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Economic History and Institutions Dept.
Universidad Carlos III de Madrid
Calle Madrid 126
28903 Getafe (Spain)
Fax (34) 91 624 9574

ADULT MORTALITY AND INVESTMENT: A NEW EXPLANATION OF THE ENGLISH AGRICULTURAL PRODUCTIVITY IN THE 18TH CENTURY[*]

Esteban A. Nicolini[+]

Abstract

We claim that the exogenous decline of adult mortality at the end of the seventeenth century can be one of the causes driving both the decline of interest rate and the increase in agricultural production per acre in preindustrial England. Following the intuition of the life-cycle hypothesis, we show that the increase in adult life expectancy must have implied less farmer impatience and it could have caused more investment in nitrogen stock and land fertility, and higher production per acre. We analyse this dynamic interaction using an overlapping generation model and show that the evolution of agricultural production and capital rates of return predicted by the model coincide fairly well with their empirical pattern.

Key words: agriculture, productivity, Agricultural Revolution, investment, capital, life expectancy, mortality, demography, life-cycle.

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[+] **Nicolini**, Economic History and Institutions Dept. Universidad Carlos III de Madrid. E-mail: nicolini@clio.uc3m.es

Abstract

En este artículo sostenemos que la disminución de la mortalidad adulta a finales del siglo XVII puede ser la causa tanto de la caída de la tasa de interés como del aumento de la producción por acre en la Inglaterra preindustrial. Siguiendo la intuición de la hipótesis del ciclo vital mostramos que el aumento de la esperanza de vida de los adultos tiene que haber implicado una menor impaciencia entre los agricultores y esto puede haber causado mayor inversión en el stock de nitrógeno y la fertilidad de la tierra y una mayor producción por acre. Analizamos esta interacción dinámica con un modelo de generaciones solapadas y mostramos que la evolución de la producción agrícola y de las tasas de retorno del capital predecidas por el modelo coinciden muy bien con su comportamiento empírico.

Palabras Clave: agricultura, productividad, Revolución Agrícola, inversión, capital, esperanza de vida, mortalidad, demografía.

1 Introduction

During the 17th and 18th century the English economy underwent a dramatic transformation: its capacity to feed an increasing population increased impressively.

It is generally accepted that during the two preceding centuries, English population evolution had exhibited clear Malthusian characteristics. Population size moved in cycles generated by the inverse relation between the population growth rates and real wages; population tended to grow when the per capita income was high but per capita income decreased when population grew excessively. In this context poverty was inevitable and population growth remained minimal.

But this pattern changed dramatically at some point during the 18th century. As Wrigley and Schofield (1981, p.412) put it: "Perhaps for the first time in the history of any country other than a land of recent settlement, rapid population growth took place concurrently with rising living standards... Past experience would have suggested a repetition of the later phases of earlier cycles -a slowing down in population growth followed by a recovery in real wages. Instead England crossed a threshold into a new era".

What was the reason for this change? One of the most widespread ideas is that, after centuries of inefficiency, agricultural productivity started to increase steadily, allowing population size and per capita income to increase together. This process was sometimes referred to as the "agricultural revolution" but its timing and intensity and the precise mechanisms behind it were a matter of intense controversy. The traditional view that the main transformations took place in the last 40 years of the 18th century are currently being challenged and the reexamination of the evidence suggests that agricultural yields started to improve well before 1760 (Overton 1996, Clark 1991, Allen 1988, 1999).

This chronological shift has re-opened the debate about the causes of the increase in yields per acre. One of the better known explanations, closely linked to the traditional view, is based on the impact of enclosures which introduced a better definition of property rights and an increase in the average size of holdings (Overton 1996). The problem with this hypothesis is that, quite apart from how important this process was, parliamentary enclosures only gained momentum from 1750 on and therefore they cannot account for all the earlier changes (Allen 1992, 1999).

Another set of explanations for the growth in yields are based on the way in which farmers handle and control the fertility of land. Before the introduction of artificial fertilizers (19th century) the main constraint on agricultural production was the fertility of land, and nitrogen was by far the most important natural fertilizer. The two most significant changes in farming practice since the Middle Ages were "convertible husbandry" (16th century) and the introduction of clover into the "Norfolk-four-course rotation" (end of the 18th and beginning of the 19th century)[1]. Both innovations can be considered as a "technical change" in the sense that they produced more output with a very similar combination of inputs. However, during the 17th and the first part of the 18th century the evolution of productivity was not driven by any technological innovation (Shiel 1991).

There are two hypotheses which do not rely on technical change to explain the growth in yields but rather on changes in relative prices and their impact on the dynamic consequences of farmers' crop choices. Jones (1967) suggested that livestock production was favoured in the second half of the 17th century by the increase in its price relative to grains, and by the introduction of new fodder crops. Consequently, farmers increased livestock density that, in turn, would have generated beneficial effects to agricultural yields. However, it is not obvious that the magnitude of the price switch was large enough to account for the change in agricultural productivity. Clark (1992) has claimed that a decline in the interest rate stimulated the intensification of economic activities which were not so productive in the short run but were beneficial for land fertility and that can be considered as investment; this increase in investment would have produced more nitrogen in the soil and higher agricultural yields. In this argument the interest rate

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[1] See Kerridge (1967) and Chorley (1981).

is taken as exogenous, without any further discussion of this assumption.

