\frac{\alpha}{p_t}\right)^{-\frac{\alpha}{\sigma(1-\alpha)}}.$$

We have the wage equation

$$w_t = \sigma(1-\alpha)\frac{Y_{at}}{L_{at}} = \sigma(1-\alpha)\frac{Y_{at}}{N_t}\left(\frac{L_{at}}{N_t}\right)^{-1} = \sigma(1-\alpha)\overline{c}^{\frac{\sigma-1}{\sigma}}\left(\frac{\alpha}{p_t}\right)^{\frac{\alpha}{\sigma(1-\alpha)}}\widetilde{A}_{at}.$$

From the labor market condition $w_t = p_tA_{nt}$, we have

$$\sigma(1-\alpha)\overline{c}^{\frac{\sigma-1}{\sigma}}\left(\frac{\alpha}{p_t}\right)^{\frac{\alpha}{\sigma(1-\alpha)}}\widetilde{A}_{at} = p_tA_{nt}$$

which yields the following

$$\begin{aligned}
p_t^M &= \left(\frac{\sigma(1-\alpha)\widetilde{A}_{at}}{A_{nt}}\right)^{\frac{\sigma(1-\alpha)}{\alpha+\sigma(1-\alpha)}}\alpha^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}}\overline{c}^{-\frac{(1-\sigma)(1-\alpha)}{\alpha+\sigma(1-\alpha)}} \\
&= \sigma(1-\alpha)\left(\frac{\alpha}{\sigma(1-\alpha)}\right)^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}}\overline{c}^{-\frac{(1-\sigma)(1-\alpha)}{\alpha+\sigma(1-\alpha)}}\frac{\widetilde{A}_{at}^M}{A_{nt}},
\end{aligned}$$

where $\widetilde{A}_{at}^{M} = \left(\widetilde{A}_{at}^{T}\right)^{\frac{\sigma(1-\alpha)}{\alpha+\sigma(1-\alpha)}} A_{nt}^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}}$, and

$$\begin{aligned}
\frac{L_{at}}{L_t} &= \overline{c}^{\frac{1}{\alpha+\sigma(1-\alpha)}} \left(\frac{\sigma(1-\alpha)}{\alpha}\right)^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}} \widetilde{A}_{at}^{M-1}, \\
w_t &= p_t A_{nt} = \sigma(1-\alpha) \left(\frac{\alpha}{\sigma(1-\alpha)}\right)^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}} \overline{c}^{-\frac{(1-\sigma)(1-\alpha)}{\alpha+\sigma(1-\alpha)}} \widetilde{A}_{at}^{M}.
\end{aligned}$$

(3) Both technologies are used: In this case, we have

$$\begin{aligned}
w_t &= \sigma(1-\alpha) \left(\frac{\alpha}{p_t}\right)^{\frac{\alpha}{1-\alpha}} A_{at}^{\sigma} \left(\frac{Z_t^M}{L_{at}^M}\right)^{1-\sigma} = \sigma A_{at}^{\sigma} \left(\frac{Z_t^T}{L_{at}^T}\right)^{1-\sigma} \\
1 &= (1-\alpha) \left(\frac{\alpha}{p_t}\right)^{\frac{\alpha}{1-\alpha}}.
\end{aligned}$$

Thus, we have

$$\begin{aligned}
\frac{Z_t^M}{L_{at}^M} &= \frac{Z_t^T}{L_{at}^T} = \frac{\overline{Z}}{L_{at}}, \\
w_t &= \sigma A_{at}^{\sigma} \left(\frac{\overline{Z}}{L_{at}}\right)^{1-\sigma} = \sigma \widetilde{A}_{at}^{\sigma} \left(\frac{L_{at}}{N_t}\right)^{\sigma-1}, \\
p_t^{mixed} &= \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}}.
\end{aligned}$$

From the labor market condition, $w_t = p_t A_{nt}$, we have

$$\begin{aligned}
\frac{L_{at}}{N_t} &= (1-\alpha)^{\frac{\alpha-1}{\alpha(1-\sigma)}} \left(\frac{\sigma}{\alpha A_{nt}}\right)^{\frac{1}{1-\sigma}} \widetilde{A}_{at}^{\frac{\sigma}{1-\sigma}}, \\
w_t &= \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}} A_{nt}.
\end{aligned}$$

