*Real Income and Mortality in a Household Production Model: English Mortality from 1541 to 1871**

Jeffrey Wagner, David Loschky and Charles McDaniel
Rochester Institute of Technology - University of Missouri-Columbia - Battlefield, Missouri

Studies of English pre-industrial mortality generally find there is no connection between income and mortality. Following Easterlin's (1995, 1999) suggestion, an estimated household health production model shows income did matter. Resolution of the problem results when explanations for cumulative shifts in the function's residual produce a zero cumulative residual. All prior studies are related in this model, producing a coherent investigation. Preliminary explanations, using all prior studies, clearly direct and suggest specific further required research. The structure produces several testable hypotheses. Easterlin's suggestion therefore yields a conceptual structure which provides a resolution, coherence in that all studies are related, directs required research and produces testable hypotheses.

1. Introduction

Despite the obvious fact that income, technical change and industrialisation played a major role in reducing mortality worldwide during the last century, economists and historians have found it extremely

* Revisions were undertaken by the first and third authors, who wish to express profound thanks to colleague and friend David Loschky for years of personal and professional guidance. David Loschky died in September 2005. For several helpful comments on our early ideas for this research, we are grateful to Larry Neal and the Economic History Workshop at the University of Illinois-Urbana. We are likewise grateful to Stanley Engerman, James Irwin, Charles Kahn, Charles Kolstad, David Mandy, Gary Santoni, and Ralph Sell for insightful comments on our manuscript in progress. Charles McDaniel's contributions to this paper are based upon his master's thesis research entitled "English Real Income: 1260-1850" submitted to the Department of Economics, University of Missouri-Columbia, 1991. Jeffrey Wagner was a graduate student at Illinois when this work began; he is grateful to the RIT College of Liberal Arts Dean's Office for supplemental research funding.

difficult to show that income had much effect upon English mortality in the nineteenth century and earlier. Perhaps no better illustration of this claim can be found than E. Anthony Wrigley and Roger S. Schofield's (1981) and Wrigley *et al.*'s (1997) treatment of mortality decline. Wrigley and Schofield (1981) summarise their findings by proposing several general models to explain population change between 1541 and 1870. These models include elements explaining mortality changes that are organised around Malthusian frameworks. Hence, Wrigley and Schofield expect that studies will show mortality between 1541 and 1870 was affected by income. By 1997, their view – expressed in Wrigley *et al.* (1997) – is different. They begin by contending that:

> "As a first approximation to the truth it might seem axiomatic to suppose that the higher the output of goods and services per head achieved by a society, the lower would be the level of mortality. A well-nourished well-clad, well-housed population that can also afford wood for heating and cooking must surely experience a lower level of mortality than one that lacks adequate food, clothing, shelter and fuel." (1997, p. 201)

But this axiomatic position is difficult to maintain because:

> "A growing body of empirical studies of mortality began to call into question any simple and predictable relationship between economic and demographic trends, and to do so even more clearly for mortality than for fertility." (1997, p. 201)

Debate concerning England's pre-industrial death rate began with publication of the original death rate series by John Brownlee (1916) and G. Talbot Griffith (1926) and their interpretations by Brownlee, Griffith and Mabel C. Buer (1926). These interpretations stressed the role of income by focusing upon medical and public health advances.

This interpretation, that medical and public health advances accounted for the fall in English mortality, was examined in great detail during the 1950s and 1960s by Thomas McKeown and associates (1955, 1962, 1976). They set up a disjunction in which any decline in mortality was attributable to either medical and public health advances or to a reduction in the virulence of disease-causing organisms or to growth in income. They examined England's medical and public health history and found nothing in this history to suggest that medical and public health developments could explain any significant drop in mortality before the nineteenth century. Arguing that there were no grounds for holding that the virulence of disease-causing organisms significantly fell during this particular period, they drew the conclusion that the remaining term in the disjunction, that is income growth, had to be the primary cause for the falling mortality shown in the existing series.

How then did income growth lead to the decline in mortality? Was it because the improved transportation network meant that when harvests were poor in a particular locality, food could be brought from surplus areas and sold at reasonable prices, thus lowering the national death toll by eliminating local dearth? And was the role shortages in short-term food supplies played in mortality significant? Different studies examined these questions by locating periods that showed considerable local spikes in food prices. These were used as indicators of food shortage, there being no existing series on food stocks. The expectation was that if income affected mortality, then very large shortages in food supplies would be related to subsequent increases in mortality. In local and regional studies covering five-year periods, they found that mortality would rise immediately following the price shock. But by the latter part of the five-year period, mortality would fall below normal; by the end of this time, mortality would be back to normal; and for the entire five-year period, mortality would be about average for any other five-year period. These studies, therefore, concluded that food shortages only killed off those who were weak and at great risk of death without affecting the overall mortality for the groups involved. This suggests that English mortality had not fallen because the country had eliminated the effects of local brief food shortages that occurred in the country. Had the English been living on the edge of subsistence, it is possible the elimination of local short-term food shortages by means of much better transportation could explain a drop in mortality throughout the whole of English society.