Our paper introduces a demographic element that has only seldom been studied in this context: in 18th century England mortality declined substantially, and after a long period of no visible trend, adult life expectancy started to increase steadily. We combine this event with the evolution in agriculture using the key intuition into the life cycle hypothesis of savings: we claim that higher life expectancy implied less farmer impatience and more incentives to save; a higher nitrogen stock in the soil; a higher production per acre and lower interest rates. We present a general equilibrium model of capital accumulation with overlapping generations in which people have a life horizon of two periods but face a probability of less than one of surviving to the second one. We find the optimal sequence of capital accumulation in this environment and then check quantitatively what happens if the probability of surviving to the second period changes. Using the results of the model, we claim that the exogenous increase in adult life expectancy in the 17th and 18th century has to be considered as a key factor in explaining the increase in the total agricultural capital and the decline in the interest rate that took place in England in this period.

The rest of this paper is organized as follows: the second section describes some stylised facts that characterise the evolution of agricultural activities during the 17th and 18th centuries. Special emphasis will be placed on the debate about the evolution of production per acre and the importance of soil fertility as capital in the pre-fertilizer era. In the third section, the evolution of adult life expectancy is examined and the hypothesis of a break in its evolution in the second half of the 17th century is proposed. The fourth section includes a brief discussion of the relationship between land tenure and farmers' incentives. In the fifth section we present the theoretical analysis of the impact of life expectancy on capital stock and the most important results. They confirm that, under general conditions, a decline in adult mortality implies more output and more investment which, in our agricultural context, means a better handling of soil fertility with an intensification of activities which were less productive in the short run but more profitable in the long run. Section 6 concludes.

2 Some Stylized Facts about Agriculture

2.1 The Evolution of Productivity and the Agricultural Revolution

There is almost general agreement that grain yields per acre more than doubled in England between the Middle Ages and the beginning of the 19th century: over this period wheat production increased from less than 10 bushels per acre to around 20 bushels. This change was sometimes termed, in a somewhat loose fashion, the "Agricultural Revolution". Labelled in this provocative way, the phenomenon has generated a lot of controversy over its measurement, its timing, and even its existence.

Overton (1979, 1991), Allen (1991), and Glennie (1991) used probate inventories to asses the evolution of agricultural production prior to and during the Industrial Revolution. All three concluded that between 1600 and 1800 wheat yields more or less doubled: from 11 bushels per acre around 1600, production expanded to 22 bushels two hundred years later. Arguing that the impact of enclosures upon agricultural productivity was substantial, Overton emphasizes that changes were concentrated within the 18th century (Overton 1996) while Allen tends to locate them in the 17th century (Allen 1999). However, checking their original estimates more carefully we can see that almost the entire distance between the two is concentrated between 1675 and 1740. Allen's series for Oxfordshire present a big jump in the period 1675-1699 while the major change in each of the series constructed by Overton for Norfolk, Suffolk and Lincolnshire begins between 1700 and 1740[2].

Jones (1981) suggested a methodology which does not rely on agricultural sources but on income and population data. It is based on an approximation of total food production through total food consumption: demographic data and series of wages are used to deduce an aggregate demand for food; the long run behaviour of food exports and imports is reconstructed and then total production is obtained adding exports to and subtracting imports from aggregate consumption. This approach (with different assumptions about the way in which the demand function is reconstructed) has produced two kind of results: Jones (1981) and Clark (1991) found the largest increase in food production during the 18th century especially in the second half, while Allen (1998, 1999) concluded that the acceleration was concentrated in the 17th and early 18th centuries.

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[2] See Allen (1988, Table 3, p. 123) and Overton (1991, Tables 11.3 and 11.4, p. 302 and 303).

Clark (1991) provided another estimate based on labour inputs. He assumed that a stable relationship existed between the amount of labor used for some tasks (like reaping) and the bushels of crop obtained in a given acre. He then approximated production per acre using data on labour inputs from 1250 to 1860. The patterns of productivity he obtained coincide fairly well with those presented by Overton through probate inventories and those obtained by Jones and Clark himself through food demand approximation.

There are two main conclusions we would like to make from the previous debate. First, we can safely state that the steady increase in yields we observe in pre-industrial times started before 1750. Second, with the exception of Allen's estimates, evidence suggest that the entire 18th century was a period of improvements in yields per acre.

2.2 Nitrogen and Fertility as Capital in the Pre-Fertilizer Era

The question for which we do not yet have a satisfactory answer is: what kind of mechanisms are behind the increase in yields per acre between the second half of the 17th century and the end of the 18th century? We have already commented that convertible husbandry and the Nofolk-four-course rotation came too early or too late to explain this process. Therefore, we have to look at a less dramatic, slow and barely noticeable process consisting of small changes mainly related to a more intensive use of traditional methods which entailed a better handling of land fertility (Allen 1999, p.227).

This better land utilization was almost always linked to a more effective optimization of land fertility which was mainly explained by the quantity of nitrogen in the soil. Before the qualitative jump obtained by the generalised use of clover within the Norfolk-four-course rotation, several rotation systems were applied and different agricultural practices were used[3]. The trade-off between higher (lower) yields in the present and lower (higher) yields in the future was controlled by deciding on, among other things, the share of land used for grain cultivation and for fallow, grass, and/or livestock. The reason for this trade-off is that with grain crops, the outflow of nitrogen from the soil is greater than the inflow, while the converse is true for grassland or fallow[4]. Incrementing the share of land devoted to grain

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[3] See Kerridge (1967), Shiel (1991), and Thirsk (1987).

