

## A New Look at Demographic and Technological Changes: England, 1550 to 1839\*

THEOFANIS C. TSOULOUHAS

*Department of Economics, University of Illinois at Urbana–Champaign*

The aim of this paper is to explain English population and technological changes from 1550 to 1839. The model developed in this paper endogenizes technological change and urbanization and incorporates both the rural and the urban sectors of the economy. Regression results contrast with the findings of neo-Malthusian approaches. Boserupian causality (demographic change determines technological change) is found to be dominant. Exogenous mortality changes drive the growth of population either directly or via the fertility rate. The growth of population, in turn, drives technological changes that support further demographic changes as a feedback. The implications of the Boserupian causality are found to be different in the two sectors. © 1992 Academic Press, Inc.

This paper explains the English demographic changes from 1550 to 1839 with a Boserupian model. The analysis indicates that exogenous mortality changes determined the population changes which, in turn, drove the technological changes. Thus, the analysis contrasts with the neo-Malthusian theme of exogenous technological change.

The debate over the cause of population growth with the emergence of the Industrial Revolution in England is long standing. The great acceleration of population growth is attributed to declining mortality or to improved living standards and rising fertility. Specifically, the Constant Fertility theory explains population growth by exogenous changes in the mortality rate. The Constant Equilibrium Wage theory argues that the standard of living is institutionalized in the long-run. Then, exogenous technological change will increase the labor demand and cause population growth until the real wage falls to its natural level. Lee (1978a) in his Synthesis theory combines the previous approaches and affirms that pop-

\* I would like to thank Larry Neal for his helpful comments and guidelines throughout the long process of writing this paper. Without his continuing support, this paper would not have been completed. The paper has also benefited from useful comments by A. Dye, C. M. Kahn, Yiu Kuen Tse, A. Villamil, the participants of the Economic History seminar at the University of Illinois, and two anonymous referees. All errors are mine.

ulation changes were primarily caused by exogenous technological changes and by exogenous mortality changes. Technological change improved the standard of living and fertility. Stavins (1988) in his Composite theory expanded Lee's original formulation by endogenizing migration.

The objective of this paper is to provide a new look at this debate using a Boserupian model of demographic changes in England from 1550 to 1839, and to evaluate the various theories on this subject. The model (which will be called the New Look model) incorporates the previous theories on this subject as special cases.

The New Look model expands on Lee's original homeostatic formulation and Stavins' endogenization of migration by endogenizing technological change and urbanization. The model also distinguishes between the urban and the rural sectors of the economy. According to the New Look approach, demographic changes cause technological changes. This causality ordering is in contrast with the Malthusian theme enhanced by the Constant Equilibrium Wage, the Synthesis, and the Composite approaches. A Granger causality test provides support for the Boserupian causality ordering. Contrary to Lee's assertion, fertility is responsive to mortality, and mortality is the only exogenous factor determining the population growth rate. Mortality drives the growth of population directly or through the fertility rate. Population growth improves technology. In the urban sector, this technological change increases the real wage and, as a result, fertility. Thus, through a feedback relationship, technology and the real wage further support population changes. In the rural sector, the feedback relationship is different. The technological change (caused by population change) results in a decreasing rural wage. Population and the rural wage are negatively related—the impact of population on demand is smaller than the impact of population on supply.

The paper is organized as follows. Section I gives a formal presentation and discussion of previous theories. Included are econometric models used to analyze the debate regarding the sources of population growth during the period of concern. Section II analyzes the English data and develops the New Look approach. Section III presents an econometric model of the New Look approach and the rationale behind its specification. It also contains the estimation results and tests of significance along with a Granger causality test for the Boserupian hypothesis. Section IV evaluates the econometric models used by the New Look, the Synthesis, and the Composite approaches by nonnested hypothesis testing. Finally, a simulation is performed which provides further support for the New Look model.

## I. THE ALTERNATIVE DEMOGRAPHIC THEORIES

The alternative demographic theories to be studied are:

(a) The Constant Fertility theory, (CF), which states that the major determinant of population changes is exogenous changes in the mortality

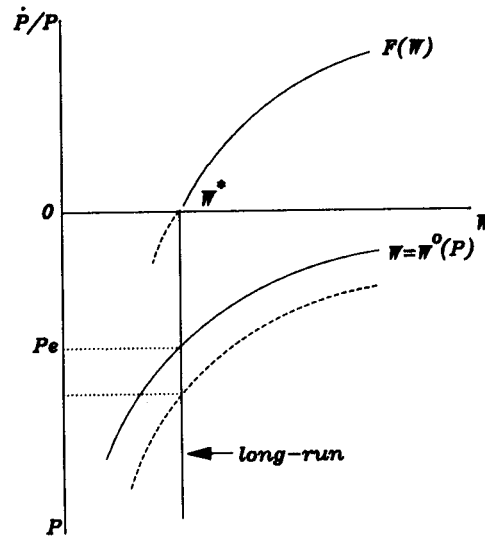


FIG. 1. The Constant Equilibrium Wage theory.

rate, since the birth rate as a function of social institutions is relatively stable.

(b) The Constant Equilibrium Wage theory, (CEW), which states that demographic changes are caused by shifts in the demand for labor. The real wage is a function of the labor supply in the short-run and is stable at its natural level in the long-run. Therefore, according to this theory the standard of living is institutionalized in the long-run. An exogenous rise in labor demand (due to technological change) will increase population until the real wage falls again to its natural level (refer to Fig. 1). Therefore, the Malthusian causality ordering is dominant: technological change causes demographic change.

This theory could be represented by the model,

$$\dot{P}/P = F(W) \quad (1.1)$$

$$W = W^0(P), \quad \text{in the short-run} \quad (1.2)$$

$$W = W^*, \quad \text{in the long-run,} \quad (1.3)$$

where  $W$  = real wage,  $P$  = population size,  $\dot{P}$  = change in  $P$ ,  $\dot{P}/P$  = the growth rate of population,  $W^*$  = natural level of  $W$ .

(c) Lee, in his Synthesis theory, combined the previous approaches (CF and CEW) (Lee, 1978a). He used data on English demographic change from 1250 to 1750, mainly provided by Wrigley,<sup>1</sup> and affirmed that pop-

<sup>1</sup> Wrigley, E. A. (1969), *Population and History*. NY: McGraw-Hill.

ulation changes and wages were simultaneously determined in a dynamic system. Population changes are caused by technological changes (in a Malthusian fashion) and exogenous mortality changes. In his framework, fertility was responsive to the wage level yet independent of mortality.<sup>2</sup> Lee showed the superiority of his Synthesis over the alternative theories for the preindustrial period.

Lee developed an homeostatic system in which “population and wages are controlled by an equilibrating mechanism, but in which the equilibrium levels toward which they converge depend very sensitively on the secular level of mortality” (Lee, 1978a, p. 63).

His original model was

$$f = \mu + a \ln W + \lambda d \quad (1.4)$$

$$W = \eta P^\beta \quad (1.5)$$

$$\dot{P}/P \equiv f - d, \quad (1.6)$$

which reduces to

$$W = \eta P^\beta \quad (1.7)$$

$$\dot{P}/P = \mu + a \ln W + (\lambda - 1)d, \quad (1.8)$$

while Lee employed the following model to test the CF, the CEW, and his Synthesis,

$$\ln W_t = \ln \eta + \beta/2 [\ln P_t + \ln P_{t-1}] \quad (1.9)$$

$$[\ln P_t - \ln P_{t-1}] = \mu + a \ln W_t + (\lambda - 1)d_t, \quad (1.10)$$

where  $\frac{1}{2}(\ln P_t + \ln P_{t-1})$  is the midpoint between  $P_t$  and  $P_{t-1}$ ;  $\ln P_t - \ln P_{t-1}$  is the growth rate of population ( $\dot{P}/P$ );  $d$  = crude death rate;  $f$  = fertility rate;  $\eta, \mu$  = constants (Lee, 1978a, pp. 78 and 86).

These theories imply the following set of restrictions (R1) which are explained below:

$$\text{CF} \quad \lambda = 0, a = 0 \quad | \quad \beta < 0$$

$$\text{CEW} \quad \lambda = 1, \quad | \quad \beta = 0$$

$$\text{Synthesis} \quad \lambda = 0, a \neq 0 \quad | \quad \beta < 0.^3$$

The CF theory asserts that the birth rate is relatively stable since it is a function of social institutions only, therefore  $\lambda = 0$  and  $a = 0$ .

The CEW theory implies that the mortality rate does not affect the population's rate of growth, therefore  $\lambda$  in Eq. (1.10) should be equal to

<sup>2</sup> In his 1985b article, Lee argues that fertility may be positively related to mortality. However he does not provide any statistical evidence for this argument.

<sup>3</sup> I consider one-sided restrictions for  $\beta$  because its sign is important as will become clear.

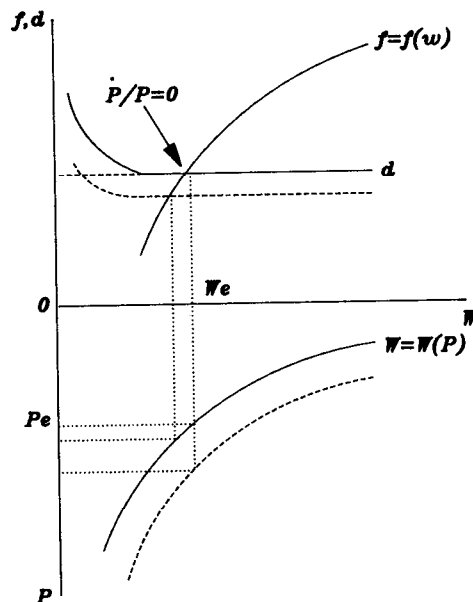


FIG. 2. Lee's Synthesis theory.

1. Also, the real wage in the long-run is stable at its natural level, therefore  $\beta$  in Eq. (1.9) should be equal to 0.

The Synthesis theory implies that fertility is responsive to the wage level; therefore,  $a$  in Eqs. (1.4), (1.8), and (1.10) should not be equal to 0. But fertility is unresponsive to mortality, therefore  $\lambda = 0$ . Also, the relationship between the population size and the short-run equilibrium wage is negative, (Lee, 1978a, pp. 23 and 45), hence  $\beta < 0$ . (The latter holds for the CF approach too.)

Lee's homeostatic system enhances a Malthusian causality. Technological changes shift the labor demand schedule and drive the population changes. This is seen by looking at the coefficients  $\beta$  (where  $\beta < 0$ ) and  $\lambda$  (where  $\lambda = 0$ ). The first coefficient implies that increases in population decrease the equilibrium wage in the short-run. The second implies that fertility is unresponsive to mortality. In this way, Lee left no room for a Boserupian causality to develop, since population increases are not allowed to drive up technology and the real wage, while population growth is attributed to fertility and exogenous mortality changes. Fertility, however, is only responsive to technological and real wage changes. Thus, the impact of technology on population is magnified by the preclusion of an impact of mortality on fertility.