In contrast to these generally negative results are the studies by Maw

Lin Lee and David Loschky (1987) and by Robert Stavins (1988). These studies both produced statistically significant coefficients for the income-mortality variables. The results were obtained using several dummy variables designed to capture the effects of exogenous variables that shifted the fundamental relationships. One factor that could shift the fundamental relationship between income and mortality emerges from the work of Nicky Hart (1993). Using infant mortality statistics from different regions of the Netherlands during the German occupation when food was in extremely short supply, she found very large variations in infant mortality. She argued that infant mortality was highly affected by nutritional history along the maternal line. Her conclusion was that, when successive members of the maternal line experienced good nutrition, the newborn's immune systems were materially strengthened, with the result that these newborns' mortality was much lower than it was for newborns of women whose maternal line of nutrition was poor. This conclusion is mirrored in the work of Wrigley (1998).

We believe it is possible to knit together these various results using the framework suggested by Richard Easterlin (1995, 1999). He suggested the use of a production function approach to the study of mortality. McKeown's results suggest that, prior to the nineteenth century, health was not produced by the accomplishments of society as a whole, such as through medical and public health advances. Consequently, while health is produced within various social institutions today – such as hospitals, clinics and health visitor associations – historically the most significant institution producing health was the household. It was the institution most associated with the "well-nourished, well-clad, well-housed population" to which Wrigley and Schofield refer. The concept of a household production function provides connections between income and mortality, since the household uses income-related inputs to produce nourishment, clothing and housing. Moreover, these are the very items that we collectively and intuitively associate with health for humans as well as for other animals. These facts suggest an exploration of English mortality history between 1541 and 1871 organised by the concept of household production. Because the English household actually produced life expectancy in those days, the basic assumptions upon which this study rests would not appear strange to any Englishman living during the period in question.

We estimate a household health-production function using Robert Solow's (1957, 1958) method for estimating technical change. We do not suggest that the residual Solow computes would count as completing the explanation for mortality change. Rather, the residual represents those changes that occurred in the production of health that remain to be explained. If the residual shows any regular pattern, that pattern may suggest solutions to the remainder of the problem. This orientation will produce not only suggestive lines for further research independent of any hypotheses generated, it will also generate testable hypotheses. We illustrate this method in what follows. And within its structure, all preceding studies find their place.

Our paper proceeds as follows. We present our model of aggregate household production in Section 2; we use Wrigley and Schofield's (1981) life expectancy at birth data, the Henry Phelps Brown and Sheila Hopkins (1981) data regarding nominal wages, expenditure shares, and food and nonfood input prices, and Solow's (1957, 1958) aggregate production function framework. We obtain empirical estimates of the model in Section 3 and show that the results are quite consistent with our economic intuition, and are certainly parallel with Solow's own results (for the relationship between output per man-hour and the capital/labour ratio in the US, 1909-1949). In Section 4 we present our results and in Section 5 we discuss how they affect our understanding of economic and demographic change in pre-industrial England. We present our conclusions in Section 6.

2. The model

Our intention is to combine the standard household production framework – as is used by researchers such as Michael Grossman (1972), Mark Rosenzweig and T. Paul Schultz (1982, 1983), Michael P. Shields (1995) and Lung-fei Lee, Rosenzweig, and Mark Pitt (1997) – with an emphasis upon life expectancy at birth as the summary indicator of aggregate household production success or efficacy. In emphasising life expectancy at birth, we share the view of Simon Szreter and Graham Mooney (1998, p. 86) and Suchit Arora (2001, p. 704) that it is the single best measure of population health. We do not intend to suggest that longevity is the sole measure of the household's welfare, either individually or in the aggregate. We assume here that *ceteris paribus* households aim to maximise longevity from their limited resources.[1] Thus, we propose a model in which life expectancy at birth is produced in the aggregate by households from quantities of food and nonfood according to the following aggregate household production function:

$$e_o = G(N,F;t) \qquad \textbf{(1)}$$

where e_o = life expectancy at birth
N = quantity of nonfood
F = quantity of food
t = time

We assume that G(·) is twice differentiable, with $G'>0$, $G''<0$ in each argument, N and F. Thus, N and F are weak substitutes in the production of life expectancy at birth, and some positive amounts of both N and F are required for life. The time element reminds us that the aggregate household production function is subject to technical change. Such technical change could be positive – as households learn by doing – and could be negative, as households find that forces generally labelled as "urbanisation" (and specifically measured as increases in factors such as particulate matter, noise, and congestion), make it more difficult at times to sustain or raise life expectancy at birth among the group from any

[1] We do employ *national* figures for life expectancy at birth reported by Wrigley and Schofield (1981), whereas researchers such as David Loschky (1972) and Szreter and Mooney (1998, p. 104) show that urban and rural differences in life expectancy at birth can be significant and perhaps affect the conclusions one can draw regarding aggregate well-being. We also do not take into account the intertemporal aspect of health stocks versus flows, such that, if the household has a relatively high stock of health (perhaps from investments in prior periods), then a drop in household inputs in this period (a negative flow shock) would be absorbed better than by a household with a relatively low stock of health brought forth from previous periods. We abstract from this aspect of household health determination over time; life expectancy at birth in the current period is posited as a function only of household input selection in the current period.