[4] A detailed analysis of the role and importance of nitrogen in traditional or pre-fertilized agriculture can be found in Shiel (1991) and Clark (1992). In this section I will follow the lines of their argumentations and I will use extensively their suggestions, findings and results.

would lead to higher yields for a while because nitrogen accumulated in fallow land is released, but after some years, this temporary gain would vanish and lower and lower yields would be produced until they stabilised below the initial level. Shiel (1991, p.73) estimates that stabilisation does not take place until at least 16 years afterwards.

Clark (1988, 1990, 1992) explicitly identifies the nitrogen stock in soil as capital in pre-industrial agriculture. His thesis is that medieval farmers knew that fallow and pasture restored fertility and that growing peas or beans in the rotation, or converting land periodically to grass or wilderness should also have fixed enough nitrogen to substantially increase grain yields. Any short term loss of production from the land would have been more than compensated for by higher yields when land was converted back to arable.

The econometric approximations of Brunt on the Agricultural Revolution (Brunt 1995, 1997) show that fallow crops (like peas, beans and turnips) are complements to wheat production and they effectively stimulated wheat yields, thus providing support for Clark's nitrogen theory. Brunt also showed that other kinds of investment like hollow drainage, liming and marling also had major impacts on land productivity.

Following Clark's thesis, we claim that since the second half of the 17th century and until the introduction of the Norfolk-four-course rotation, the increase in yields per acre was mainly due to a higher farmers' investment in land quality. Finding conclusive direct evidence to support this point is quite difficult because the more or less detailed reconstruction of day-to-day activities on a pre industrial farm is not an easy task. Moreover, the small changes which could have produced the core of the productivity gains during our period were undoubtedly among the least recorded and the most difficult to track. However, we have some indications that at the end of the 17th and beginning of the 18th century some of these changes were already working.

One indication is related to land rotation practices applied during the 18th century. Overton (1996, p.93), using probate inventory data, shows that the proportion of land devoted to pastures increased steadily between 1700 and 1800 and declined sharply between 1800 and 1830. Allen´s conclusion using a different kind of data (Allen 1994, p.104) is a persuasive confirmation of this trend[5]. This data strongly suggests not only that farmers, before the generalisation of the Norfolk-four-course rotation, were able to increase yields per acre reducing the overexploitation of land but also that, in fact, they did so during the 18th century.

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[5] Unfortunately, data before 1700 is not available from the mentioned sources.

The other piece of information is presented by Glennie (1988) and shows that, in Hertfordshire, farmers changed their attitude toward soil protection in the second half of the 17th century and involved themselves in conscious and demanding land preparation before sowing. Moreover, he also shows that this trend to augment investment is confirmed by the increasing valuation of farm equipment which after 1670 is higher than ever before[6].

Why did peasants start to make more intensive use of old farming methods that decreased yields in the short run but increased them in the long run? Why did they expand investment in land fertility or in land quality using land preparation, drainage, liming, marling...? Lastly, why did they reduce the share of land devoted to grain and dedicate more land to fallow, livestock or pastures?

Jones (1965) relates the growth of grain yields at the end of 17th century with the trend in relative prices between animal products and grains. In the second half of the 17th century, relative prices favoured animal products and encouraged farmers to specialise in that kind of products. The availability of new fodder crops would also have encouraged an increase in livestock density that, in turn, generated more natural fertilizers and higher grain yields. However, it has been more recently argued that the change in relative prices was a rather weak signal that could not have significant effects on farmers' specialisation (O'Brien 1985).

Clark (1992) showed that before 1750, farmers had available crops other than clover to increase land nitrogen stock and suggested that peasants were unwilling to invest in soil fertility. They usually sowed a major proportion of the arable land, maximising short run output and did not improve land quality or augmented nitrogen stock through more grassland or fallow. Impatience made this way of increasing yields unattractive because it required large capital investment and delayed consumption for several years. Hence, low agricultural yields would have been caused by high capital rates of return: facing the high cost of capital, farmers would deplete the fertility of land because investment in land quality and soil fertility took time to realize. When, in the last third of the 17th century, interest rates started to decline, farmers increased their savings and yields per acre grew.

But, why should we assume that interest rate determination is completely exogenous to the whole agricultural economy? Obviously, some factors unrelated to the agricultural world have had an impact on the interest

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[6] It can be argued that some of the techniques which stimulated higher yields entail an increase in labour rather than more capital. However, as long as the extra labour led to a durable improvement, it can also be considered as investment. We discuss the role of an intesified labour in section 5.

rate[7], but it is no less true that the behaviour of savings and investment within agriculture (around 40 % of the economy) must have been key elements in the determination of the interest rate. What we will show in the next sections is that a very important piece of the puzzle is being forgotten: the noticeable reduction in mortality that took place during the 18th century. We claim that this is an important issue since the aforementioned debate suggests that farmers' dynamic choices play a crucial role in inducing more investment in land fertility and augmenting productivity. Moreover, using the intuition of the life cycle model of savings, we can expect that higher adult life expectancy lengthens the retirement period and induces more savings. In other words, given that the interest rate is closely linked with the subjective discount of future consumption which relates to the life expectancy,an increase in this viarables would have induced more savings.

3 The impact of longer lives

The notion of life expectancy provides the most important tool to examine the phenomenon of mortality, taking into account the age structure of the population. Life expectancy at age x is the average number of years that a person of age x will still survive at a given date. The most commonly used indicator is e_0, life expectancy at birth (or at age 0), but sometimes other statistics like e_1,e_5, e_{20}, e_{50} are also tabulated. Their main advantage is that they capture age-specific mortality profiles: for instance, an increase in mortality concentrated in the age group between 20-25 (due, for instance, to a long war) would affect e_0 but not e_{30} because the probability of survival, given that a person is already 30, does not change.