Lee's synthesis model is depicted in Fig. 2. Technological change shifts

the labor demand schedule thus increasing the equilibrium population. Exogenous mortality changes also increase the equilibrium population.

(d) Stavins' Composite theory uses an expanded and revised data base provided by Wrigley and Schofield (1981) for the period of 1573 to 1873, which includes the years of the British Industrial Revolution, not covered by Lee. Based on the new data set, Stavins asserts that net migration from England was small but not negligible, and therefore, he makes migration behavior endogenous in his model. He also introduces the neo-Malthusian theme of exogenous technological change, but measures it by using the degree of urbanization as a proxy (Stavins, 1988).

Stavins utilizes and expands Lee's model in the following way,

$$\ln W_t = \ln \eta + \beta/2[\ln P_t + \ln P_{t-1}] + \delta U_t \quad (1.11)$$

$$[(\ln P_t - \ln P_{t-1}) + m_t] = \mu + a \ln W_t + \pi \ln W_{t-1} + (\lambda - 1)d_t \quad (1.12)$$

$$m_t = \ln \gamma + p \ln W_{t-1}, \quad (1.13)$$

where  $U$  = percentage of population residing in urban areas of population 10,000 or greater,  $m$  = net out-migration rate.

In particular, Stavins' contribution is to endogenize migration and incorporate urbanization (which Stavins perceives to be exogenous) into Lee's model. The rationale behind Stavins' work is that, with the emergence of the Industrial Revolution, the population size–wage relationship changed significantly due to an outward shifting labor demand schedule. He conjectures that the shift in the labor demand schedule occurred because of technological change, and the urbanization component  $U$  is used as a proxy for technological change. Thus, he argues that, during the preindustrial period, the crucial factor in the determination of demographic changes was the mortality level. However, he claims that, after the emergence of industrialization, shifts in the demand for labor were the dominant factor behind demographic changes. Unfortunately, Stavins does not confirm this assertion since he uses only one model for both the pre- and the post-Industrial Revolution periods.

In Stavins' framework, the alternative demographic theories imply the following set of restrictions (R2), which are explained below:

$$\text{CF} \quad \lambda = 0, a = 0, \pi = 0, \delta = 0 \mid \beta < 0$$

$$\text{CEW} \quad \lambda = 1, \quad \delta \neq 0 \mid \beta = 0$$

$$\text{Synthesis} \quad \lambda = 0, a \neq 0, \pi \neq 0, \delta = 0 \mid \beta < 0$$

$$\text{Composite} \quad \lambda = 0, a = 0, \pi = 0, \delta \neq 0 \mid \beta < 0.$$

Exogenous technological change is introduced only in the CEW and the Composite approaches, so  $\delta \neq 0$  only in these approaches.

Stavins modifies Eq. (1.4) to allow for the lagged endogenous variable

$\ln W_{t-1}$  whose coefficient is  $\pi$ . He argues that fertility is not responsive to the wage level and mortality, so  $a$ ,  $\pi$ , and  $\lambda$  are restricted to zero. For the CF theory the birth rate is relatively stable, so  $\pi = 0$ . Since Lee treats fertility as responsive to the wage level,  $\pi$  is not equal to zero in the Synthesis approach. Stavins argues that emigration is small but not negligible and depends on the real wage, so  $p \neq 0$ , while  $\beta < 0$  as in Lee's synthesis.

Stavins does not change the model in any fundamental way. He endogenizes migration, but this does not alter the causal relationships. He also wants to introduce exogenous technological change in a Malthusian fashion, but he proxies it by the degree of urbanization. Urbanization, however, cannot be perceived as exogenous in a model of demographic changes. In fact, urbanization cannot but be endogenous. Even the Greek origin of the word demography indicates that the demographic changes are endogenous. Demographic changes connote changes in the population size, in the composition of the population with respect to various aspects of it, and in the dispersion and regional density of the population. Stavins implicitly acknowledges this problem by suggesting that a "further refinement" in his specification should be to make urbanization endogenous. Urbanization would then be a function of the urban–rural wage differential. Obviously, a simple refinement is not sufficient. The exogenous influence of urbanization is crucial in his model because it is used as a proxy for technological change. Therefore, urbanization cannot be endogenized in Stavins's model because it is a proxy for exogenous technological change.

In testing these alternative theories of demographic change, there are some empirical problems as well.

(i) It is a matter of debate whether Wrigley and Schofield's estimates for the fertility or the mortality rate are reliable. As to the fertility rate, their "residual adjustments" may reveal a systematic bias as P. Lindert (1983) showed. In particular, Lindert notes that the impressive rise in fertility suggested by Wrigley and Schofield's data series—the "baby-boom" during the Industrial Revolution—may emerge "from their technical final adjustments" (Lindert, 1983, p. 136). Thus, there may not really have been a baby-boom in the Industrial Revolution. Lindert's skepticism stems from five good reasons why fertility should not have risen between 1750 and 1815. "(1) The period ended with a significant share of young adult males in the armed forces, away from their current or potential wives; (2) the relative price of food rose severely, raising the relative price of extra children; (3) living space for children became relatively more expensive as population and production expanded; (4) literacy, a consistently anti-natal force in modern times, was on the rise among young adults; and most importantly, (5) the real incomes of the lower and middle classes were not rising" (Lindert, 1983, p. 134).

Lindert develops a series for births per thousand of population that might have occurred in addition to those estimated by Wrigley and Schofield (Lindert, 1983, Table 2, p. 145).

Lee utilizes the initial Wrigley series, but he accepts that "its significance derives from Wrigley's position as a leader in current work on local population studies and family reconstitution in England" (Lee, 1978a, p. 163).<sup>4</sup> Therefore, sole dependence on this data series may be misleading. It is a matter that needs further consideration.

(ii) The data sets Lee and Stavins use, except for the population size, are 50-year and 25-year arithmetical averages (respectively) of the relevant data sets. The smoothing is done because the analysis relates to long-term phenomena. But given the length of the intervals, the sample size is not large enough to carry out reliable regressions and valuable tests. One can use 10-year averages, instead, to increase the sample size considerably and then, if needed, adjust the lags of the variables.

## II. THE NEW LOOK MODEL: THEORY AND EVIDENCE

In footnote (3) in his 1985b article, Lee states: "It is also possible that population size and density were themselves powerful influences on technological change, as many authors have argued, most notably Ester Boserup . . . ." However, it is either technological change that causes demographic change or demographic change that causes technological change. The aim of this paper is to show that there is enough evidence suggesting that the Boserupian causality ordering is dominant.

Section II is organized as follows. First, a careful look at the data for the period 1550 to 1840 will provide the foundation for the New Look model, since they indicate that the trend change in the growth rate of technology followed that of population. Then, the New Look model will be developed.

Figure 3 plots the population data for this period. The population figures that are utilized here are derived from the data provided by Wrigley and Schofield (1981) adjusted for the total births by using Lindert's figures. The plot indicates that population increased until the middle of the period from 1650 to 1700 following roughly a logarithmic pattern. From then on, it increased exponentially (except for a short period around 1725). In other words, population increased at a decreasing rate until roughly the middle of the period from 1650 to 1700, and from then on it switched to an increasing rate. Hence, the change in the trend growth of population must have occurred around 1670 to 1680.

The growth rate of population is plotted in Fig. 4. This figure indicates

<sup>4</sup> Lee also argues that the quality of the fertility data is poor: "Fertility responded weakly although positively to the real wage, and varied little over the long run; the poor quality of the fertility data rendered these conclusions uncertain" (Lee, 1985b, p. 637).



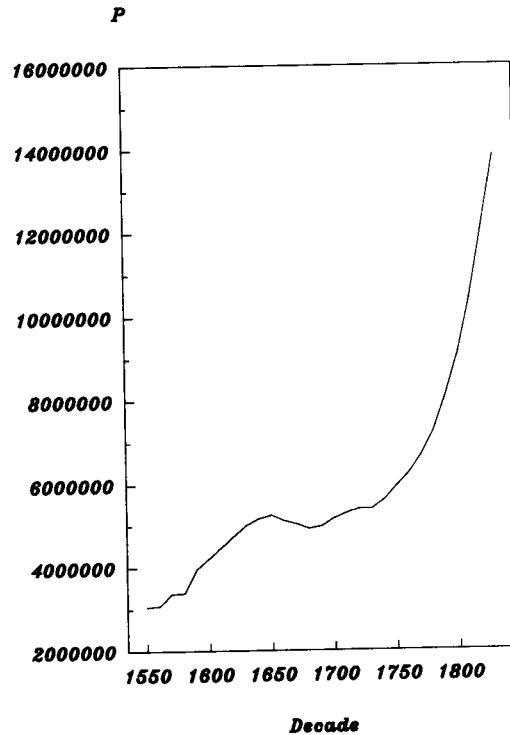


FIG. 3. Population size, 1550–1839.

that the trend change in the growth rate of population occurred somewhere in the middle of the period from 1650 to 1700, while there is a smaller trend change around 1730 to 1740.<sup>5</sup>

One could get a better picture of how population evolved by an open quasi cubic spline for the growth rate of population. The cubic spline results are depicted in Fig. 5.<sup>6</sup>

In Figure 6, the growth rate of population is smoothed in order to determine when the drastic trend change took place. The smoothing was carried out by a polynomial trend of the second order. It indicates that the trend change is confined to the decade 1670–1680.

The next task of the analysis is the comparison of the development of

<sup>5</sup> The Wrigley and Schofield (1981) population series gives the same growth rate without Lindert's figures for the additional births, since Lindert thought that there was nothing wrong with the Wrigley and Schofield natural rate of growth of population.

<sup>6</sup> These results derive from a fifth-order polynomial interpolation, where both the first and the second derivatives were preserved at the knots (Hazony, 1979).