given bundle of food and nonfood inputs. If we can assume that such technical change is neutral with respect to N and F, then we can introduce $A(t)$ as the cumulative technical change factor and write the production function **(1)** as:

$$e_0 = A(t)g(N,F) \qquad \textbf{(2)}$$

The usual household production framework has the household producing output from household inputs in order to maximise a household utility function defined over a vector of household outputs. Robert Pollak and Michael Wachter (1975) and Nancy Bockstael and Kenneth McConnell (1983) have shown that joint production and non-constant returns to scale create difficulties in interpreting the welfare implications of results derived from household production models. As Shields (1995, pp. 122-123) points out, however, limiting the household's production possibilities to a single output (in our case, life expectancy at birth) and to constant returns to scale enables us to meet the Pollak and Wachter (1975) conditions, and to assert that the household will be maximising utility by maximising output, so long as the marginal utility from output can be assumed to be strictly positive. We assume in our abstract model that these conditions are reasonable, and thus conceptualise the aggregate household economic problem as one of maximising the production of life expectancy, e_0, subject to the aggregate household budget constraint,

$$Y = P_F F + P_N N \qquad \textbf{(3)}$$

where Y = nominal wage index.
P_F = perfectly competitive price of food.
P_N = perfectly competitive price of nonfood.

We may easily construct a Lagrangian equation from **(2)** and **(3)**, and show that, in the aggregate, households would maximise life expectancy at birth by choosing food and nonfood such that the marginal rate of technical substitution just equals the input price ratio. From this point of tangency, back substitution would yield the highest life expectancy that can be obtained, given the current household technology, nominal wages, and relative prices of food and nonfood. An exogenous increase (decrease) in nominal wages would shift the budget line outward (inward) to a tangent with a higher (lower) isoquant, enabling a higher (lower) life expectancy at birth in the households. If the price of one of the inputs rises (falls), then the budget line twists downwards (upwards) to a tangency with a lower (higher) isoquant; the households substitute away from (toward) the relatively more expensive (less expensive) input, and life expectancy at birth in the households falls (rises).

Our chief concern in this paper, however, regards the problem of understanding household production of longevity, in the presence of probable technical change, from observed time series data on life expectancy at birth; nominal wages; food and nonfood prices; and either quantities of food and nonfood, or expenditure shares on food and nonfood. Technical change has the effect of shifting the household isoquants over food and nonfood in the production of life expectancy. Thus, we cannot immediately say whether an observed change in life expectancy should be attributed to a change in income (the household's budget constraint) or a change in the underlying household technology. As we described in the Introduction, we feel that resolving these two effects is the key to understanding the income-mortality relationship.

Solow's (1957) approach to measuring technical change suggests a way forward, in that under certain assumptions, we can disentangle movements *along* the aggregate production function from *shifts* in the function arising from technical change. We proceed under the assumption of constant factor shares, so that the method suggested by Solow (1958, pp. 411-412) is most appropriate for our situation.[2] Solow suggests proceeding with a Cobb-Douglas form for our production function **(2)**:

$$\frac{e_o}{F} = A(t)\left(\frac{N}{F}\right)^{W_N} \qquad \textbf{(4)}$$

[2] We shall discuss further the constant factor share assumption below when we discuss the estimation procedure and the data.

Letting $q = \dfrac{e_o}{F}$ and $n = \dfrac{N}{F}$, we can write **(4)** as:

$$q(t) = A(t)n(t)^{w_N} \quad \textbf{(5)}$$

And the technical change shift factor is straightforwardly given by:

$$A(t) = \frac{q(t)}{n(t)^{w_N}} \quad \textbf{(6)}$$

Thus, given *q(t), n(t),* and a constant w_N, the technical change shift factor (also known as the Solow residual) can be obtained. It is worth repeating that *A(t)* is, under the assumption of Cobb-Douglas production with constant factor shares, a measure of the parallel shifts in household isoquants that transform food and nonfood quantities into output (taken here to be the life expectancy at birth).

3. Model estimation

The life expectancy data presented by Wrigley and Schofield (1981, pp. 528-529) is presented at five-year centred intervals (i.e., 1539, 1540, **1541**, 1542, 1543, 1544, 1545, **1546**, 1547, 1548, ...), such that the data set comprises only the data points in bold.[3] With the quinquennial life expectancy data in hand, we must construct quantity indexes, *F* and *N*, from data regarding nominal wages, prices for food and nonfood, and expenditure shares in England for this period.[4] The nominal wage series is that for craftsmen compiled by Phelps Brown and Hopkins (1981, pp. 11-12). Wrigley and Schofield (1981, p. 640) also use this particular series, and we follow their methodology for smoothing the nominal wage series by interpolation (as there are a few data points missing). They then let the 6*d* nominal wage in 1500 equal an index number of 10,000 and go

[3] We also conducted our analysis utilizing life expectancy at birth data introduced in Wrigley *et al.* (1997, p. 614); however, the results were by and large similar.