For given $\widetilde{A}_{at}$ and A_{nt}, the economy uses traditional technology if and only if

$$(1-\alpha)\left(\frac{\alpha}{p_t^T}\right)^{\frac{\alpha}{1-\alpha}} \leq 1$$

and

$$(1-\alpha)\left(\frac{\alpha}{p_t^M}\right)^{\frac{\alpha}{1-\alpha}} < 1.$$

This requires that

$$p_t^T = \sigma \overline{c}^{\frac{\sigma-1}{\sigma}} \frac{\widetilde{A}_{at}}{A_{nt}} \geq \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}},$$

$$p_t^M = \left(\frac{\sigma(1-\alpha)\widetilde{A}_{at}}{A_{nt}} \right)^{\frac{\sigma(1-\alpha)}{\alpha+\sigma(1-\alpha)}} \alpha^{\frac{\alpha}{\alpha+\sigma(1-\alpha)}} \overline{c}^{-\frac{(1-\sigma)(1-\alpha)}{\alpha+\sigma(1-\alpha)}} > \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}}.$$

The later inequality is equivalent to

$$\left(p_t^T\right)^{\frac{\sigma(1-\alpha)}{\alpha+\sigma(1-\alpha)}} > \alpha^{\frac{\sigma(1-\alpha)}{\alpha+\sigma(1-\alpha)}} (1-\alpha)^{\frac{1-\alpha}{\alpha} \frac{\alpha(1-\sigma)+\sigma(1-\alpha)}{\alpha+\sigma(1-\alpha)}}$$

or

$$p_t^T > \alpha(1-\alpha)^{\frac{\alpha(1-\sigma)+\sigma(1-\alpha)}{\alpha\sigma}} = \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}} (1-\alpha)^{\frac{1-\sigma}{\sigma}}.$$

Apparently, as long as $p_t^T \geq \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}}$, the above inequality is automatically satisfied. Therefore, the necessary and sufficient condition for the economy to use traditional technology is

$$\sigma \overline{c}^{\frac{\sigma-1}{\sigma}} \frac{\widetilde{A}_{at}}{A_{nt}} \geq \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}},$$

or

$$\frac{A_{nt}}{A_{at}\left(\overline{Z}/N_t\right)^{\frac{1-\sigma}{\sigma}}} \leq \Phi_l$$

For given $\widetilde{A}_{at}$ and A_{nt}, the economy uses modern technology if and only if

$$(1-\alpha)\left(\frac{\alpha}{p_t^T}\right)^{\frac{\alpha}{1-\alpha}} > 1$$

and

$$(1-\alpha)\left(\frac{\alpha}{p_t^M}\right)^{\frac{\alpha}{1-\alpha}} \geq 1.$$

Again, the two conditions can be written as

$$p_t^T = \sigma \overline{c}^{\frac{\sigma-1}{\sigma}} \frac{\widetilde{A}_{at}}{A_{nt}} < \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}},$$

$$p_t^T = \sigma \overline{c}^{\frac{\sigma-1}{\sigma}} \frac{\widetilde{A}_{at}}{A_{nt}} \leq \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}} (1-\alpha)^{\frac{1-\sigma}{\sigma}}.$$

Both will be satisfied if the later is satisfied. So, the necessary and sufficient condition for the economy to use modern technology only is

$$\sigma\overline{c}^{\frac{\sigma-1}{\sigma}}\frac{\widetilde{A}_{at}}{A_{nt}} \leq \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}}(1-\alpha)^{\frac{1-\sigma}{\sigma}},$$

or

$$\frac{A_{nt}}{A_{at}\left(\overline{Z}/N_t\right)^{\frac{1-\sigma}{\sigma}}} \geq \Phi_h.$$

When

$$\Phi_l < \frac{A_{nt}}{A_{at}\left(\overline{Z}/N_t\right)^{\frac{1-\sigma}{\sigma}}} < \Phi_h,$$

neither traditional technology only nor modern technology only can be an equilibrium. The only possible equilibrium is when both technologies are used.