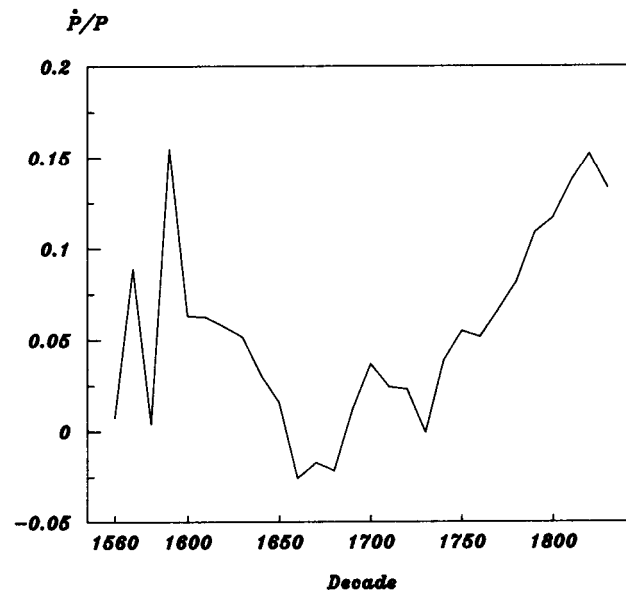


FIG. 4. The growth rate of population, 1560–1839.

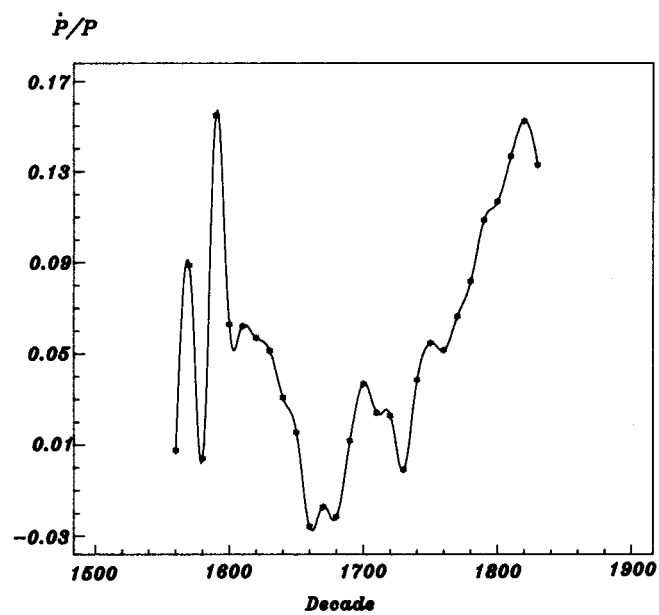


FIG. 5. A quasi cubic spline for the growth rate of population, 1560–1839.

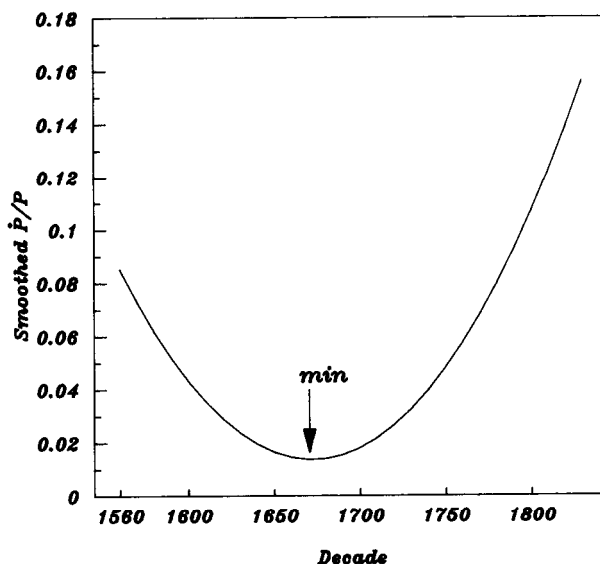


FIG. 6. The smoothed growth rate of population, 1560-1839.

population to that of technology. Therefore, a measure of technological development is needed.

Two possible measures of the technological development of English agriculture are discussed in Sullivan (1984). The first is the number of patents issued in English agriculture. The second is the number of titles of books on agricultural techniques. Sullivan argues that the latter measure may be better than patent data, first because ideas that led to technological improvements may have been expressed in books although a patent may not have been issued. Second, Sullivan argues that literacy rates in early modern England were high enough so that there was a large potential audience for books on agricultural techniques. Third, it is seen in Fig. 7 that the fluctuations of book titles are similar to the fluctuations of patents. Both the patent and the book titles data, however, are subject to criticism as far as the weighting of more valuable patents or books is concerned. Also, Sullivan claims that because of the growth of agricultural periodicals, book titles become suspect in reflecting agricultural technology after the middle of the 18th century.

Following this discussion, it appears that book titles may be a better measure of technological change than patents are. Therefore, in what follows, the number of titles (first printings) of books on agricultural techniques published in every period is used as a proxy for technological change or, at least, for inventions and innovations. An additional advantage in using the book titles is that the relevant data cover a longer period

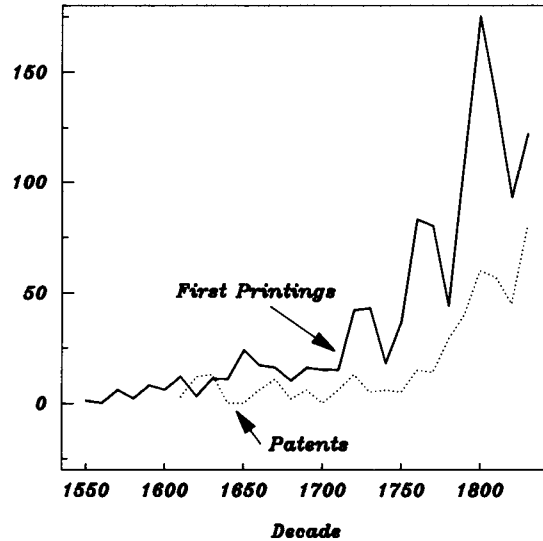


FIG. 7. Agricultural patenting, 1611–1840, and publications (first printings), 1550–1840.

than the patent data. For every period, the data for book titles over the current and all past periods were summed up to form a measure of the level of technology for the period. Then, the growth rate was calculated. Although it can reasonably be argued that there is an adding up or weighting problem, since new technology may replace old technology, or new technology is usually better than old technology, still there is no better alternative. At least, this procedure will provide some indication of when the trend change in the growth rate of technology occurred. The percentage growth rate of agricultural technology ( $\dot{T}_r/T_r$ ) is depicted in Fig. 8.

As is seen in Fig. 8, the growth rate of technology in the rural sector does not show any significant increase after 1700. There are two possible explanations for this. First, the trend change in the growth rate of population around 1730 to 1740 may have pulled down the growth rate of technology. Second, according to Sullivan's claim, book titles alone may underestimate technology after the middle of the 18th century because of the growth of agricultural periodicals.

The smoothed growth rate of agricultural technology, which was derived from polynomial smoothing of second order, is depicted in Fig. 9. The smoothed values indicate that the drastic change in the growth rate of agricultural technology must be traced to around 1740 to 1750.

Further evidence on how technology in England developed may arise from patent data for the urban sector. These data, which were used as proxies for inventions and innovations, are provided by Sullivan (1986)

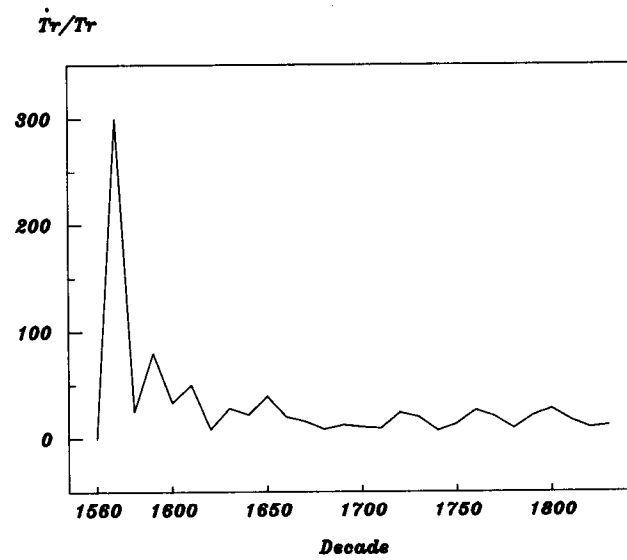


FIG. 8. The percentage growth rate of agricultural technology, 1560-1840.

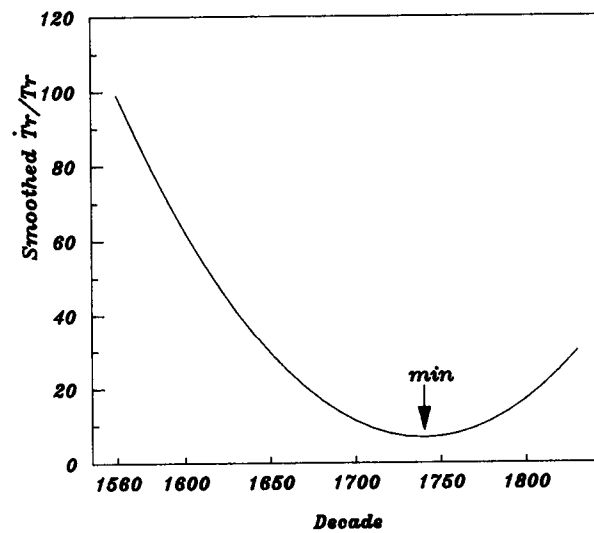


FIG. 9. The smoothed percentage growth rate of agricultural technology, 1560-1840.

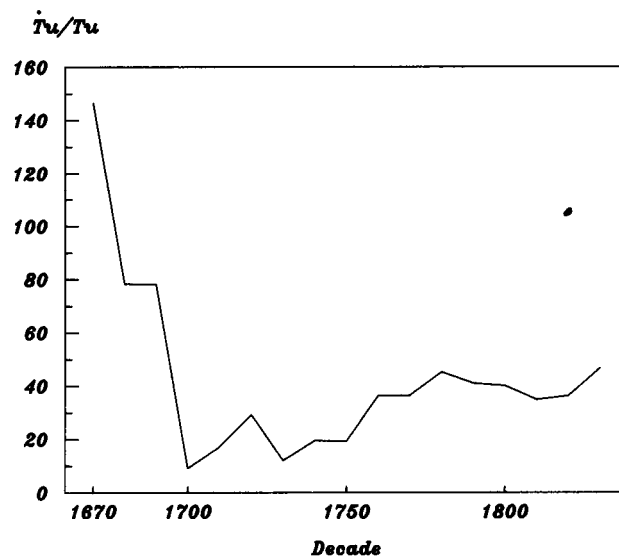


FIG. 10. The percentage growth rate of technology in the urban sector, 1670–1840.