[4] We provide additional details regarding the data and the estimation procedure in the Appendix.

from there. Our series starts in 1541, at which point nominal wages are interpolated to equal 6.5*d*; we therefore let the nominal wage of 6.5*d* in 1541 be equal to 10,000.

Phelps Brown and Hopkins (1981, pp. 44-59) compiled the price series data we use. They construct a price series for four different food categories (farinaceous, meat/fish, cheese/butter, and drink) and two nonfood categories (fuel/light, and textiles). As with the nominal wage series, there are a few missing prices over the period 1541-1871. We followed the procedures of Wrigley and Schofield (1981, pp. 638-641) for completing the data set by dividing the gaps between data points into equal increments and interpolating the missing points. The only other gap to fill in our particular study is the absence of butter prices from 1541 until 1561. In this case, we ran the 1561 butter price of 370 back through 1541.

Now, in order to use the nominal wage and price series data to obtain quantity indexes for food and nonfood, we employ the Phelps Brown and Hopkins (1981, p. 14) observation that households fairly consistently allocate their budgets *in nominal terms* according to 20% farinaceous, 25% meat, 12.5% butter, 22.5% drink, 7.5% fuel and light, and 12.5% textiles. Therefore, expenditures upon food comprise 80% and expenditures upon nonfood comprise 20%. We multiply the nominal wage index by this vector of percentages and obtain a vector of *nominal expenditures* upon each consumption good.[5] We then divided each nominal expenditure by its respective price index, yielding a quantity index. Thus, if the unit price of meat is \$25 in the above example, then the quantity of meat purchased was $\frac{\$2500}{\$25} = 100$ units. In order to obtain the aggregate (abstract) food index, *F*, we added the four resulting food quantity indexes; to obtain the aggregate (abstract) nonfood index, *N*, we added the two resulting nonfood quantity indexes.

Next, it must be remembered that the life expectancy at birth data is reported by Wrigley and Schofield (1981) in five-year centred intervals. In order to proceed with our estimation of technical change in the aggregate household production function, we needed to compute food

[5] For example, if the nominal wage index is \$10,000 in a given year, the representative household is assumed to spend \$2000 on farinaceous goods, \$2500 on meat, and so forth.

and nonfood *quantity averages* corresponding to the years for which we have life expectancy data. The completion of these steps enables us to compute the substitutions for $q = \frac{e_o}{F}$ and $n = \frac{N}{F}$. Lastly, we must postulate a parameter value for the share (contribution) of nonfood toward the production of life expectancy, denoted as in equation **(6)**. This parameter is likewise known in this context as the elasticity of output with respect to nonfood, $\frac{\delta e_o}{\delta N} \frac{N}{e_o}$. While we have data for N and e_o, we do not have data for $\frac{\delta e_o}{\delta N}$. Thus, we use the observation of Phelps Brown and Hopkins (1981, p. 14) that the nominal share of nonfood in the household budget is fairly consistently 0.20 across many centuries of our investigation. This implies that the life expectancy at birth that we observe is 20% motivated by the contribution of nonfood to the production process. We therefore employ a constant parameter of 0.20 for w_N in equation **(6)**. With all data in place, we are then in the position to estimate A(t), equation **(6)**, the technical change shift factor in the relationship between households' consumption of food and nonfood versus the production of life expectancy at birth.

4. Results

Figure 1 presents the relationship between the nonfood/food ratio (on the x-axis) and the life expectancy at birth per unit of food (on the y-axis), adjusted for cumulative aggregate household technical change. We obtain a closely fitting function. The marginal product of nonfood is higher at low nonfood inputs and then falls off. Diminishing returns are evident. Since our production function assumes diminishing returns, this finding does not count as confirmation of this method.

Our next result, shown in *Figure 2*, emerges from revisiting equation **(6)** and obtaining a different equation by dividing both sides of equation **(2)** by the nonfood index. We again find a closely fitting function.

There are substantial shifts in the household's production function and these are fairly continuous throughout the period we investigate. The cumulative shifts in household production that yielded the results in *Figure 1* and *Figure 2* are presented in *Figure 3*. There appear to be four general periods in *Figure 3*. The function shifts upward between the start of our observations (1541) and continues to shift upward until about 1641. By that time the life expectancy per unit of input has about doubled. The second period also is about a century long. It lasts from about 1641 to about 1735. During this century the function shifts downward, and at the end of the period it is about where it started in 1541. The third period is shorter than the preceding two. It lasts from about 1735 until about 1811. In this 75-year period the function shifts upward but the extent of the shift is smaller and at the end of the period the function sits at about 1.5 times its original level. The fourth period lasts until the end of our data (1871). By this time the function has shifted downward again and in the 60 years it has returned to about its initial level.

5. Discussion

The residual now requires explanation. When the residual is reduced to zero, the explanation is counted as being complete. An important feature of any structure is that it tells the reader when closure is obtained, and closure here is provided by a zero residual. This is not to say that several different explanations are not possible.

Lee and Loschky (1987) and Stavins (1988) found a statistically significant relationship between income and mortality. This finding is consistent with and supports the closely-fitting functional relationship between food and nonfood inputs we find in this model. Both Lee and Loschky (1987) and Stavins (1988) used dummy variables for different periods to represent shifts in the functional relationships in their estimates. The approach we take in this paper is to endogenise the shifts in the relationship between income and mortality to make them more readily accessible to explanation.