Proof of Proposition 2

The derivations of expressions for price p_t, wage w_t and employment share L_{at}/N_t are already given in the proof of Proposition 1. For the rental price of land, using the property of Cobb-Douglas production function, we have

$$r_t = (1-\sigma)Y_{at}/\overline{Z} = (1-\sigma)N_t\overline{c}/\overline{Z}.$$

Thus,

$$y_t = w_t + r_t\overline{Z}/N_t = \left[1-\sigma+\sigma\overline{c}^{-\frac{1}{\sigma}}\widetilde{A}_{at}\right]\overline{c}.$$

Proof of Proposition 3

In the steady state, equation (8) becomes

$$1 = \gamma_a\left[g(y^*)\right]^{-\frac{1-\sigma}{\sigma}}$$

or

$$g(y^*) = \gamma_a^{\frac{\sigma}{1-\sigma}}.$$

Under Assumption 1, g is continuous and strictly increasing over the interval $[\overline{c}, \widehat{y}]$ and $g(\overline{c}) < 1 \leq \gamma_a^{\frac{\sigma}{1-\sigma}} < g(\widehat{y})$. Therefore, there exists a unique $y^* \in (\overline{c}, \widehat{y})$ such that $g(y^*) = \gamma_a^{\frac{\sigma}{1-\sigma}}$. The corresponding $\widetilde{A}_a^*$ is given by

$$y^* = \left[1-\sigma+\sigma\overline{c}^{-\frac{1}{\sigma}}\widetilde{A}_a^*\right]\overline{c}$$

or

$$\widetilde{A}_a^* = \left[\frac{y^*}{\overline{c}} - 1 + \sigma\right]\sigma^{-1}\overline{c}^{\frac{1}{\sigma}} > 0.$$

Proof of Proposition 4

For the rental price of land, we have

$$r_t = (1-\sigma)Y_{at}^T/Z_t^T = (1-\sigma)\left(A_{at}\frac{L_{at}^T}{Z_t^T}\right)^{\sigma} = (1-\sigma)\left(A_{at}\frac{L_{at}}{\overline{Z}}\right)^{\sigma}.$$

Substituting the expression for L_{at}/N_t derived in the proof of Proposition 1 into the equation above yields the expression for r_t in equation (10). Equation (11) can be derived directly from the expression for w_t derived in the proof of Proposition 1 and the expression for rental price that is just derived. To derive the expression for the percentage of land used for modern agricultural production, note that the goods market clearing conditions require that

$$\begin{aligned} N_t\overline{c} &= (Z_t^T)^{1-\sigma}(A_{at}L_{at}^T)^{\sigma} + \left[(Z_t^M)^{1-\sigma}\left(A_{at}L_{at}^M\right)^{\sigma}\right]^{1-\alpha}X_t^{\alpha} \\ &= (Z_t^T)^{1-\sigma}(A_{at}L_{at}^T)^{\sigma} + \left(\frac{\alpha}{p_t}\right)^{\alpha/(1-\alpha)}(Z_t^M)^{1-\sigma}\left(A_{at}L_{at}^M\right)^{\sigma}. \end{aligned}$$

In the mixed economy, we have

$$(1-\alpha)\left(\frac{\alpha}{p_t}\right)^{\alpha/(1-\alpha)} = 1$$

or

$$\left(\frac{\alpha}{p_t}\right)^{\alpha/(1-\alpha)} = (1-\alpha)^{-1}.$$

So,

$$\begin{aligned} N_t\overline{c} &= (Z_t^T)^{1-\sigma}(A_{at}L_{at}^T)^{\sigma} + (1-\alpha)^{-1}(Z_t^M)^{1-\sigma}\left(A_{at}L_{at}^M\right)^{\sigma} \\ &= Z_t^T\left(A_{at}\frac{L_{at}^T}{Z_t^T}\right)^{\sigma} + (1-\alpha)^{-1}Z_t^M\left(A_{at}\frac{L_{at}^M}{Z_t^M}\right)^{\sigma}. \end{aligned}$$

From the proof of Proposition 1, we have

$$\frac{L_{at}^T}{Z_t^T} = \frac{L_{at}^M}{Z_t^M} = \frac{L_{at}}{\overline{Z}}.$$

So, we have

$$
\begin{aligned}
N_t\overline{c} &= \left[Z_t^T + (1-\alpha)^{-1} Z_t^M\right] \left(A_{at}\frac{L_{at}}{\overline{Z}}\right)^{\sigma} \\
&= \left[\overline{Z} + \alpha(1-\alpha)^{-1} Z_t^M\right] \left(A_{at}\frac{N_t}{\overline{Z}}\right)^{\sigma} \left(\frac{L_{at}}{N_t}\right)^{\sigma}.
\end{aligned}
$$

Substituting the expression for L_{at}/N_t derived in the proof of Proposition 1 into the equation above and solving for $Z_t^M/\overline{Z}$ yields equation (12) regarding the use of land.