Decisions about future capital and consumption are not taken by the agent when he is born but, rather, when he is twenty or twenty five years old. Therefore, the relevant survival profile for considering the influences of mortality over investment choices is given by adult life expectancy. In fact, making the distinction between e_0 and adult life expectancy is especially important for our problem because adult mortality behaves in a completely different way from infant and child mortality in the first half of the 18th century: adult mortality rates decreased very sharply from the end of the 17th century, while infant and childhood mortality rates were unusually high between 1680 and 1750[8].

INSERT FIGURE 1 HERE

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[7] See North and Weingast (1989) and Clark (1996).

[8] Wrigely et al. (1997, p. 224 and ss.).

Looking at Figure 1 it is fairly clear that e_{25} had a positive trend from the end of 17th century[9]. Complementing the information of the Cambridge Group reconstitution with Chester Beatty Life Tables (Wrigley et al. 1997, p.281), it is noticeable that the positive trend continues until the 20th century. Is it possible to identify a structural change in this time series?

We have ten-year observations for male e_{25} from 1605 until 1815 from the Cambridge Group reconstitutions[10]. To test the existence of some structural change in the observed series, it is possible to assume a linear trend and perform a Chow test on the parameter of the time variable. To avoid *a priori* hypothesis about the specific period in which the structural change took place, the test was performed at every period of the series with the exception of the first two and the last two. The results are summarized in Table 1.

Table 1: Adult Male Life Expectancy and F-test values.

Year	**e(25)**	**F-stat.**	**Year**	**e(25)**	**F-stat**
1625	31.17	2.9545	**1715**	32.77	1.7639
1635	30.16	2.4979	**1725**	32.07	1.9135
1645	29.94	2.4908	**1735**	34.28	0.7193
1655	29.56	2.3670	**1745**	33.90	0.4017
1665	30.84	2.9488	**1755**	36.34	0.3974
1675	28.99	2.6941	**1765**	33.20	0.3162
1685	26.73	**6.0879**	**1775**	34.62	0.7909
1695	31.68	**3.5459**	**1785**	32.95	0.4546
1705	31.36	3.0585	**1795**	34.61	0.5243

Given that the 95% confidence value of F[2,20] is 3.49, we can conclude that the only periods when the hypothesis of a structural change is accepted are at 1685 or 1695, with a strong indication that is in the former when the change is more likely[11]. After this change a positive trend exists: $t = 0.49$ at any level of significance for the subsample for $n \geq 9$.

The causes for this decline in adult mortality from the end of the 17th century onwards have still not been definitively stated but it seems clear

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[9] See also Wrigley et al. (1997, Figure 6.15, p.283).

[10] I thank Jim Oeppen for providing the corresponding data set.

[11] The very bad years around 1675-1680 had some impact over the point of structural break. If the value corresponding to 1685 is "smoothed", the structural break is also accepted at 1675.

that they are not linked to economic factors such as changes in real income per head but rather they are attributable to the evolution of the biological or epidemiological environment[12].

Then, in the second half of the 18th century, a new positive trend in life expectancy caused by an exogenous change in mortality coincided with the transformation of the agrarian system and the increase in agricultural output. Longer lives and economic growth are closely linked to each other by the life cycle hypothesis (Modigliani 1955) which states that savings are motivated to smooth consumption throughout the life cycle and agents have positive savings when they are young (with high income) and negative savings when they are old (with lower or zero income). Several empirical tests have been implemented in order to validate the predictions of this theory but the debate about the quantitative relevance of the hypothesis is far from being closed (Kotlikoff and Summers 1981, Hurd 1989, Kuehlwein 1991)

In the historical context, some evidence concerning the US in the 18th, 19th and 20th centuries seems to support not only the existence of an important life cycle motivation in personal savings in the 18th and 19th centuries (Kearl and Pope 1983, Di Matteo 1998) but also a stronger motivation in the 18th century than later (Kearl and Pope 1983). Horrel and Oxley (2000) provide other kind of evidence with the study of an age-specific income profile of a working class familiy in London in 19th century. They show that the male worker's earnings are a declining part of household income since he is 40 years old and that income from lodgers in the familiy house, which is a form of revenue of capital, is around 30 % of total income of the household in the later stages. There are examples in England of the 'old folks at home' with agreements with the youths establishing, for instance, that after the marriage of his son, the new couple will live in the cottage providing that the father had meat, drink, firing and all his domestic needs for his lifetime[13].

If life cycle inspiration was present in rural England in the 18th century, farmers who were becoming aware that old people were gradually living for longer periods must have been more concerned about their own means of subsistence in the future. This may have been an important stimulus to reduce consumption, increase savings and take into account longer horizons.

The gain in adult life expectancy between 1700 and 1800 is around four years which, without further analysis, is perhaps considered as a minor

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[12] See for instance Saito (1996, p. 543), Wrigley and Schofield (1997, p.552) or Easterlin (1999).

[13] See Spufford (1976, p.174-175).

change. We will show in section 5.1 that this is not the case and that, indeed, numerical simulations produced by a calibrated model of capital accumulation suggest that the impact of this change on economic variables is substantial. It is also convenient to remark that the demographic data we are using is a national aggregate which combines rural and urban counties. Given the perfectly well-known health handicap prevalent in cities, the improvement in mortality is quite probably higher in rural districts and, therefore the quantitative consequences of higher life expectancy on economic activity can be even more conclusive than the results of our model[14].