The materials we have to explain these shifts in the relationship between income and life expectancy include urbanisation (since urban death rates are well above rural death rates, increasing urbanisation increased England's death rates);[6] McKeown's analysis of developments

[6] An example of the national rate adjusted for urbanization can be found in Loschky (1972).

in medicine and public health; Hart's (1993) findings and the work of Wrigley (1998) related to stillborns; and the impact of improved housing.

Urban death rates were well above rural death rates and the percentage of England's population living in urban areas increased consistently over our period. This means that urbanisation lowered English life expectancy. If we were to construct a national life expectancy from which we eliminated urbanisation's effect, it would be higher. Since we estimated the residual using a life expectancy series which was not adjusted for urbanisation's effect, this means adjusting for urbanisation will increase the residual because the dependent variable would be larger and the requisite shifts in the production function would be greater. Because urbanisation was a continual process, the residual would be affected more and more as time went on. The greatest effect would show at the end of the period analyzed, in other words, during the 1800s. Whether it could account for the downward shift in the residual we see in the period from 1811 to 1871 remains a subject for further investigation. Moreover, the timing of the peaks and troughs in cumulative residual shift series would shift. How strong this effect would be also remains as a subject for further investigation.

McKeown argues that in the nineteenth century there were sufficient medical and public health advances to bring about a fall in the death rate. This should show up as an increase in life expectancy, an upward shift in the production function, and therefore, as an increase in the cumulative shift series. Because McKeown's findings would explain an upward shift in the production function – if we take these arguments into account and were to subtract them from the cumulative residual – we would see the unexplained residual fall. It should be possible to determine the impact of these medical and public health improvements through local studies. If the combined consequences of increased urbanisation and McKeown's thesis fail to produce a residual near to zero, then this finding will suggest lines for further research.

Since local studies examining the effect of food shortages show that the effect was strictly of a very short-term nature, there should be a weak and temporary fall in life expectancy. As our data cover five-year periods, we should not observe this effect.

Sustained income changes and their effect upon life expectancy should appear according to Hart's argument. She argued a sustained increase in nutrition along the maternal line led to a strengthened immune system. If this effect works both ways, then a sustained degradation in nutrition along the maternal line leads to a reduction in the strength of the immune system. A sustained reduction in nutrition will lead to a downward shift in the production function, since the production of health per unit of short-run food input will fall. This should lead to a reduction in the residual. According to our structure, this effect is subtracted from the residual. Similarly, a sustained rise in income will lead to upward shifts in the production function and this again will lead to an increase in the residual. According to our structure, this also is subtracted from the residual. Three issues for further research arise. Does the strengthened immune system in the infant, for this is all that she argued, confer better health throughout life? How strong is this effect as a function of the degree of altered nutrition along the maternal line? Some suggestions concerning this issue may well emerge from studies of stillbirths such as that developed by Wrigley (1998). Thirdly, what kinds of lags are involved? It would appear these may be quite long, as Hart refers to several generations of improved nutrition. Each of these issues suggest lines of further research.

Taking these implications of Hart's argument into account, and recognising the tenuous nature of the argument because of the uncertainties involved as suggested above, we can offer some suggestions concerning the residual. Firstly, there was a sustained fall in real income starting in the early sixteenth century and continuing into the very early seventeenth century. This should lead to a decline in the residual. Instead, we find an increase that appears quite substantial. It is possible that this upward shift in the production function may have arisen because of the substantial improvements in housing that occurred during the sixteenth century (Dyer, 1986). These would appear as upward shifts in the production function that would apply to all periods following these improvements. Life in houses with plank floors and with fireplaces can be expected to lead to fewer deaths because of respiratory diseases, the remarks of some contemporaries notwithstanding.[7] Research into the causes for deaths before and after the introduction of these newer houses can test the hypothesis that this change produced an upward shift in the household production function and, therefore, to an increase in the residual. If housing improvements are inadequate to convert what, according to the Hart thesis, should be a decline in the residual, into the observed rise in the residual, then this structure will have pinpointed a major issue for investigation.

The suggestions for research advanced above do not exhaust the potential of the structure presented here. M. M. Postan (1950) and Postan and J. Z. Titow (1959) argued forcefully that the English experienced a Malthusian crisis during the fourteenth century. Firstly, if Postan were correct, then this analysis suggests that during the fourteenth century the marginal product of food would be higher than we find. A second hypothesis is that we would expect diminishing returns to food to set in much later in the fourteenth century than in our later time period.

6. Conclusion

Many careful prior studies have failed to find a strong, or even weak, positive relationship between historic income and English mortality. We argue this may be due more to the concepts used to study the relationship than to the lack of any relationship. We suggest the use of a household production function in which the household produced health and life expectancy. We estimate this function for England between 1541 and 1871. We find a consistent relationship between food and life expectancy and a consistent relationship between nonfood and life expectancy. We also find considerable shifts in the household production function. These shifts lead to a residual that, in turn, becomes the element to be explained.