Proof of Proposition 5

Similar to that of Proposition 2.

Incorporating Trade

With trade, all the equilibrium conditions are the same as before except for the following two market clearing conditions for the agricultural and non-agricultural goods:

$$
\begin{aligned}
(1+i_t)Y_{at} &= N_t\overline{c}, \\
Y_{nt} &= N_t c_{nt} + X_t + E_t.
\end{aligned}
$$

Here E_t is the amount of export in nonagricultural goods. Since the market clearing condition for agricultural goods can be rewritten as

$$Y_{at} = N_t\overline{c}_t,$$

where $\overline{c}_t = \overline{c}/(1+i_t)$, Propositions 1 to 5 stay the same if we replace $\overline{c}$ with $\overline{c}_t$. Note that the condition for balanced trade requires that

$$p_t^w E_t = i_t Y_{at},$$

or

$$E_t = p_t^{w-1} i_t Y_{at} = p_t^{w-1} N_t \frac{i_t}{1+i_t}\overline{c}.$$

Substituting this equation into the market clearing condition for nonagricultural goods yields the following:

$$c_{nt} = \frac{Y_{nt} - X_t}{N_t} - p_t^{w-1}\frac{i_t}{1+i_t}\overline{c}.$$

If the economy is in the traditional regime, we have $X_t = 0$ and

$$\frac{Y_{nt}}{N_t} = A_{nt}\left(1 - \frac{L_{at}}{N_t}\right) = A_{nt}\left(1 - \overline{c}_t^{\frac{1}{\sigma}}\widetilde{A}_{at}^{-1}\right).$$

Thus,

$$c_{nt} = A_{nt}\left(1 - \overline{c}_t^{\frac{1}{\sigma}}\widetilde{A}_{at}^{-1}\right) - p_t^{w-1}\frac{i_t}{1+i_t}\overline{c}.$$

Since per capita consumption of the agricultural good is always $\overline{c}$, the representative household's welfare is determined by the consumption of the nonagricultural good c_n. For the trade to be welfare non-decreasing at the margin, we need to have the following condition:

$$\frac{\partial c_{nt}}{\partial i_t} \geq 0.$$

From the equation for c_{nt} above, we have

$$\frac{\partial c_{nt}}{\partial i_t} = \frac{1}{\sigma}\overline{c}_t^{\frac{1}{\sigma}-1}\frac{A_{nt}}{\widetilde{A}_{at}}\frac{1}{(1+i_t)^2} - p_t^{w-1}\frac{1}{(1+i_t)^2}\overline{c}.$$

Thus, $\partial c_{nt}/\partial i_t \geq 0$ is equivalent to

$$\frac{1}{\sigma}\overline{c}_t^{\frac{1}{\sigma}-1}\frac{A_{nt}}{\widetilde{A}_{at}}\frac{1}{(1+i_t)^2}\overline{c} - p_t^{w-1}\frac{1}{(1+i_t)^2}\overline{c} \geq 0$$

or

$$p_t^w \geq \sigma\overline{c}_t^{\frac{\sigma-1}{\sigma}}\frac{\widetilde{A}_{at}}{A_{nt}} = p_t^T.$$

This ineqaulity suggests that the condition for trade being welfare improving requires the relative price of the nonagricultural good in the world market is higher than or equal to the domestic relative price. Similar conditions can be proved for the cases of the mixed economy and modern growth.