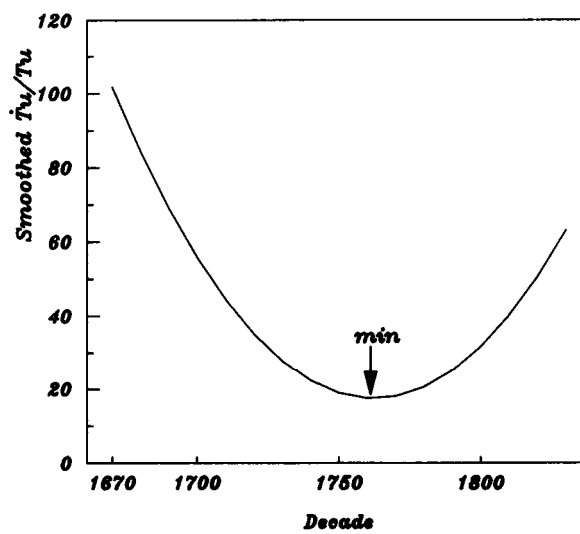


FIG. 11. The smoothed percentage growth rate of technology in the urban sector, 1670–1840.

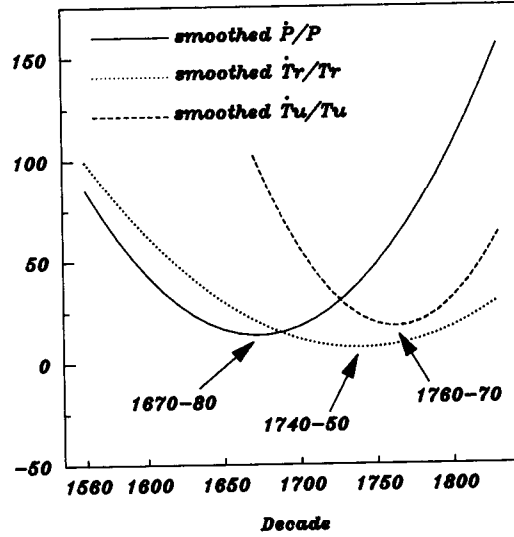


FIG. 12. Smoothed growth rates: population versus technology.

for the period 1661 to 1850.<sup>7</sup> From these figures, the percentage growth rate of technology in the urban sector ( $\dot{T}_u/T_u$ ) was derived. The series is plotted in Fig. 10. Then, the series was smoothed by polynomial smoothing. The relative data are plotted in Fig. 11. The smoothed series indicates that the trend change in the growth rate of technology in the urban sector occurred around 1760 to 1770.

Finally, the three smoothed series for the growth rates of population and technology are plotted in Fig. 12 (where, for ease of comparison, the percentage growth rate of population multiplied by 10 is plotted.)

To conclude, this evidence suggests that the trend change in the growth rate of population preceded that of technology. Therefore, the English data imply that demographic changes for this period should be explained by a Boserupian model. The New Look model, Eqs. (2.1)–(2.4), incorporates the Boserupian theme.

$$f = f(W, d) \quad (2.1)$$

$$W = W(I) \quad (2.2)$$

$$I = I(P) \quad (2.3)$$

$$\dot{P}/P = f - d - m \quad (2.4)$$

<sup>7</sup> See the derivation of IU, below.

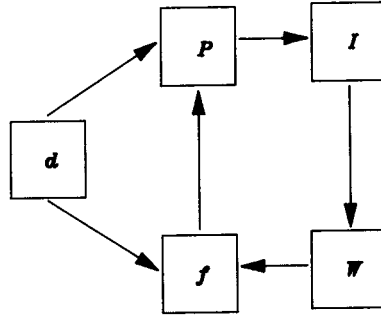
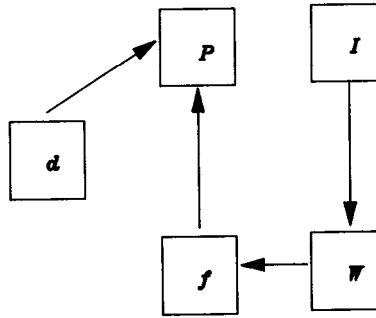
*Causality in the New Look Approach**Causality in Lee's Approach*

FIG. 13. Causality in the New Look approach versus causality in Lee's approach.

and  $d$  is exogenous, which reduces to

$$W = W(I) \quad (2.5)$$

$$I = I(P) \quad (2.6)$$

$$\dot{P}/P + m \equiv f(W, d) - d = \Phi(W, d), \quad (2.7)$$

where  $I$  = inventions and innovations;  $I$  accounts for technological change.

The Boserupian causality embodied in the New Look model flows as follows. The mortality rate, which is exogenous, affects the growth rate of population directly or via the fertility rate which is responsive to mortality. This population change generates technological changes which, in turn, affect the real wage. The real wage changes affect the growth rate of population through fertility. Hence, there are feedbacks from the technological change to the growth rate of population through fertility. As is



illustrated in Fig. 13, there is a continuous loop from population change to technological and real wage change, that feeds back into the population change. However, the factor that drives the ascension of the system is exogenous mortality shocks.<sup>8</sup> The link between population and technology is motivated by an increased aggregate demand for the means of subsistence (which arises when population increases) that can be met by technological change.

To contrast the New Look approach and Lee's approach, Fig. 13 also depicts the causality scheme in the Synthesis model. Population change is primarily caused by exogenous technological change through real wage, and hence fertility, changes. Exogenous mortality changes also play a role in population changes. However, fertility is not responsive to mortality.

The task of the analysis is the development of a general model that could embody the Boserupian theme the English data reveal, as well as accommodate all the previous approaches as special cases. In order to facilitate the development of such a formulation, the previous model of Eqs. (2.5)–(2.7) reduces to the following:

$$W = W(I) = W(I(P)) = H(P) \quad (2.8)$$

$$\dot{P}/P + m = \Phi(W, d) \quad (2.9)$$

$$I = I(P). \quad (2.10)$$

The last equation, which is seemingly redundant, is preserved in this formulation to highlight the separate effects of population on technological change.

Before proceeding to convert this general model to an econometric model, two important points must be taken into account. First, as the series for urbanization ( $U$ ) indicates, the percentage of population residing in urban areas increased constantly throughout this period. The total population size and its components (the rural and the urban population) are plotted in Fig. 14. So the model must account for the shift in population toward the cities by endogenizing urbanization. Second, as shown in Fig. 15, although the urban wage exhibited an upward trend throughout the period of concern, the rural wage exhibited a downward trend. Since the behavior of the real wage is different in the two sectors, the model must incorporate the two sectors separately.

The econometric model in its final form is presented in the following section.

<sup>8</sup> As a matter of fact, no model has yet endogenized mortality convincingly.

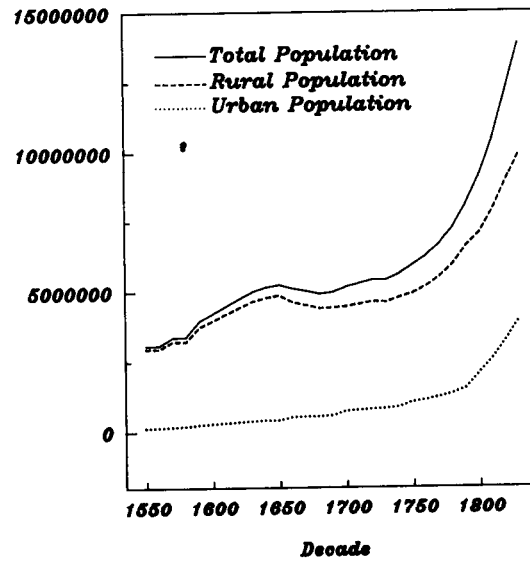


FIG. 14. Population: total, rural and urban, 1550–1839.

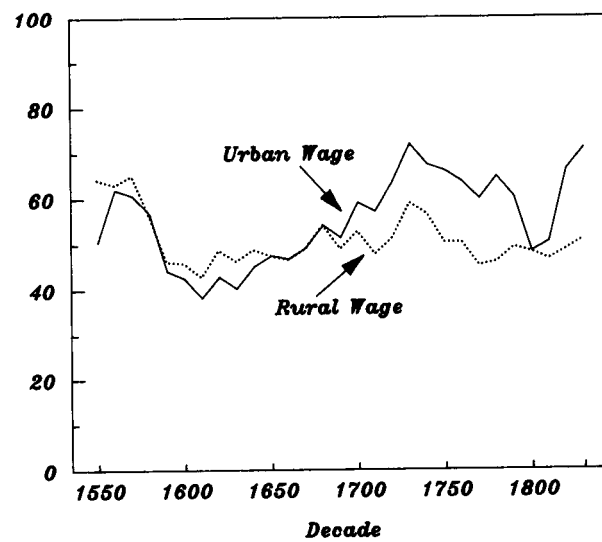


FIG. 15. Urban real wage and rural real wage, 1550–1839.

### III. THE NEW LOOK MODEL: SPECIFICATION, JUSTIFICATION AND ECONOMETRIC RESULTS

#### *IIIa. Econometric Model Specification*

The New Look model expands on Lee's model. It highlights the Boserupian element in demographic changes by endogenizing technological change. It accounts for endogenous urbanization and distinguishes between rural and urban sectors by developing and utilizing a real rural wage series. It uses Lindert's series of additional births to adjust the population size figures provided by Wrigley and Schofield. It provides for endogenous outmigration by adjusting Stavins' migration equation. Finally, it employs 10-year averages to increase the sample size and yet retain its relevance for examining long-run phenomena.

The model that is estimated is the following.

$$\ln W_t = \ln \eta + \beta \ln PU_t + b \ln W_{t-1} + \theta \ln WR_t \quad (3.1)$$

$$\ln WR_t = \ln \nu + \kappa PR_t + \zeta \ln W_t \quad (3.2)$$

$$[(\ln P_t - \ln P_{t-1}) + m_t] = \pi \ln W_{t-3} + \phi \ln WR_{t-3} + (\lambda - 1)d_t \quad (3.3)$$

$$m_t = q \ln W_{t-2} + \psi WR_{t-2} \quad (3.4)$$

$$\ln PU_t = \tau + \chi IR_t + \rho \ln PU_{t-1} \quad (3.5)$$

$$IR_t = \varepsilon + \xi \ln P_t \quad (3.6)$$

$$IU_t = \sigma + \omega \ln P_t, \quad (3.7)$$

where PU = urban population size; PR = rural population size; WR = real wage in rural areas. (See Appendix I for the derivation of WR); IR = inventions and innovations in the rural sector; IU = inventions and innovations in the urban sector;<sup>9</sup> and  $\eta, \nu, \tau, \varepsilon, \sigma$  = constants.

As far as the real wage is concerned, Wrigley and Schofield give only  $W$ , the real wage in occupations in urban areas. Lee and Stavins treat  $W$  as the real wage for all sectors.