[7] When people were moving into the modern houses with vertical walls (which made windows possible), plank floors and crude fireplaces, some of the older generation grumbled that these newfangled houses would surely weaken the English. After all, it was believed that, just as surely as smoke from the fires cured bacon in the roof, and it obviously did, it also just as surely must have cured and, therefore, strengthened the lungs of all people living in the houses.

Prior studies are set against the cumulative residual. Each can be fitted into the picture produced by the estimated household production function. Each suggests interesting and possible lines for future research. Additionally, testable hypotheses concerning other interpretations present themselves.

REFERENCES

S. Arora, 'Health, human productivity, and long-term economic growth', *Journal of Economic History* 61 (2001), pp. 699-749.

N. E. Bockstael and K. E. McConnell, 'Welfare measurement in the household production framework', *American Economic Review* 73 (1983), pp. 806-814.

J. Brownlee, 'The history of the birth and death rates in England and Wales taken as a whole, from 1570 to the present time', *Public Health* (June 1916), pp. 211-222, and (July 1916), pp. 228-238.

M. C. Buer, *Health, Wealth and Population in the Early Days of the Industrial Revolution,* (London 1926, reissued in 1968).

C. Dyer, 'English peasant buildings in the later middle ages (1200-1500)', *Medieval Archaeology* 30 (1986), pp. 19-43.

R. A. Easterlin, 'Industrial revolution and mortality revolution: two of a kind?' *Journal of Evolutionary Economics* 5 (1995), pp. 393-408.

R. A. Easterlin, 'How beneficent is the market? A look at the modern history of mortality', *European Review of Economic History* 3 (1999), pp. 257-294.

G. T. Griffith, *Population Problems of the Age of Malthus*, 2nd Edition, (New York 1967).

M. Grossman, 'On the concept of health capital and the demand for health', *Journal of Political Economy* 80 (1972), pp. 223-255.

N. Hart, 'Famine, maternal nutrition and infant mortality: A re-examination of the Dutch hunger winter', *Population Studies* 47 (1993), pp. 27-46.

L. Lee, M. R. Rosenzweig, and M. M. Pitt, 'The effects of improved nutrition, sanitation and water quality on child health in high-mortality populations', *Journal of Econometrics* 77 (1997), pp. 209-235.

M. L. Lee and D. Loschky, 'Malthusian population oscillations', *Economic Journal* 97 (1987), pp. 727-739.

D. Loschky, 'Urbanization and England's eighteenth-century crude birth and death rate', *Journal of European Economic History* 1 (1972), pp. 697-712.

C. L. McDaniel, *English Real Income: 1260-1850*, master's thesis submitted to the Department of Economics, University of Missouri-Columbia, 1991.

T. McKeown and R. G. Brown, 'Medical evidence related to English population changes in the eighteenth century', *Population Studies* 9 (1955), pp. 119-141.

T. McKeown and R. G. Record, 'Reasons for the decline in mortality in England and Wales during the nineteenth century', *Population Studies* 16 (1963), pp. 94-122.

T. McKeown, *The Modern Rise of Population*, (New York 1976).

H. Phelps Brown and S. Hopkins, *A Perspective of Wages and Prices*, (London and New York 1981).

R. A. Pollak and M. L. Wachter, 'The relevance of the household production function and its implications for the allocation of time', *Journal of Political Economy* 83 (1975), pp. 255-278.

M. M. Postan, 'Some economic evidence of declining population in the later middle ages', *Economic History Review*, Second Series, II (1950), pp. 221-246.

M. M. Postan and J. Z. Titow, 'Heriots and prices on Winchester manors', *Economic History Review*, Second Series, XI (1959), pp. 392-411.

M. R. Rosenzweig and T. P. Schultz, 'Market opportunities, genetic endowments and intrafamily resource distribution: child survival in rural India', *American Economic Review* 72 (1982), pp. 803-815.

M. Rosenzweig and T. P. Schultz, 'Estimating a household production function: heterogeneity, the demand for health inputs, and their effects on birth weight', *Journal of Political Economy* 91 (1983), pp. 723-46.

M. P. Shields, 'Time, hedonic migration and household production', *Journal of Regional Science* 35 (1995), pp. 117-134.

R. Solow, 'Technical change and the aggregate production function', *Review of Economics and Statistics* 39 (1957), pp. 312-320.

————, 'Technical progress and production functions: reply', *Review of Economics and Statistics* 40 (1958), pp. 411-413.

R. Stavins, 'A model of English demographic change: 1573-1873', *Explorations in Economic History* 25 (1988), pp. 98-116.

S. Szreter and G. Mooney, 'Urbanization, mortality and the standard of living debate: new estimates of the expectation of life at birth in nineteenth-century British cities', *Economic History Review*, Second Series, LI (1998), pp. 84-112.

E. A. Wrigley, 'Explaining the rise in marital fertility in England in the 'long' eighteenth century', *Economic History Review* 51 (1998), pp. 453-464.

E. A. Wrigley and R. S. Schofield, *The Population History of England, 1541-1871: A Reconstruction*, Reprint Edition (Cambridge 1989).