4 Length of Land Tenure and Incentives

The duration of land tenure is clearly linked to farmers' incentives to maintain land quality and fertility. Uncertainty about the length of the lease, or very short leases could have eliminated any investment motive and led farmers to maximize short term profits and jeopardise nutrients and future land productivity. Long enough leases tended to induce peasants to invest considering long term benefits because they were sure that they would recover the future profits of present investment; hence, longer leases would have had advantages in providing better incentives for maximizing long term production[15].

Another issue emerges from land tenure arrangements if we analyse them in a context of increasing farm profitability: if yields per acre tend to grow each year, landlords have incentives to shorten leases because a fixed rent could fail to extract the maximum possible surplus from tenats. Hence, from a landlord's point of view, optimal contractual arrangements should have combined the rigidity of long leases to provide the right incentives to farmers, and the flexibility of adjustable rent mechanisms to be able to extract a large as possible share of profits from tenants.

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[14] At this point it is also appropriate to acknowledge that we are combining national aggregate demographic data with regional estimates of the evolution of agricultural productivity. It is possible that the change in mortality in different regions did not follow a perfectly coordinated pattern and the aggregate data has some positive or negative lag with respect to regional evolution. Taking an optimistic view, it may be that life expectancy reacted at different rates, depending on the county, so that data on productivity for each individual area would give a more accurate correlation.

[15] There exist interesting debates about the incentive structure of different contractual arrangements in the context of historical changes in agriculture (Offer 1991, Galassi 1992, Epstein and Galassi 1994). However their dynamic implications have not been studied in depth. The only exception I am aware of is Mokyr (1985).

What do we observe from the evolution of lease arrangements? The duration of a tenancy is termed the ‘estate’ for which the tenant holds the land. The most common form of occupancy before enclosure were secure and long tenancies whose duration was denominated in named lives and amounted to a form of quasi-ownership (Offer 1991, p.5). The only form of estate that gave the tenant the right to transfer the land in inheritance was the one called ‘fee’, although this right was not absolute and there were some restrictions. Several categories of estates were for life: land could be held just for the life of the tenant, or for the life of the tenant, his wife and his heir. After that, landlord and tenant had to renegotiate the estate (Overton 1996).

In the 18th century, landlords stopped renewing beneficial leases. These were replaced by leases of shorter duration, or tenancies at will, with no written agreements whatsoever(Allen 1991, p.96 and ss.). This change can be considered as a rational reaction of landlords, if the profitability of farms was increasing due to higher yields per acre.

Although it might be argued that shorter leases could have induced tenants to under-invest, evidence shows that landlords maintained the turnover of tenants low. There was some competition among prospective lease-holders at the outset, but a commitment by both partners signified an end to the search (Offer 1991). Moreover, incentive problems were taken into account by a more precise definition of property rights concerning land quality and investment goods: ”The tenant-right system, in which the incoming tenant paid the outgoing one for residual manures in the soil and for other improvements, was designed to encourage a long-term commitment in a short-term tenant” (Offer 1991, 11).

5 The Model

In this section we will present an **overlapping generations model** to approach the way in which farmers decided on the optimal amount of consumption and investment and also to investigate the impact that different adult mortality profiles have on this optimal choice. In this model, which is a version of the classical Diamond’s (1965) model of overlapping generations, agents (farmers) work when they are young and save a part of their income for consumption when they are old and retired. In a context of general equilibrium, they optimally choose investment and accumulate capital.

In terms of agricultural practices in pre-industrial England, this capital accumulation can be identified with the improvements in land quality and fertility and the accumulation of nitrogen in soil obtained by the deliberate action of deferring consumption and using the land for purposes which, although they are less productive in the short run, have beneficial effects on future land productivity. Other forms of investment were land improvements like marling, liming, enclosing, building drainage structures, etc. The idea of 'retirement' might seem strange in the context of traditional agricultural societies, although it is just a simple way to introduce the idea that elder people are increasingly less productive and their consumption depends on provision made in previous periods[16].

We want to insist that the purpose of the model is to provide some numerical evaluation of the impact of the decline in mortality on the economic variables. Perhaps, more complicated models would have provide a more accurate description of the complex agricultural practices, demographic pattern and familiy structure prevailent in England in the 18th century. However, any gain in complexity would have implied a larger arbitrariness in the definition of functional forms and parameter values and a less plausible simulation. Hence, although all the assumptions of the model are dabatable, we always tried to choose the simplest and more standard possibility.

We will assume that agents born at t live through two periods (t -young- and $t+1$ -old-): the first one with probability one and the second one with probability $\Theta_{t+1} \in (0,1)$ $\forall t \geq 1$. If total utility is additive we can write the total utility function of agents born at t as $U_t = u(c_t^y) + \beta\theta_{t+1}u(c_{t+1}^o)$ where c_t^y is young consumption at t and c_t^o is old consumption at t. In this case the discount of future utilities is given by the usual parameter β and a parameter $\theta_{t+1} \in \{0,1\}$ which is a binomial random variable indicating whether the agent who is young at t is still alive at $t+1$ ($\theta_{t+1} = 1$) or has not survived ($\theta_{t+1} = 0$). Θ_{t+1} is the probability of θ_{t+1} being 1 and then $E_t(\theta_{t+1}) = \Theta_{t+1}$. Assuming that utilities are logarithmic, the expected utility of the agent is

$$E_t(U_t) = \log(c_t^y) + \beta\Theta_{t+1}\log(c_{t+1}^o) \tag{1a}$$

Changes in Θ reflect changes in life expectancy. We assume perfect foresight about the value of Θ of each generation.