The various approaches require the following set of restrictions (R3):

$$\text{CF: } \lambda = 0, a = 0, \pi = 0, \delta = 0, \quad \phi = 0, \quad | \quad \beta < 0$$

$$\text{CEW: } \lambda = 1, \quad \delta \neq 0, b = 0, \quad \xi = 0, \omega = 0 \quad | \quad \beta = 0$$

$$\text{Synthesis: } \lambda = 0, a \neq 0, \pi \neq 0, \delta = 0, b = 0, \phi \neq 0, \xi = 0, \omega = 0 \quad | \quad \beta < 0$$

<sup>9</sup> A proxy for this figure is the number of patents of inventions issued in six sectors except for field agriculture: heavy chemicals, steam engines, production machines, metal and mining, textiles, and railroads and shipping. The data are provided by Sullivan (1986, Table 6, p. 18). For the period 1661–1670 to 1830–1839, the relative data are as follows: 28, 41, 54, 96, 20, 41, 82, 43, 79, 93, 210, 287, 487, 640, 882, 1077, 1597, 2644.

Composite:  $\lambda = 0, a = 0, \pi = 0, \delta \neq 0, b = 0, \phi = 0, \xi = 0, \omega = 0 \mid \beta < 0$   
 New Look:  $\lambda \neq 0, a = 0, \pi \neq 0, \delta = 0, b \neq 0, \phi \neq 0, \xi \neq 0, \omega \neq 0 \mid \beta > 0$ .<sup>10</sup>

The restrictions implied by the New Look approach derive from the Boserupian perspective. Population increases drive up technology and the real wage, hence  $\beta > 0$ . Fertility is responsive to mortality, so  $\lambda \neq 0$ . Also,  $\pi \neq 0$  and  $\phi \neq 0$  because real wage changes affect population growth through fertility; however, the real wage changes are feedbacks from population changes as represented in Eq. (3.1). For the Composite approach, the growth rate of population is not responsive to real wage changes, so  $\phi = 0$ . Also, for the Constant Fertility approach, the fertility rate is only a function of social institutions, so  $\phi = 0$ . Contrary to this, for the Synthesis approach, the growth rate of population is responsive to real wage changes, so  $\phi$  is not equal to zero as well as  $a$  and  $\pi$ . Since the CEW, Synthesis, and Composite models are Malthusian, the coefficients  $\xi$  and  $\omega$  are equal to zero. Technology enters these models through Eq. (3.1) with an upward shift of the labor demand schedule (due to technological change).

### IIIb. Parameter Estimation and Hypotheses Testing

*Estimation procedure.* Equations (3.1), (3.2), (3.5), and (3.6) are estimated by TSLS, (all four equations are overidentified), where the instrumental variables are the predetermined variables. In the rest of the equations (except for (3.7)) the endogenous variables are regressed on predetermined variables only, so these equations are estimated by OLS. Since data for IU, are available only for the period 1661 to 1839, Eq. (3.7) is estimated independently from (3.1) to (3.6) (using OLS). However, the OLS results should not differ greatly from the TSLS results, as preliminary results for (3.6) show.

*Testing for autocorrelation.* The test of Godfrey (1978) was applied to all the equations. The hypothesis of no autocorrelation was not rejected for Eqs. (3.1), (3.2), (3.3), and (3.5); Eqs. (3.4) and (3.6) were corrected for second order autocorrelation; and Eq. (3.7) for first order autocorrelation.

*Testing for heteroscedasticity.* The test that was applied to check for heteroscedasticity is related to a modification of the test of Breusch and Pagan (1979) proposed by Koenker (1981).<sup>11</sup> The test did not show any significant heteroscedasticity for any of the equations.

<sup>10</sup> With regards to this set of restrictions, please note the following. Parameter  $a$  is the coefficient of  $\ln w_t$  in Eqs. (1.4), (1.8), (1.10), and (1.12). This coefficient was not introduced in (3.3) because preliminary econometric results indicate that it is not significant. Parameter  $\delta$  is the coefficient of  $U_t$  in (1.11).

<sup>11</sup> The test, which is robust against nonnormality, is as follows: the squares of the residuals from the original regression are regressed on a constant and on the explanatory variables

TABLE 1  
Regression Results for the New Look Model

	$\ln\eta$	$\beta$	$b$	$\theta$	$\ln\nu$	$\kappa$	$\zeta$	$\pi$
Estimates	-3.364	0.097	0.401	1.143	4.564	-0.118	0.289	0.189
<i>t</i> statistics	-1.891	3.541	2.352	2.128	5.799	-2.030	3.294	4.434
	$\phi$	$\lambda - 1$	$q$	$\psi$	$\tau$	$\chi$	$\rho$	
Estimates	-0.094	-1.166	-0.0183	0.0216	0.848	0.0018	0.940	
<i>t</i> statistics	-2.113	-5.079	-4.9267	5.6995	1.294	1.8190	18.080	
	$\varepsilon$	$\xi$	$\sigma$	$\omega$				
Estimates	-2850.23	147.26	-39904.07	2574.22				
<i>t</i> statistics	-10.93	11.15	-7.12	7.24				

*Testing for normality.* The test of Jarque and Bera (1987) was applied in all the equations to test whether the distribution of the error terms is normal. The test shows that the hypothesis of normality is not rejected for each equation.<sup>12</sup>

*Parameter estimates.* The estimation of the model equations yielded the results summarized in Table 1.

*Evaluation of the regressions.* The *t* statistics presented in Table 1 indicate that all regression coefficients are significant. In fact, most of them are significant at very low levels of significance such as 0.005. In addition, as Table 2 indicates, the overall significance of most of the regressions is high.<sup>13</sup>

of the original regression:  $\hat{e}_i^2 = c_0 + c_1x_{1i} + \dots + c_kx_{ki} + u_i$ . The statistic used is equal to  $nR^2$  where  $R^2$  is the coefficient of determination for this auxiliary regression. Under homoscedasticity, it can be shown that the statistic is asymptotically distributed as a  $\chi^2_k$ . The null hypothesis of homoscedasticity is rejected at  $\alpha$ , if  $nR^2 > \chi^2_{k,\alpha}$ . See Judge *et al.* (1985), pp. 446-447 and Amemiya (1985), pp. 198-207.

<sup>12</sup> The Bera-Jarque test is based on the following statistic:  
 $L = n[m_3/(6m_2^2) + (m_4/m_2^2 - 3)^2] + [(3m_3^2)/(2m_2) - (m_3m_1)/m_2^2]$ . If  $m_1 = 0$ , then the statistic reduces to:

$L = n[(\sqrt{b_1})^2/6 + (b_2 - 3)^2/24]$ , where  $\sqrt{b_1}$  and  $b_2$  are the skewness and kurtosis sample coefficients, respectively. ( $\sqrt{b_1} = m_3/(m_2^{3/2})$ ,  $b_2 = m_4/m_2^2$ , the *r*th moment  $m_r = (1/n) \sum_{i=1}^n (\hat{e}_i - \bar{e})^r$ , and  $\bar{e}$  is the mean of the residuals  $\hat{e}_i$ .  $\sqrt{b_1} = 0$  and  $b_2 = 3$  for a normal distribution.) Under the hypothesis of normality,  $L$  is asymptotically distributed as a  $\chi^2_2$ . The hypothesis of normality is rejected if  $L > \chi^2_2, \alpha$ .

<sup>13</sup> In interpreting the table results, one should keep in mind that  $R^2$  and the *F* statistic are inflated when there is a lagged dependent variable. Also, when TSLS is used in the estimation,  $R^2$  no longer shows the percentage of the variation of the dependent variable that is explained by its association to the independent variables. As far as Eq. (3.2) is concerned, there was no plausible way of improving its explanatory power.

TABLE 2  
The Overall Significance of the New  
Look Equations

Eq. No.	$R^2$	$\bar{R}^2$	$F$ statistic
3.1	0.782	0.752	26.30
3.2	0.325	0.266	5.53
3.3	0.647	0.617	21.11
3.4	0.504	0.481	22.23
3.5	0.991	0.990	1255.53
3.6	0.850	0.843	124.34
3.7	0.893	0.887	134.22

### *IIIc. Justification of the Model Equations*

Figure 15 shows that the behavior of the real wage is different in the two sectors. In addition, the estimation results indicate that the nature of the relationship between the real wage and technological change is also different in the two sectors.

The urban sector is best represented by Eq. (2.8). Increases in population drive the technological changes (as shown in Eq. (3.7)) which in turn cause real wage increases (apparently through increases in productivity). Increases in the lagged real wage and the rural wage also increase the urban wage.

These results contrast with the results found by Lee and Stavins. As already discussed, the Synthesis and the Composite approaches find  $\beta$  in the wage equation to be negative. Lee derives this result by using 50-year averages (Lee, 1978a) or by including a polynomial trend to allow for secular change in the demand for labor due to technological change (Lee, 1985b). Stavins (1988) includes urbanization instead. Then, both Lee and Stavins estimate an outward shifting labor demand schedule (due to technological change). This can be understood by an analogy. In econometrics, when you want to detrend a time series you can, among other procedures, regress it on a variable for time or on a polynomial trend. If a trend is included in a regression, the variation of the dependent variable due to time is eliminated. Lee and Stavins, by including a measure of technology or secular trend in the wage equation, eliminate the variation of the real wage due to technology. Then, the relationship between the real wage and population becomes a short-run one, like a labor demand schedule. This labor demand schedule was shifting due to technological change (see Fig. 2). In their framework, no room is left for a Boserupian causality to develop. Technological and real wage changes drive up fertility and population. However, population (as a proxy for the labor force) affects the real wage negatively in the short run.

In the New Look equation, the rationale behind the positive sign of  $\beta$  is in the Boserupian causality that the English data reveal. Population drives up technology and the real wage. Then, the effect of real wage changes on population growth (in Eq. (3.3)) is a feedback from the influence of population changes on technological changes. Given the specification of the New Look model, there is no need for including technological change in Eq. (3.1).

The rural sector behaved differently. The coefficient  $\kappa$  in Eq. (3.2) is negative, indicating that population increases had a negative effect on real wages in the rural sector. This can be interpreted as follows. Equation (3.2) (as well as (3.1)) is like a reduced form equation of the labor market. A larger population shifts the labor supply curve to the right and the labor demand curve upward (due to technological change). The effect on the equilibrium wage is indeterminate and is therefore an empirical matter. It appears that in the urban case the demand shift was larger than the supply shift, and, therefore, the real urban wage was rising with technological change. In the rural case, however, the supply shift was larger than the demand shift, and, therefore, the real rural wage was falling while technology was improving. One possible speculation as to why this might have occurred is that, perhaps, urban technology had a bigger payoff relative to rural technology, which resulted in relatively large shifts in the demand for urban labor.<sup>14</sup> This is likewise the intuition behind the specification of Eq. (3.5).