Agricultural Value-Added

In the traditional economy, agricultural value-added simply equals agricultural output, $Y_{at} = (A_{at}L_{at})^\sigma\,\overline{Z}^{1-\sigma}$. In a mixed economy, agricultural value-added (or net output) is

$$\widehat{Y}_{at} = r_t\overline{Z} + w_t L_{at}.$$

From Proposition 4, we have

$$\begin{aligned}
\widehat{Y}_{at} &= r_t\overline{Z} + w_t L_{at} \\
&= (1-\sigma)\left(\frac{\sigma \widetilde{A}_{at}}{p_M A_{nt}}\right)^{\frac{\sigma}{1-\sigma}} N_t + p_M A_{nt} L_{at}, \text{ and} \\
L_{at} &= \left(\frac{\sigma \widetilde{A}_{at}}{p_M A_{nt}}\right)^{\frac{1}{1-\sigma}} \widetilde{A}_{at}^{-1} N_t.
\end{aligned}$$

Therefore, we can derive

$$\begin{aligned}
\widehat{Y}_{at} &= (1-\sigma)\left(\frac{\sigma \widetilde{A}_{at}}{p_M A_{nt}}\right)^{\frac{\sigma}{1-\sigma}} N_t + p_M A_{nt}\left(\frac{\sigma \widetilde{A}_{at}}{p_M A_{nt}}\right)^{\frac{1}{1-\sigma}} \widetilde{A}_{at}^{-1} N_t \\
&= (1-\sigma)\left(\frac{\sigma \widetilde{A}_{at}}{p_M A_{nt}}\right)^{\frac{\sigma}{1-\sigma}} N_t + \sigma\left(\frac{\sigma \widetilde{A}_{at}}{p_M A_{nt}}\right)^{\frac{\sigma}{1-\sigma}} N_t \\
&= \left(\frac{\widetilde{A}_{at} L_{at}}{N_t}\right)^{\sigma} N_t.
\end{aligned}$$

Then, applying the definition of $\widetilde{A}_{at}$, we have $Y_{at} = (A_{at}L_{at})^{\sigma}\,\overline{Z}^{1-\sigma}$ in the mixed economy as well.

B. Description of the Data

Population and sectoral labor share. The first population census of Great Britain was conducted in 1801 and once every 10 years thereafter. We use the arithmetic average of the 1801 and 1811 figures in England as its population for the decade 1800-09, and then apply the same estimate for later decades. For the period from 1700 to 1799, we deploy the yearly population estimates used by Wrigley and Schofield (1981), which are reconstructed from local parish registers. To be consistent with the timing of the census, a simple arithmetic average of yearly population figures—starting from the first year of one decade to the first year of the next decade – is used as the decennial population figure. Then, we connect population figures from the two sources to cover the entire period 1700-1909.

The share of employment in agriculture is approximated by the share of males employed in agriculture (Clark, 2001), where the number of farm workers is estimated from the population censuses of 1801 an onwards. For the years before 1800, Clark builds on an estimate made by Lindert and Williamson (1982) that the farm labor force was no more than 53 percent of the adult male population in the 1750s. Clark applies a linear interpolation method to recover the share of male labor in agriculture for the 1750-1800 period and applies an income elasticity approach to recover that share in agriculture back to 1700.

Per capita GDP. For the period from 1700 to 1869, Clark (2001) provides decennial real per capita GDP for England and Wales. We use this data series for England with the implicit assumption that per capita GDP is the same across the two regions, an assumption that is often made by economic historians in similar constructions of income data. To construct real per capita GDP for the 1870-1909 period, we use the growth rates of real GDP per worker reported in the most recent study published by Feinstein (1990). We use his updated figures because his earlier estimates of per capita GDP were previously regarded as the best available information (Mitchell, 1988). Based on Feinstein (1990), the growth rates of real GDP per worker in the United Kingdom was 1.32 percent for 1856-73, 0.9 percent for 1873-82, 1.43 percent for 1882-99, and 0.31 percent for 1899-1913. Using these figures, we compute the weight-adjusted decennial growth rates of real GDP per worker for the four decades from 1870 to 1909, and we are thus able to form an index of decennial real GDP per worker. Combining this with information on the share of the labor force in the total population from the decennial population census (Mitchell, 1962), we are able to construct an index of decennial real per capita GDP for the United Kingdom. Connecting this index with the index for earlier decades reported in Clark gives us an index of real per capita GDP for England for 1700-1909.

Agricultural mechanization and food imports. The systematic adoption and diffusion of farm machinery in England began in the early 1800s. Despite the sparsity of historical data, John Walton creatively relied on farm sale advertisements to quantitatively document the adoption of farm machines for selective regions of England and Wales for the period between 1753 and 1880 (Walton, 1979). The original data consist of 3,115 advertisements for dispersal sales of farm stocks that appeared in the *Reading Mercury* and *Jackson's Oxford Journal* in Oxfordshire in England. Walton's study presents time series information on the percentage of farm households adopting each of eight farm machines, including turnip cutters, cake crushers, and reaping, mowing, haymaking, chaff, threshing and winnowing machines.