Concerning the demographics of the model, we keep things as simple as possible: each agent has one child so that each family has two agents: one Young and one Old. We standardise the young population size to 1 and

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[16] See in section 3 the debate about the life-cycle hypothesis and the qualitative evidence on 'retirement' strategies.

therefore Θ_t is the size of the old population at t. At the end of the period t, Young has a child and then he dies with probability Θ_{t+1} or he becomes Old with probability $(1-\Theta_{t+1})$. If Old is still alive, he dies with certainty at the end of this period. There are no insurance markets and young agents save only for life cycle reasons[17].

Goods in the economy, Y_t, are produced using capital K_t, and labor L_t. We assume that the production function is Cobb Douglas, then

$$Y_t = F(K_t, L_t) = AK_t^{\alpha} L_t^{\beta}$$

Labour is provided inelastically by Young and, after standardisation, $L_t = 1$[18]. Note that land is not explicitly included in the production function: as it is a non-accumulable factor, we can assume $Y_t = AK_t^{\alpha} L_t^{\beta} T^{1-\alpha-\beta}$ where T is land and standardise $T = 1$. In this case $L_t = 1 \forall t \geq 1$ and $T = 1$, which implies that the ratio between young population and land is fixed[19]. Capital depreciation is 1.

For simplicity we will assume that the old receive the marginal return of capital and the young receive the marginal productivity of labor although alternative age-specific income distributions can be introduced without altering the results[20]. An extra assumption should be made regarding revenues from the capital of the proportion of population which does not survive. This amounts to $(1-\Theta_{t+1}) * K_t * A\alpha K_t^{a-1}$.We do not assume a standard inheritance scheme because this would imply that some agents receive inheritance, some others do not and saving decisions would depend on the entire family history of each agent. This kind of inheritance scheme would yield an analytically intractable model. Hence, what we assume is that

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[17] Alternative sets of assumptions, which in general do not affect the qualitative conclusions of the model, are further developed in Nicolini (2000).

[18] There is evidence that during the 18th century the labour provided by each worker increased substantially (Voth 1998) and this fact is totally consistent with the results we will present. We do not introduce an endogenous supply of labor in our model because the simplicity of our results and the direct intuition of our simulation would be affected. However, it is quite easy to see that if labour is endogenous, as long as leisure and consumption are normal goods, any increase in savings will be optimally obtained by reducing both consumption and leisure, and therefore increasing the labour supply. Consequently, any enlargement of the capital stock obtained by the intensification of labour goes in line whith a hypothetical model of the kind we present but augmented with endogenous labour.

[19] To include in the model an exogenous rate of population growth is straightforward, and the inverse relation between capital per capita and population growth rate arises naturally.

[20] Cobb Douglas production function implies that each generation receive a fixed proportion of the total ouptut, which provides perhaps a more intuitive justification of the intra-family distribution of income.

each young agent receives an identical portion of the total amount of capital left for the previous generation; this assumption excludes the possibility of discussing distributional issues but allows us to capture the main features of the aggregate process. Thus the income of young agents is the marginal productivity of labor $\left(A\left(1-\alpha\right)K_t^{\alpha}\right)$ plus the 'inheritance' they receive $\left(\left(1-\Theta_{t+1}\right)A\alpha K_t^{\alpha}\right)$

So, the budget constraints that the young farmers face are

$$\begin{aligned} c_t^y &= A\left(1-\alpha\right)K_t^{\alpha}+\left(1-\Theta\right)A\alpha K_t^{\alpha}-K_{t+1} \\ c_{t+1}^o &= A\alpha K_{t+1}^{\alpha} \end{aligned} \tag{2}$$

This means that the problem solved by the agents is to maximize the function given by 1a, subject to the constraints described by 2.

5.1 Results

The solution to this problem is a policy function that defines the optimal choice for capital each period, given the capital that comes from the previous period and the cohort-specific life expectancy[21]. This function is given by

$$K_{t+1}=\frac{A\beta\Theta_{t+1}\left(1-\alpha\Theta_t\right)}{1+\beta\Theta_{t+1}}K_t^{\alpha}$$

Then, for any initial level of capital and for a constant level of life expectancy, the variables of the economy converge towards a stationary equilibrium in which they are constant, including capital. It is not difficult to show that for this specification, and for reasonable values of the parameters, the steady state level of capital is positively related with life expectancy[22].

Therefore, a reduction in mortality may be the cause of an increase in savings, income and capital stock and a reduction in the rate of return of capital. Moreover, given that the reduction in mortality is a key transformation in England before and during the Industrial Revolution, the explanations of economic growth and savings behaviour in that period should take demographic changes into account.

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[21] More detailed analytical results are presented in section 7.1.

[22] A simple exercise of comparative statics provides a range of the parameter for which higher life expectancy causes a higher level of capital in the steady state. $\alpha < 0.5$ OR $\Theta < .5$ are sufficient conditions for $\frac{dK^{ss}}{d\Theta} > 0$. For more details on this analysis, see Nicolini (2000).