In Eq. (3.3), the population's growth rate is affected positively by the real wage in the urban sector. An increased urban wage results in an increasing fertility. In contrast, the negative relationship between the real rural wage and population reappears in this equation. The reason is that, as discussed before, an increased rural wage is associated with a decreased demand for farm labor. This is also the interpretation behind the relationship between outmigration<sup>15</sup> and the rural wage in Eq. (3.4). By contrast, emigration decreases when the urban wage increases.

Thus, the rural wage gives opposite results from the urban wage. Furthermore, these results are consistent throughout the model.

The link between technological (or technical) change and population in the New Look Eqs. (3.6) and (3.7) emerges from a reasoning similar

<sup>14</sup> This speculation was offered by an anonymous referee.

<sup>15</sup> There is currently a controversy on the sources of productivity advance in English agriculture, as demonstrated in Allen (1986, 1987, 1988) and Clark (1987, 1989a,b, 1990). Allen explains the rapid growth in labor productivity between 1600 and 1800 as a two-part development: first there was the rise in corn yields in the 17th century. Throughout the 18th century, however, enclosure and the increase in farm size reduced the labor employed per acre. Clark argues that the productivity rise resulted primarily from more labor inputs per worker and more intense work. The arguments of both Allen and Clark also infer a shift in population toward the cities, or outmigration.

to that of Simon and Sullivan (1989).<sup>16</sup> When population increases, the market increases, in other words the aggregate demand for the means of subsistence (and not only for food as in Simon and Sullivan) increases. This increased demand can be met by technological change as long as it is profitable to do so. A large population, if it is not followed by technological change, will fall into poverty. Therefore, there is also a socioeconomic pressure on technology to improve. It may be the case that the scenario did not work that way for other countries besides England. It is the case that in the 20th century overpopulated countries are devastated by poverty because their technology has not improved. However, the English data for the period 1550 to 1840 suggest that, in that country at that time, population did pull up technology.

In addition to population, it would be appropriate and desirable to have the accumulated technology in both the urban and rural sectors (and not only in the rural sector as in Simon and Sullivan (1989)<sup>17</sup>) as an explanatory variable in both Eqs. (3.6) and (3.7). This was not feasible since, first, there is no series for the number of publications on urban sector technology, and there is no reliable way of combining the existing series of patents issued with that of agricultural publications. At any rate, the data set for patents does not cover the entire period. Second, as already discussed, adding up inventions and innovations does not give the most reliable measure of existing technology.

### *IIId. A Granger Test for the Boserupian Causality Ordering*

Although the previous analysis has provided enough evidence for the dominance of the Boserupian causality over the Malthusian, a formal causality test will strengthen the argument. The causality notion adopted is the Granger one (subject to the axioms postulated in Appendix II), and the test that is performed is the Granger causality test. Thus, two bivariate autoregressive processes of order four are fitted to the data for

<sup>16</sup> Simon and Sullivan (1989) argue that total population, along with accumulated agricultural technology and food prices, is a significant explanatory variable of invention in farming. When population increases, the demand for food increases, and hence the demand for technical change increases. The supply of technical ideas, on the other hand, is facilitated by a greater supply of persons who may produce new ideas, when population increases. Simon and Sullivan include that the price of food in their equation, although it seems that there was no reason to do so. Population increases result in an increasing demand for food which likely causes higher prices that motivate technology to improve. Why should we then include the price of food independently in the equation to the additional risk of hindering the effect of population on technology? Finally, Simon and Sullivan, although their work is in the line of Boserup, do not show that the Boserupian causality ordering is dominant.

<sup>17</sup> The production of new agricultural technology should depend not only on the existing agricultural knowledge, but also on technology developed in the urban sector.



TABLE 3  
Regression Results for the Granger Test

Eq. No.	Independent variables							
	IR <sub>t-1</sub>	IR <sub>t-2</sub>	IR <sub>t-3</sub>	IR <sub>t-4</sub>	P <sub>t-1</sub>	P <sub>t-2</sub>	P <sub>t-3</sub>	P <sub>t-4</sub>
3.8	1.051 (3.600)	-0.893 (-2.800)	0.949 (2.500)	-0.010 (-0.020)	59.300 (0.500)	29.500 (0.200)	-261.500 (-1.500)	173.100 (1.500)
3.9	0.000 (0.000)	0.000 (0.600)	-0.000 (-0.200)	0.000 (0.100)	1.431 (5.900)	0.006 (0.020)	-0.662 (-2.000)	0.226 (1.000)

Note. Top numbers are estimates of the coefficients. *t* statistics are shown in parentheses.

agricultural technological change (that was proxied by IR<sub>*t*</sub>) and the population size (P<sub>*t*</sub>). The processes are as follows:

$$IR_t = \sum_{j=1}^4 \pi_{1j} IR_{t-j} + \sum_{j=1}^4 \rho_{1j} \ln P_{t-j} + u_t \quad (3.8)$$

$$\ln P_t = \sum_{j=1}^4 \pi_{2j} \ln P_{t-j} + \sum_{j=1}^4 \rho_{2j} IR_{t-j} + v_t. \quad (3.9)$$

The estimation of the processes yields the results summarized in Table 3.

The estimation of the processes indicates that both  $\rho_{13}$  and  $\rho_{14}$  are significant at 0.1, meaning that P<sub>*t-3*</sub> and P<sub>*t-4*</sub> affect IR<sub>*t*</sub>, while  $\rho_{11}$  and  $\rho_{12}$  are not significant. As to the second regression, all the coefficients of the lagged IR<sub>*t*</sub> variables are insignificant, meaning that these variables do not affect P<sub>*t*</sub>.

Thus, the Granger causality test indicates that population caused agricultural technology to grow, while technological change was not causally prior to population.

The Granger causality test was not applied for the urban technology, simply because there are only 18 observations available for IU<sub>*t*</sub>. An estimation of autoregressive processes for IU<sub>*t*</sub> and P<sub>*t*</sub>, such as those in Eqs. (3.8) and (3.9), would result in a great loss in the degrees of freedom.

#### IV. ECONOMETRIC EVALUATION OF THE NEW LOOK, SYNTHESIS AND COMPOSITE MODELS

##### IVa. Nonnested Hypothesis Testing

The three econometric models derived from the New Look, the Synthesis, and the Composite approaches are evaluated by nonnested hypothesis testing. Thus the *J* test is applied to evaluate the explanatory power of the three approaches. (A description of the *J* test is in Appendix III). The models used are derived from the actual models that were

estimated in the three approaches, applying restrictions (R1) for the Synthesis approach, restrictions (R2) for the Composite approach, and restrictions (R3) for the New Look approach.

Equations (3.2), (3.5), (3.6), and (3.7) are not introduced in any other approach, therefore the test is not applied to them.

*Equation (3.1).*

$$\begin{array}{ll} \text{New Look (NL)} & \ln W_t = \ln \eta + \beta \ln P U_t + b \ln W_{t-1} + \theta \ln W R_t \\ \text{Synthesis (S)} & \ln W_t = \ln \eta + \beta \ln P_t \\ \text{Composite (C)} & \ln W_t = \ln \eta + \beta \ln P_t + \delta U_t. \end{array}$$

The Synthesis hypothesis is nested within the Composite hypothesis, therefore a simple test of significance for  $\delta$  can show whether the explanatory power of the regression improves by the introduction of  $U$ . It turns out that the  $t$  statistic is 5.98, therefore  $\delta$  is significant.<sup>18</sup> Given this result, it is enough to compare the New Look to the nonnested Composite approach, and the results that hold for the Composite approach will also hold for the Synthesis.

The application of the  $J$  test for the New Look and the Composite approaches, yields

(a) For the test

$$\begin{array}{l} H_0: \text{NL} \\ H_1: \text{C}, \end{array}$$

the  $t$  statistic is  $t = 0.98$ , hence  $H_0: \text{NL}$  is not rejected at any level of significance  $\alpha$ .

(b) For the test

$$\begin{array}{l} H_0: \text{C} \\ H_1: \text{NL}, \end{array}$$

the  $t$  statistic is  $t = 4.98$ , hence  $H_0: \text{C}$  is rejected at any  $\alpha$ .

The results are clearly in favor of the New Look equation over the Composite.

*Equation (3.3).*

$$\begin{array}{ll} \text{New Look} & [(\ln P_t - \ln P_{t-1}) + m_t] = \pi \ln W_{t-3} + \phi \ln W R_{t-3} \\ & \quad + (\lambda - 1) d_t \\ \text{Synthesis} & [(\ln P_t - \ln P_{t-1}) + m_t] = \mu + a \ln W_t + (\lambda - 1) d_t \\ \text{Composite} & [(\ln P_t - \ln P_{t-1}) + m_t] = \mu + (\lambda - 1) d_t. \end{array}$$

The Composite hypothesis is nested within the Synthesis, therefore a simple test of significance for  $a$  can show whether the explanatory power of the regression improves by the introduction of  $W_t$ . The  $t$  statistic is

<sup>18</sup> Lee (1985b) includes a polynomial trend in the wage equation to allow for secular change in the demand for labor. Stavins analysis indicates that  $U_t$  yields superior results. In addition, Stavins argues that  $U_t$  is a better proxy for technological change and industrialization (Stavins, 1988, p. 105).

equal to 0.77 which implies that  $a$  is not significant. Therefore, the Synthesis and the Composite equation have the same explanatory power.

The application of the  $J$  test for the New Look and the Synthesis approach yields

(a) For the test

$$H_0: \text{NL}$$

$$H_1: S,$$

the  $t$  statistic is  $t = 0.77$ , hence  $H_0: \text{NL}$  is not rejected at any  $\alpha$ .

(b) For the test

$$H_0: S$$

$$H_1: \text{NL},$$

the  $t$  statistic is  $t = 4.09$ , hence  $H_0: S$  is rejected at any  $\alpha$ .

Thus the results are clearly in favor of the New Look equation over the Synthesis or the Composite equation, while the Synthesis and the Composite equation have the same explanatory power.

*Equation (3.4).*

$$\text{New Look } m_t = q \ln W_{t-2} + \psi W_{t-2}$$

$$\text{Composite } m_t = \ln \gamma - p \ln W_{t-3}$$

This equation is not introduced in the Synthesis approach.

The application of the  $J$  test yields

(a) For the test:

$$H_0: \text{NL}$$

$$H_1: C,$$

the  $t$  statistic is  $t = -0.013$ , hence  $H_0: \text{NL}$  is not rejected at any  $\alpha$ .

(b) For the test

$$H_0: C$$

$$H_1: \text{NL},$$

the  $t$  statistic is  $t = 3.92$ , hence  $H_0: C$  is rejected at any  $\alpha$ .