E. A. Wrigley, R. S. Davies, J. E. Oeppen, and R. S. Schofield, *English Population History from Family Reconstitution, 1580-1837*, (Cambridge 1997).

Appendix

Real Income and Mortality in a Household Production Model: English Mortality from 1541 to 1871

Appendix: Notes on Excel spreadsheet of data

Col A: Years 1541-1873.
Col B: Farinaceous price series from Phelps Brown and Hopkins (PBH), pp. 44-59.
Col C: Meat price series from PBH.
Col D: Butter price series from PBH.
Col E: Drink price series from PBH.
Col F: Fuel price series from PBH.
Col G: Textile price series from PBH.
Col H: Whole price series from PBH.
Col I: (Smoothed) Nominal wage series from PBH, pp. 11-12. We follow Wrigley and Schofield (1981, pp. 638-644) in utilizing the PBH wage series for craftsmen, and we utilize linear interpolation to smooth occasional gaps in the PBH series.
Col J: Normalization of Col I such that first value in the series is equal to 10,000.
Col K: Quantity of farinaceous goods. Here we used the budget share data reported by PBH p.14 and multiplied the farinaceous share of 20% by Col J, and divided this result by the price of farinaceous goods in Col B.
Col L: Quantity of meat, by procedure corresponding to that described in Col K.
Col M: Quantity of butter, by corresponding procedure.
Col N: Quantity of drink, by corresponding procedure.
Col O: Quantity of fuel, by corresponding procedure.
Col P: Quantity of textile, by corresponding procedure.
Col Q: Quantity of food. We add Columns K, L, M, and N to obtain a food quantity index.
Col R: Quantity of nonfood. We add Columns O and P to obtain a nonfood quantity index.
Col S: Year marker, to facilitate reading spreadsheet.
Col T: Expectation of life at birth from Wrigley and Schofield (1981, pp. 528-529).
Col U: Year again; however, here we pull the data into five-year increments, since Wrigley and Schofield report life expectancy at birth in five-year centred intervals.
Col V: Same data as presented in Col T, but with spaces removed.
Col W: Qfavg is the quantity of food index reported in Col Q, averaged over five-year intervals centered on the dates for which we have the life expectancy at birth in Col V. The centering years are 1541, 1546, 1551, etc. In order to obtain a centered average for 1541, we needed the quantity data for 1539 and 1540. We retrieved the price data for those years from PBH as follows:

Year	Fa	M	B	D	Fuel	Text	W	Nom Wage	Norm Wage
1539	132	168	370	139	103	148	147	6.5	10,000
1540	144	190	370	144	96	149	158	6.5	10,000

These prices and wages (and the PBH budget share information invoked to construct Col K through Col P) enable us to obtain the following quantities per good per year:

Year	Qfa	Qm	Qb	Qd	Qfuel	Qtext	Qfood	Qnonfood
1539	15.15	14.88	3.38	16.19	7.28	8.45	49.60	15.73
1540	13.89	13.16	3.38	15.63	7.81	8.39	46.05	16.20

We then add these Qfood indices from 1539 and 1540 to those for 1541, 1542 and 1543 (in the spreadsheet) and divided by five in order to obtain the 46.034 figure reported in cell W2. This is the average quantity of food over the five years centred on 1541. We repeated this procedure for each of the five year centred intervals through 1873.

Col X: Qnonfood average obtained by procedure corresponding to that just described to obtain Col W.
Col Y: "solowq81" is Col V divided by Col W, or the life expectancy at birth divided by the quantity of food. This yields the $q = e_0/F$ substitution just after eq. (4) on p. 9 of our manuscript.
Col Z: "solowx" is Col X divided by Col W, or the quantity of nonfood divided by the quantity of food. This yields the n = N/F substitution just after eq. (4) on p. 9 of our manuscript.
Col AA: Solow's "W_X" is our W_N, the share of Nonfood in the production function. As we discuss on page 12 of our paper, we assume this is constant at $W_N = 0.2$, based upon Phelps Brown and Hopkins observation that the share of nonfood in household budgets is fairly constant at 0.2 across several centuries (with share of food, therefore, equal to 0.8).
Col AB: "Input" is Col Z raised to the $W_N = 0.2$ power.
Col AC: A(t) is the technical change shift factor, also known as the Solow residual, obtained in this case of constant factor shares by dividing Col Y by Col AB.
Col AD: A(t) normed to one, such that A(1) = 1.
Col AE: q/A is Col Y divided by Col AD, or life expectancy divided by food, all divided by our normed measure for cumulative technical change. Then Figure 1 comprises Col Z on the x-axis and Col AE on the y-axis.
Col AF: Year.
Col AG: blank.
Col AH: Col W divided by Col X, all raised to the 0.8 power.
Col AI: Col V divided by Col X, or life expectancy at birth divided by nonfood.
Col AJ: Cumulative technical change, the same measure here as is presented in Col AC, because we are assuming neutral technical change.
Col AK: Same as Col AD.
Col AL: Col W divided by Col X, or food divided by nonfood.
Col AM: Col AI divided by Col AK, or life expectancy at birth divided by nonfood, all divided by our normed measure for cumulative technical change. Thus, Figure 2 comprises Col AL on the x-axis and Col AM on the y-axis, while Figure 3 comprises the year on the x-axis and Col AD on the y-axis.