5.2 Quantitative Predictions

In this section we will calibrate the parameters of the model in order to obtain quantitative predictions of the evolution of economic variables, if we assume that the economy is in a steady state and introduce an exogenous change in life expectancy similar to the one empirically documented for England between 1600 and 1800 and discussed in section 3. Once we have assigned values to the four parameters of the model $(\alpha,\ \beta,\ \Theta,\ A)$[23] we explore the endogenous response of the relevant variables of the economy if e_{25} presents a jump and reaches the value corresponding to 1800.

The results of the simulation are presented in Table 2. The values of the first row were obtained assuming that the economy is in a steady state which is consistent with the level of adult life expectancy (e_{25}) prevailing in 1600 ($\Theta^l = 0.2$). Capital stock is low, production is low and the interest rate is high. What we present in the second row are the values of the same variables after they have been adjusted to a change in life expectancy such that $\Theta^h = 0.35$, which corresponds to e_{25} around 1800.

Table 2: Steady State values of the relevant variables

	Y	K	$\frac{\partial Y}{\partial K}$	K/Y
Θ^l	8.6	0.73	3.51	0.08
Θ^h	10.40	1.39	2.25	0.13

The evolution of total production and capital rates of return are particularly relevant because we can compare the predictions of the model with empirical data. Given the assumptions we made about the production function and our calibration strategy, Y is equivalent to the production per acre of total land (under crop and fallow). It is well known that a change in grain production per total acre (PPTA) is usually less acute that the corresponding change in grain production per sown acre (PPSA) since, for a given a rotation practice, an increase in the latter is achieved, in general, reducing the share of land devoted to grain crops. Shiel (1991, Table 2.1, 71) formalised this relationship, assessing the total amount of food produced by a farm for each different combination of land use (pastures, grain crops and fallow). From this source we have a correspondence between PPTA and PPSA for English traditional farming[24].

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[23] The adopted criteria are discussed in the appendix.

[24] "Traditional" means before the generalised adoption of the Norfolk four course rotation.

We used this correspondence to calibrate the parameters of the model in the following form: we know from probate inventories that at the beginning of the 16th century PPSA was around 11 bushels and (using the aforementioned Shiel's table) the corresponding value of PPTA is 8.6 bushels. As our value Y in the model embodies the production per total acre, we set $Y = 8.6$ before the change in Θ[25]. The second column of Table 2 indicates that the increase in life expectancy produced more investment, and consequently, PPTA increased to 10.40 or, following Shiel's correspondence again, PPSA reached 17 bushels. This means that, regarding production, our simulation suggests that more than half of the increase in agricultural land productivity reported by probate inventories can be accounted for by the new investment motivation in farmers' behaviour.

The capital rate of return of our simulated economy decreased from 3.5 to 2.25. As we assume that depreciation is complete over the period of 25 years, these rates of return imply that around 1600 the investment of £ 1 in agricultural capital yielded £ 3.5 twenty five years later, assuming that this rate of return is net[26]. This amounts a decline of 36 %. Clark (1998) reports returns on rent charges as 6.025 % and 4.46 % per year around 1600 and 1800 respectively which gives a reduction of 26 %. Although the historical evolution of the interest rate is a process with a very complex causality, our simulation suggests that the small and slow change in life expectancy during the 17th and 18th centuries can produce important quantitative effects on interest rates.

6 Conclusions

This is the first time that several relevant facts regarding English economic performance in the 18th century are included altogether in a general explanation: adult life expectancy increased, farmers became more patient and invested more, rates of return fell, shares of arable land declined, and arable land became more productive with traditional methods.

Trying to find an explanation for the increase in productivity, Glennie and Clark highlighted the importance of the nitrogen cycle and crop rotation mechanisms. Concerning the ultimate cause of the change in peasants' behaviour, Jones stressed the role of relative prices between agricultural and livestock products. Clark emphasised the role of nitrogen as capital claim-

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[25] For more details see the appendix.

[26] For instance, in this simple model we are not taking into account the existence of taxes or other charges.

ing that the reduction in the rate of return of capital was a key element in explaining the increase in investment and the growth in productivity.

Our hypothesis exploits the well-known properties of simple dynamic economic models but also includes the less common feature of variable mortality. We have shown that a reduction in adult mortality is a very strong force that could have induced an increase in capital stock, an increase in production per acre, and a reduction in the rate of return of capital. With plausible parameter values, a simulation of the quantitative effects of a change in life expectancy accurately matches empirical evidence: production per sown acre practically doubled, overall production including meadows increased by 25 %, and rates of return declined by almost 35 %.

Therefore, we claim that this demographic force can potentially be the cause of asignificant prportion of the economic transformations in agriculture prior to the industrial revolution and this should be considered as a complementary explanation together with more traditional hypotheses.

Our findings also open up possibilities for further research, in the sense that they re-direct, at least partially, the debate on the productivity of agriculture in the context of economic growth before and during the Industrial Revolution. When looking for the contribution of the agricultural sector to aggregate growth, researchers have focused on changes in Total Factor Productivity (Crafts 1985, Clark 1999) since traditional growth theory predicts that technology is the exogenous force that drives the economy and this is ultimately responsible for long run economic growth. The results of this paper show that TFP may fail to describe the relevant changes in pre-industrial agriculture because the decline in mortality is another exogenous factor that caused economic growth. Changes generated by this factor appear to be enough to explain a substantial part of the growth in agricultural productivity between 1600 and 1800.