The results are clearly in favor of the New Look equation over the Composite.

In conclusion, as far as the econometric models involved in the different approaches are concerned, a nonnested hypothesis testing favors the New Look model against the Synthesis and the Composite models.

#### *IVb. Simulation Results*

Simulation results provide further support for the New Look approach. Both a static or historical and a dynamic simulation are run. A simulation is static when actual realized values of the lagged endogenous variables are used, and dynamic when earlier simulated values of the lagged endogenous variables are used in place of the actual values.

TABLE 4  
Simulation Results

Dependent variable	<i>u</i>	
	Dynamic	Static
$\ln W_t$	0.0152	0.0108
$\ln WR_t$	0.0085	0.0078
$(\ln P_t - \ln P_{t-1}) + m_t$	0.1218	0.1491
$m_t$	0.1891	0.1290
$\ln PU_t$	0.0063	0.0026
$IR_t$	0.1880	0.1880

Theil's inequality coefficient is used to evaluate the simulation results. It is defined as

$$u = \frac{\sqrt{(1/T) \sum_{t=1}^T [Y_t^s - Y_t^a]^2}}{\sqrt{(1/T) \sum_{t=1}^T [Y_t^s]^2} + \sqrt{(1/T) \sum_{t=1}^T [Y_t^a]^2}},$$

so  $0 \leq u \leq 1$ , where  $Y_t^s$  is the simulated value of  $Y_t$ ,  $Y_t^a$  is the actual value of  $Y_t$ , and  $T$  is the number of periods in the simulation. If  $u = 0$  the fit is perfect (Table 4).

Therefore, as far as the dynamic simulation results are concerned,  $u$  is close to zero for all the variables, and it does not exceed 0.19 for any variable. Thus, the ability of the model as a whole to reproduce the historical values of the endogenous variables is satisfactory. The results improve considerably in the static simulation case.

## V. SUMMARY

This paper shows that the English data reveal a Boserupian causality ordering. Regression results indicate that population caused technology to grow, and there is evidence suggesting that the trend change in the growth rate of population preceded that of technology. The rationale behind this causality is traced to the effect of population change on the aggregate demand for the means of subsistence, which can be satisfied by technological change.

Both Lee and Stavins, by including some measure of technology or secular trend in the wage equation, estimate<sup>a</sup> labor demand schedule which is shifting due to technological change. Therefore, in their models population does not determine technology, and it affects the real wage negatively in the short-run. No room is left for the Boserupian causality to

develop. Population change is responsive to exogenous mortality changes. Fertility, however, is not responsive to mortality. It is only responsive to real wage changes determined by technological changes. Thus, their analysis favors a Malthusian causality—population changes are primarily caused by exogenous technological changes.

The New Look approach develops a simultaneous equations model that can accommodate all the previous approaches as special cases. It expands on Lee's original homeostatic formulation and Stavins' endogenization of migration by introducing and endogenizing technological change and urbanization. Finally, it distinguishes between the rural and the urban sectors of the economy. It turns out that the nature of the relationships between technological changes and the wage and between population changes and the wage are different in the two sectors.

Contrary to Lee's assertion, the fertility rate is responsive to mortality changes. Therefore, in both sectors, exogenous mortality decreases drove the growth rate of population (directly or indirectly through the fertility rate) during the entire period of concern. Contrary to the Constant Equilibrium Wage, the Synthesis and Composite approaches, the New Look results show that population drove up technology (refer again to Fig. 13). In the urban sector, technological change drove up the real wage. The real wage change increased fertility. Thus, technological and real wage changes supported further population changes as feedback. In the rural sector, the technological change (caused by population change) resulted in a lower real wage. Population and the rural real wage were negatively related—the impact of population on demand is smaller than the impact of population on supply. Finally, technological change motivated the shift in population toward the cities.

The New Look model was evaluated by tests of significance, simulation results and the nonnested hypothesis testing, with satisfactory results. The nonnested hypothesis testing provides especially strong evidence of the superiority of the New Look model over the other alternatives.

## APPENDIX I: THE BASIC DATA SERIES

TABLE 5  
The Data

Decade <i>t</i>	$P_t^a$	$W_t^b$	$WR_t^c$	$m_t^d$	$d_t^e$	$U_t^f$	$IR_t^g$
1550-59	3,068,904	50.58	64.0	0.0135	0.3247	3.73	1
60-69	3,092,400	61.98	62.8	0.0114	0.2638	4.19	0
70-79	3,379,951	60.70	64.9	0.0130	0.2335	4.65	6
80-89	3,393,419	56.72	56.0	0.0152	0.2346	5.11	2
90-99	3,961,583	44.12	45.9	0.0179	0.2596	5.57	8
1600-09	4,219,218	42.45	45.6	0.0165	0.2376	6.10	6
10-19	4,490,276	38.17	42.6	0.0121	0.2597	6.40	12
20-29	4,754,209	42.89	48.5	0.0097	0.2589	6.70	3
30-39	5,005,171	40.23	46.0	0.0142	0.2607	7.00	11
40-49	5,161,609	45.05	48.6	0.0207	0.2592	7.30	11
50-59	5,242,577	47.47	47.2	0.0241	0.2710	7.25	24
60-69	5,109,116	46.74	46.4	0.0198	0.2917	9.70	17
70-79	5,022,547	49.14	48.8	0.0121	0.2865	10.15	16
80-89	4,915,504	54.11	53.9	0.0077	0.3267	10.60	10
90-99	4,973,811	51.28	48.7	0.0084	0.2851	11.05	16
1700-09	5,160,508	59.06	52.6	0.0100	0.2676	13.64	15
10-19	5,286,715	57.05	47.5	0.0104	0.2742	13.98	15
20-29	5,408,972	63.58	51.1	0.0101	0.3280	14.32	42
30-39	5,404,278	71.92	58.8	0.0091	0.2956	14.66	43
40-49	5,617,033	67.33	56.3	0.0096	0.2936	15.00	18
50-59	5,933,482	66.01	50.1	0.0112	0.2612	17.06	37
60-69	6,247,712	63.60	50.1	0.0107	0.2844	17.42	83
70-79	6,676,512	59.77	45.0	0.0072	0.2661	17.78	80
80-89	7,245,677	58.77	45.8	0.0045	0.2777	18.14	44
90-99	6,977,432	66.11	49.1	0.0050	0.2638	18.40	77
1800-09	9,078,892	48.23	48.0	0.0067	0.2586	22.35	175
10-19	10,409,161	50.43	46.4	0.0089	0.2556	24.40	137
20-29	12,120,254	66.16	48.5	0.0113	0.2350	26.45	93
1830-39	13,844,091	70.90	50.8	0.0136	0.2218	28.50	122

<sup>a</sup> The population size data,  $P_t$ , are 10-year averages of the annual data provided by Wrigley and Schofield (1981, Table A3.3, p. 531), adjusted for the total births by using Lindert's series for English births per thousand of population that might have occurred in addition to those estimated by Wrigley and Schofield (Lindert, 1983, Table 2, p. 145).

<sup>b</sup> The urban real wage,  $W_t$ , is a 10-year average, based on an annual real wage index (divided by 10) provided by Wrigley and Schofield (1981, Table A9.2, p. 642), and is produced from a nominal wage series for building craftsmen and laborers, and a price index provided by Brown and Hopkins (1966a,b), who in turn, relied mainly upon material collected by Rogers down to 1700.

<sup>c</sup> The real rural wage,  $WR_t$ , is drawn from the agricultural day wage-rates in Southern England which are provided in the Agrarian History of England and Wales (Finberg and Thirsk, 1967) for the period 1500-1649 (Table XV, p. 864). The rates of growth of the average daily wage-rate in certain areas of England, that is provided in the Agrarian History of England and Wales (Thirsk, 1985), were utilized for the period 1650-1749 (Table XXVIII, p. 877). Two observations for 1750-1759 and 1760-1769 were drawn from a series for 1750-1772 provided by Gilboy (1934) (p. 150, wages for mowing), while B. R. Mitchell (1962) provides an index series for the period 1770-1839 (Wages and the Standard of Living 3, p. 348). Then, in order to obtain a series consistent with the one provided by Wrigley and Schofield, the observation of 1500-1509 was set equal to 10,000 and an index was developed. The series was deflated by using the Brown and Hopkins price index. The real wage series was compared to another series which I derived by using a similar approach from the Rogers (1882) series (for the period until 1700) and from the Gilboy and Mitchell series. Although the latter series gave similar results, the performance of the former is superior.

<sup>d</sup> The net migration rate,  $m_t$ , is derived from data provided by Wrigley and Schofield (1981, Table A3.3, p. 531 and Table 7.11 p. 219).

<sup>e</sup> The crude death rate,  $d_t$ , is derived from data provided by Wrigley and Schofield (1981, Table A3.3 p. 531).

<sup>f</sup> In the absence of any other more detailed and reliable series, the urbanization component,  $U_t$ , is derived from 50-year averages provided by de Vries (1984, Table 3.7, p. 39 and Table 3.8, p. 45), by linear interpolation.

<sup>g</sup> The data for inventions and innovations in the rural sector,  $IR_t$ , are proxied by the data for the number of titles of books on agricultural techniques provided by Sullivan (1984, Table 1, p. 274), which was compiled from Perkins' bibliography.  $IR_t$  accounts for technological change.

## APPENDIX II: THE GRANGER-WIENER CAUSALITY

*The Granger definition of causality.* Let  $F(\chi|\Omega)$  be the conditional probability distribution of  $\chi$  given  $\Omega$ . Let  $I_t$  be the information set available at time  $t$ , excluding  $X_{t-\mu}$ ,  $\mu \geq 0$ . Let  $J_t$  be the expanded information set which is defined as follows:  $I_t$  plus  $X_{t-\mu}$ ,  $\mu \geq 0$ . Suppose that the following axioms hold:

*Axiom I.* The past and present may cause the future, but the future cannot cause the past.

*Axiom II.* A causality ordering contains unique information about an effect that is not available elsewhere.

Given these axioms, the following definition is derived.

$X_t$  does not cause  $Y_{t+\delta}$  with respect to  $J_t$ , if  $F(Y_{t+\delta}|I_t) = F(Y_{t+\delta}|J_t)$ ,  $\forall \delta > 0$ , (i.e. the extra information in  $J_t$  about  $X_{t-\mu}$  does not affect the conditional distribution). A necessary condition is that  $X_t$  does not cause  $Y_t$  in mean with respect to  $J_t$ , i.e.,  $E(Y_{t+\delta}|I_t) = E(Y_{t+\delta}|J_t)$ ,  $\forall \delta > 0$ , where  $E(\cdot)$  is the mean of the conditional distribution of  $Y_{t+\delta}$ .