We construct two decennial indices of agricultural mechanization for England for the 1700-1909 period. Using information on the farm ownership of specific machines, we compute the first index as the probability of a typical farm household adopting at least one machine and the second index as the probability of it adopting at least two machines during individual decades. We use these two indices to approximate the extent of agricultural mechanization.

Quantitative analysis of the model, which assumes subsistence food consumption in a closed economy, requires making adjustments to England's food trade with other economies. In particular, the model simulation uses information on food imports or exports as a percentage of domestic agricultural production. Although Mitchell (1962) reports the value of net food imports into the United Kingdom from 1854 onwards, estimates of earlier years had to be drawn from other sources. Overton (1996) and Deane and Cole (1967) both present decennial data on food imports relative to domestic production, but there are trade-offs in choosing between the two sources—the former covers the longer data series of 1700 to1859, but has missing values for several decades, whereas the latter has a shorter series, from 1700 to 1820, but without missing values. On the whole, the two data series report very consistent trends. We construct a net import/output series for 1700-1851 based on the Overton series by applying a linear interpolation scheme to fill in the missing data. For 1850-1909, we divide the value of decennial imports (grain and flour plus meat and animals) taken from Mitchell (1962, pp. 298-300) by the value of agricultural production he reports (p. 366). We connect the two time series by normalizing the overlapping decade of 1850 to a common value.

Relative price. Clark (2004) uses a consistent method to construct an annual price series for English agricultural output in the years 1209-1912. This series consists of information from 26 commodities: wheat, barley, oats, rye, peas, beans, potatoes, hops, straw, mustard seed, saffron, hay, beef, mutton, pork, bacon, tallow, eggs, milk, cheese, butter, wool, firewood, timber, cider, and honey. We take the arithmetic average of farm price indices within decades to form our decennial agricultural price series for the period from 1700 to 1909.

There is no single data source that provides aggregate price series on nonagricultural production for the English economy during the historical period we cover. However, Mitchell's work (1962) contains sufficient information to enable the construction of a long price series for principal industrial products. For the period between 1700 and 1800, we use the Schumpeter-Gilboy price indices for producer goods, which consist of 12 industrial products—bricks, coal, lead, pantiles, hemp, leather backs, train oil, tallow, lime, glue, and copper. This series ends in 1801.

To continue the price series for 1800-1913, we adopt the Rousseaux price index for principal industrial products, which significantly overlaps in terms of product coverage with the Schumpeter-Gilboy price index (Mitchell, 1962). From 1800 to 1850, the Rousseaux price index covers coal, pig iron, mercury, tin, lead, copper, hemp, cotton, wool, flax, tar, tobacco, hides, skins, tallow, hair, silk, and building wood. For the years between 1850 and 1909, the index covers coal, pig iron, tin, lead, copper, hemp, cotton, wool, linseed oil, palm oil, flax, tar, jute, tobacco, hides, skins, foreign tallow, native tallow, silk, and building wood. We connect the two price indices and use them as a constructed price series for the nonagricultural sector.

We acknowledge that more direct data for the prices of industrial machinery or capital goods would be better indictors for the costs of agricultural machinery that influence their adoption in farming. However, statistical data on the prices of industrial goods, such as household durables and transport equipment and vehicles, did not become available until after 1930 (Mitchell, 1988). Neither did Walton (1979) report systematic price information on agricultural machinery. Because the prices of principle industrial products are closely correlated with the prices of industrial machinery or capital goods, the Schumpeter-Gilboy and Rousseaux price indices appear to be the best available measures that can serve as a proxy for the prices of industrial products.

Wage and land rent. In his study of agricultural performance and the Industrial Revolution, Clark (2002) assembles data on the key variables for English agriculture for 1500-1912 from various published sources. Based on Clark's analysis, we use the average day wages of adult male farm workers outside harvest time as a proxy for the wages of basic labor—the trend of this series closely resembles the changes in real wages for all workers from 1770 to 1870, the period studied by Feinstein (1998). The land rents are the market rental values of farmland, including payments for tithes and taxes.