7 Appendix

7.1 Explicit Results for Section 5.1

A necessary condition in order that a sequence of capital is the solution to Problem 1 is the first order condition that can be written as

$$\frac{1}{AK_t^{\alpha}\left(1-\alpha\Theta_t\right)-K_{t+1}}=\frac{\beta\Theta_{t+1}}{K_{t+1}} \tag{3}$$

from which we obtain the policy function

$$K_{t+1} = \frac{A\beta\Theta_{t+1}\left(1-\alpha\Theta_t\right)}{1+\beta\Theta_{t+1}}K_t^{\alpha}$$

Policy function shows what is the choice of K_{t+1} given K_t and the parameters of the economy.

Given this policy function, for any initial level of capital the variables of the economy converge towards a steady state in which they (including capital) are constant. The level of capital in the steady state is :

$$K^{ss} = \left[\frac{\beta\Theta A\left(1-\alpha\Theta\right)}{1+\beta\Theta}\right]^{\frac{1}{1-\alpha}} \tag{4}$$

7.2 Calibration Details

7.2.1 Demography and Preferences

- Value of Θ: we will call Θ^h and Θ^l the parameter corresponding to 1800 and to 1600 respectively. From Wrigley et al. (1997) we make an approxmate estimate of adult life expectancy which is $e_{25} = 30$ in the first half of the 17th century and $e_{25} = 33.8$ around 1800. Assuming periods of 25 years we can get values for Θ^h and Θ^l with a simple calculation $75\Theta^l + 50(1-\Theta^l) = 55$ where 55 is the average length of life in the first half of the 17th century for a person who is 25 years old. This implies that $\Theta^l = \frac{5}{25} = 0.2$. Similarly $75\Theta^h + 50(1-\Theta^h) = 58.8$ where 58.8 comes from $25 + 33.8$, and $\Theta^h = \frac{8.8}{25} = 0.35$.

- Value of β: A calibration of a model with periods of one year generally assumes $\beta \in (0.97, 0.99)$ (Rios Rull 1996) which implies that for periods of 25 years $\beta \in (0.47, 0.75)$. We assume $\beta = 0.5$.

7.2.2 Technology

We will identify production in the model (AK^{α}) with the total production of arable land. The variable K is the accumulable asset embodied in land and incorporated in agricultural production: fertility of land (in terms of nitrogen) and land improvements. Hence, investment is the reduction of consumption today by leaving more land fallow and/or devoting resources to improve land quality with fencing, hedging, etc.

- Value of α: the Cobb Douglas technology assumption implies that α should be the share of the total income paid to capital. In our case capital is what lasts for one generation (but disappears after more or less 25 years): fertility of land, land improvements (fences, hollow drainage, etc.), agrarian capital (tools). Clark (1999, p.230) assumes that the share of capital is 20 % (although he is considering capital in a more restricted way) and of land and labor it is 40 %. The literature about modern economies suggests a share of capital between 0.3 and 0.4. We will use $\alpha = 0.3$.

- Value of A: Given the scarcity of available information, we cannot easily assign a value to A which embodies the technological capacity of the economy to transform a combination of inputs into output. To overcome this difficulty, we will assume that around 1600 the economy was in a steady state (the slow change in production and mortality at this time makes this assumption not completely unreasonable) and the parameter A will be calibrated in order to fit with available empirical evidence on agricultural production per acre. Most estimates of grain yields around 1600 are between 10 and 13 bushels per acre of sown land (Clark 1991, p.457). Shiel (1991) suggests that in medieval farming 40 % of arable land was sown with grain and, given the productivity of grassland and its equivalence in terms of grains, he estimates the production per acre of total land as equivalent to 8.6 bushels[27]. Thus $AK_{1600}^{\alpha} = 8.6$ what implies that $K_{1600} = \left(\frac{8.6}{A}\right)^{1/\alpha}$. If K_{1600} is the steady-state level of capital, then (using formula 4) $K_{1600}^{ss} = \left[\frac{\beta\Theta A(1-\alpha\Theta)}{1+\beta\Theta}\right]^{\frac{1}{1-\alpha}}$ and therefore $\left(\frac{8.6}{A}\right)^{1/\alpha} = \left(\frac{\beta\Theta A(1-\alpha\Theta)}{1+\beta\Theta}\right)^{\frac{1}{1-a}}$. Using the values of β, α,and Θ that we obtained above we obtain a unique value for A. In this case $A \cong 9.43$.

7.2.3 Alternative parametrisation

In Table 3 we present the evolution of the variables under analysis using alternative assumptions about some parameters, the determination of which may be a matter of debate. With respect to α, we revise its value downwards making the calibration more in accordance with other assumptions in the literature. The value of β is revised upwards to check the other extreme of its plausible range.

Table 3: Steady State values of the relevant variables

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[27] A complementary explanation of this assumptions is offered in the section 5.2.

Alternative calibration

$\alpha = 0.2;\ \beta = 0.7$	Y	K	$\frac{\partial Y}{\partial K}$	K/Y
Θ^l	8.6	1.01	1.69	0.12
Θ^h	9.6	1.75	1.09	0.18

These new parameter values slightly reduce the change in production (Y) which would imply that the change in Θ would account for something less than half of the change in land productivity[28]. They also bring down interest rate levels while increase their relative change whic now stands at 55 % . This implies that with the alternative calibration our model predicts the capital rate of return with less precision and overestimates its change. However, this sensitivity analysis confirms that, under alternative reasonable parametrizations, the reduction of adult mortality can produce endogenous changes in agricultural production and rates of return in the right direction. Moreover, the results of Table 2 showed that parameter values within very plausible intervals produce quantitative transformations which are very similar to empirically observed changes.

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[28] If PPTA is 9.6, the corresponding value of PPSA is around 15 bushels per acre.

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