*The Granger Causality Test.* The test involves fitting a bivariate autoregressive process of sufficiently high order to the data

$$Y_t = \sum_{i=1}^m \pi_i Y_{t-i} + \sum_{i=1}^m \rho_i X_{t-i} + u_t.$$

A test of the hypothesis that  $X_t$  does not cause  $Y_t$  is equivalent to testing  $\rho_i = 0$ ,  $\forall i$ .

*The Sims Causality Test.* A test of the hypothesis that  $X_t$  does not cause  $Y_t$  is equivalent to testing  $\alpha_i = 0$ ,  $i = -m_1, \dots, -2, -1$ , in the regression

$$Y_t = \sum_{i=-m_1}^{m_2} \alpha_i X_{t+i} + e_t.$$

The problem with this test is that  $e_t$  is not necessarily *white noise*.

The references for the Granger-Wiener Causality and the tests are Wiener (1956), Granger (1969), Granger (1980), Sims (1972, 1977, 1980a,b), Newbold (1982), Granger and Newbold (1986).

## APPENDIX III: NONNESTED HYPOTHESIS TESTING

Davidson and MacKinnon (1981) propose several tests for model specification in the presence of alternative hypothesis.

$$\begin{aligned} \text{Let } H_0: y_i &= f_i(x_i, \beta) + \varepsilon_{0i}, & \varepsilon_{0i} &\sim \text{NID}(0, \sigma_0^2), \\ H_1: y_i &= g_i(z_i, \delta) + \varepsilon_{1i}, & \varepsilon_{1i} &\sim \text{NID}(0, \sigma_1^2) \text{ if } H_1 \text{ is true.} \end{aligned}$$

Assume that  $H_1$  is not nested within  $H_0$  and  $H_0$  is not nested within  $H_1$ .

Davidson and MacKinnon recommend the use of the  $J$  test when  $H_0$  is linear. Thus, the hypotheses can be written as follows:

$$\begin{aligned} H_0: y &= x\beta + \varepsilon_0 \\ H_1: y &= z\delta + \varepsilon_1. \end{aligned}$$

The following auxiliary regression is run in order to perform the test:

$$y = x\beta(1 - \alpha) + (z\hat{\delta})\alpha + \varepsilon.$$

Then, if  $H_0$  is true, it is implied that  $\alpha = 0$ . If  $H_1$  is true, it is implied that  $\alpha$  tends to 1. One may use an asymptotic  $t$  test to evaluate  $\alpha = 0$ . Several alternatives can also be tested simultaneously by using an  $F$  test.

As Davidson and MacKinnon indicate, a  $t$  statistic which is valid for testing the truth of  $H_0$ , will not be valid for testing the truth of  $H_1$ . The simplest procedure to test  $H_1$  is to reverse the roles of  $H_0$  and  $H_1$  and carry out the test again.

## REFERENCES

- Allen, R. C. (1986), *Enclosure, Capitalist Agriculture and the Growth in Corn Yields in Early Modern England*. U.B.C. Department of Economics Discussion Paper 86-39.
- Allen, R. C. (1987), *The "Capital Intensive Farmer" and the English Agricultural Revolution: A Reassessment*. U.B.C. Department of Economics Discussion Paper 87-11.
- Allen, R. C. (1988), "The Growth of Labor Productivity in Early Modern English Agriculture." *Explorations in Economic History* 25, 117–146.
- Amemiya, Takeshi (1985), *Advanced Econometrics*. Cambridge: Harvard Univ. Press.
- Boserup, Ester (1981), *Population and Technological Change*. Chicago: Univ. of Chicago Press.
- Breusch, T. S., and Pagan, A. R. (1979), "A Simple Test for Heteroscedasticity and Random Coefficient Variation." *Econometrica* 47, 1287–1294.
- Brown, Phelps E. H., and Hopkins, Sheila V. (1966a), "Seven Centuries of Building Wages." In E. M. Carus-Wilson (Ed.), *Essays in Economic History*. New York: St. Martin's Press. Vol. II, pp. 168–178.
- Brown, Phelps E. H., and Hopkins, Sheila V. (1966b), "Seven Centuries of the Prices of Consumables, Compared with Builder's Wage-Rates." In *Essays in Economic History*, New York: St. Martin's Press. Vol. II, pp. 179–196.
- Clark, G. (1987), "Productivity Growth Without Technical Change in European Agriculture before 1850." *Journal of Economic History*, 47(2).
- Clark, G. (1989a), "Productivity Growth without Technical Change in European Agriculture: Reply to Komlos." *Journal of Economic History*, 49(4).
- Clark, G. (1989b), *Yields per Acre in English Agriculture 1266–1860: Evidence from Payments to Labor*. Discussion paper, Department of Economics, University of Michigan.
- Clark, G. (1990), "Labour Productivity in English Agriculture, 1300–1860." Forthcoming



- in B. Campbell and M. Overton (Eds.), *Productivity Change and Agricultural Development*.
- Crafts, N. F. R. (1985), *British Economic Growth during the Industrial Revolution*. Oxford: Clarendon Press.
- Davidson, R., and MacKinnon, J. G. (1981), "Several Tests for Model Specification in the Presence of Alternative Hypotheses." *Econometrica* **49**, 781–793.
- de Vries, Jan (1984), *European Urbanization 1500–1800*. Cambridge: Harvard Univ. Press.
- Finberg, H. P. R. (Gen. Ed.), and Thirsk, J. (Ed.) (1967), *The Agrarian History of England and Wales: Volume IV 1500–1640*. Cambridge: Cambridge Univ. Press.
- Gilboy, E. W. (1934), *Wages in Eighteenth Century England*. Cambridge: Harvard Univ. Press.
- Godfrey, L. G. (1978), "Testing against General Autoregressive and Moving Average Error Models When the Regressors Include Lagged Dependent Variables." *Econometrica* **46**(6), 1293–1302.
- Granger, C. W. J. (1969), "Investigating Causal Relationships by Econometric Models and Cross-Spectral Methods." *Econometrica* **37**(3), 424–438.
- Granger, C. W. J. (1980), "Testing for Causality: A Personal Viewpoint." *Journal of Economic Dynamics and Control* **2**, 329–352.
- Granger, C. W. J., and Newbold, Paul (1986), *Forecasting Economic Time Series*. San Diego: Academic Press.
- Hazon, Y. (1979), "Algorithms for Parallel Processing: Curve and Surface Definitions with Q-splines." *Computers and Graphics* **4**, 165–176.
- Jarque, C. M., and Bera, A. K. (1987), "A Test For Normality of Observations and Regression Residuals." *International Statistical Review*.
- Judge, G. G., et al. (1985), *The Theory and Practice of Econometrics*, 2nd ed. New York: Wiley Series.
- Koenker, R. (1981), "A Note on Studentizing a Test for Heteroscedasticity." *Journal of Econometrics* **17**, 107–112.
- Lee, R. D. (1973), "Population in Preindustrial England: An Econometric Analysis." *Quarterly Journal of Economics* **87**, 581–607.
- Lee, R. D. (1978a), *Econometric Studies of Topics in Demographic History*. Ph.D. thesis, Harvard University, 1971. New York: Arno Press.
- Lee, R. D. (1978b), "Models of Preindustrial Population Dynamics with Application to England." In C. Tilly (Ed.), *Historical Studies of Changing Fertility*. Princeton: Princeton Univ. Press. Pp. 155–207.
- Lee, R. D. (1980), "A Historical Perspective on Economic Aspects of the Population Explosion: The Case of Preindustrial England." In R. A. Easterlin (Ed.), *Population and Economic Change in Developing Countries*. Chicago: Univ. of Chicago Press. Pp. 517–566.
- Lee, R. D. (1984), "Malthus and Boserup: A Dynamic Synthesis." *Research Working Paper in Population No. 15*. Berkeley: Univ. of California.
- Lee, R. D. (1985a), "Inverse Projection and Back Projection: A Critical Appraisal and Comparative Results for England, 1539 to 1871." *Population Studies* **39**, 233–248.
- Lee, R. D. (1985b), "Population Homeostasis and English Demographic History." *Journal of Interdisciplinary History* **15**, 4, 635–660.
- Lindert, Peter H., and Williamson, J. G. (1983), "English Workers' Living Standards During the Industrial Revolution: A New Look." *The Economic History Review*, 1–25.
- Lindert, Peter (1983), "English Living Standards, Population Growth, and Wrigley-Schofield." *Explorations in Economic History* **20**, 131–155.
- Mitchell, B. R., with the collaboration of Phyllis Deane (1962), *Abstract of British Historical Statistics*. Cambridge: Cambridge Univ. Press.

- Newbold, Paul (1982), "Causality Testing in Economics." In O. D. Anderson (Ed.), *Time Series Analysis: Theory and Practice I*. Amsterdam: North-Holland.
- Rogers, James Edwin Thorold (1882), *A History of Agriculture and Prices in England*. Oxford: Clarendon Press. Vol. IV, V.
- Simon, J. L., and Sullivan, R. J. (1989), "Population Size, Knowledge Stock, and Other Determinants of Agricultural Publication and Patenting: England, 1541–1850." *Explorations in Economic History* **26**, 21–44.
- Sims, C. A. (1972), "Money, Income, and Causality." *American Economic Review* **62**, 540–552.
- Sims, C. A. (1977), "Exogeneity and Causal Ordering in Macroeconomic Models." In C. A. Sims (Ed.), *New Methods in Business Cycles Research*. Minneapolis: Federal Reserve Bank of Minneapolis.
- Sims, C. A. (1980a), "Comparison of Interwar and Postwar Cycles: Monetarism Reconsidered." *American Economic Review* **70**, 250–257.
- Sims, C. A. (1980b), "Macroeconomics and Reality." *Econometrica* **48**, 1–48.
- Stavins, Robert (1988), "A Model of English Demographic Change: 1573–1873." *Explorations in Economic History* **25**, 98–116.
- Sullivan, R. J. (1984), "Measurement of English Farming Technological Change, 1523–1900." *Explorations in Economic History* **21**, 270–289.
- Sullivan, R. J. (1986), "The Industrial Distribution of Patenting in England, 1617–1852." For presentation at the meeting of the Social Science History Association.
- Thirsk, J. (Gen. Ed. and Ed.) (1985), *The Agrarian History of England and Wales: Volume V 1640–1750. II. Agrarian Change*. Cambridge: Cambridge Univ. Press.
- Wiener, N. (1956), "The Theory of Prediction." E. F. Beckenbach (Ed.), *Modern Mathematics for Engineers*. New York: McGraw-Hill.
- Wrigley, E. A., and Schofield, R. S. (1981), *The Population History of England 1541–1871, A Reconstruction*. London: Arnold.