FIGURE 1

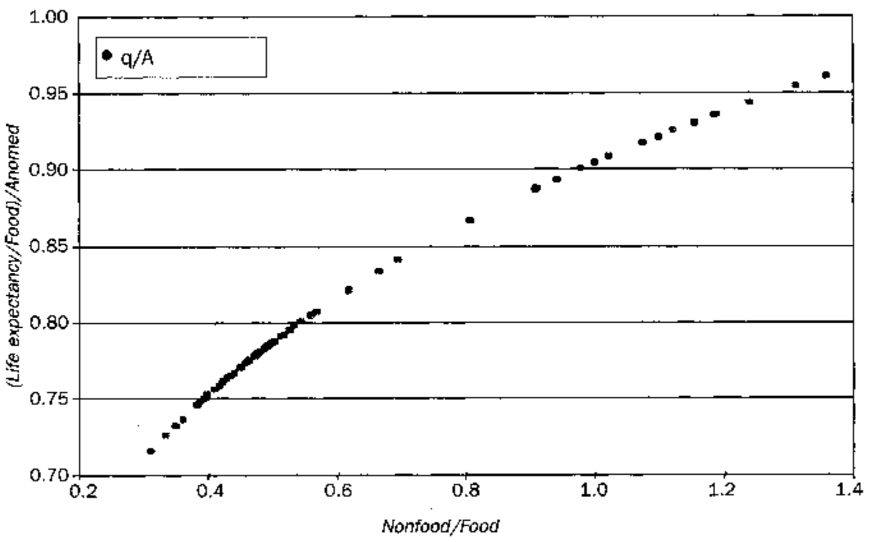


FIGURE 2

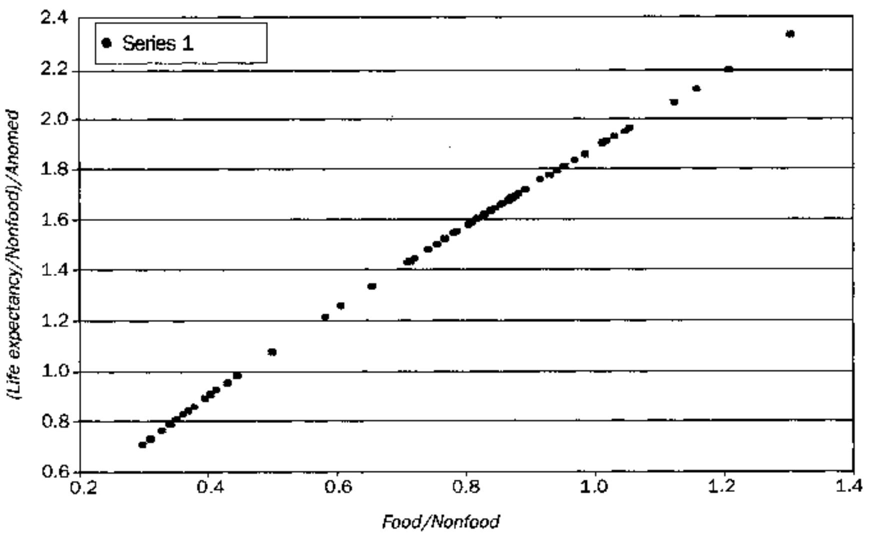
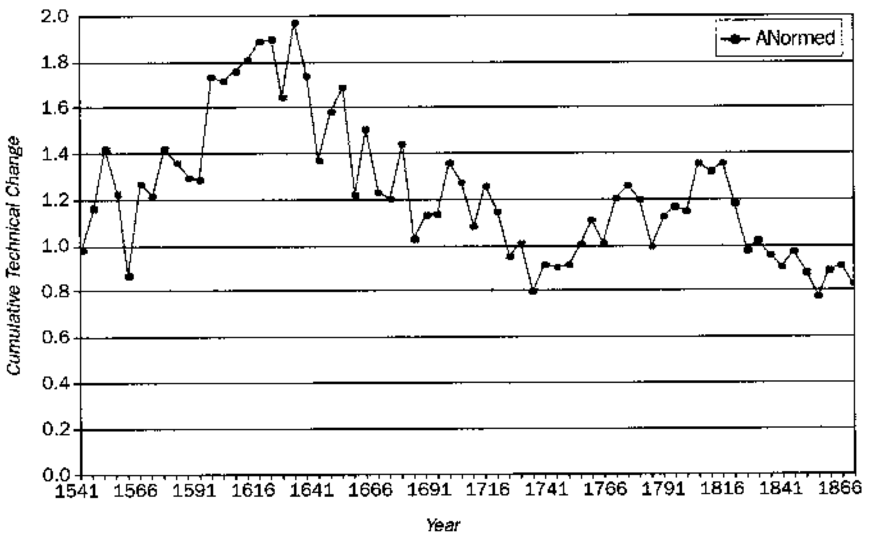


FIGURE 3. Cumulative technical change



notes