Journal of Macroeconomics 44 (2015) 219–233

Contents lists available at ScienceDirect

Journal of Macroeconomics

journal homepage: www.elsevier.com/locate/jmacro

Accounting for breakout in Britain: The industrial revolution through a Malthusian lens ☆

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A R T I C L E I N F O

Article history:
Received 29 July 2014
Accepted 30 January 2015
Available online 18 March 2015

JEL classification:
N13
N33
O1
O41
O52

Keywords:
Industrial Revolution
Malthusian dynamics
Maximum sustainable population growth
Development
Demographics

A B S T R A C T

This paper introduces a simple dynamic model to examine the breakout from a Malthusian economy to a modern growth regime. It identifies several factors that determine the fastest rate at which the population can grow without engendering declining living standards. We then apply the framework to Britain and find a dramatic increase in sustainable population growth at the time of the Industrial Revolution, well before the beginning of modern levels of income growth. The main contributions to the British breakout were technological improvements and structural change away from agricultural production, while coal, capital, and trade played a minor role. In addition to solidifying the link between the Industrial Revolution and rising living standards, this research reconciles the gradualist and limited Crafts–Harley view of the Industrial Revolution with a dramatic and rapid change in Britain's macroeconomic character.

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1. Introduction

Economic historians have pointed to a number of factors that potentially explain the first breakout from a Malthusian economy to a modern growth regime that occurred in Britain in the 19th century. Yet, the specific links between these factors and the beginnings of modern growth are often tenuous, and precisely which factors are important is still the subject of considerable debate. This paper introduces a simple model that determines the fastest rate at which a population can grow without engendering declining living standards; this is termed maximum sustainable population growth. The model accounts for the existence of both Malthusian and growth economies, and is then utilized to evaluate the importance of competing explanations for the beginning of income growth in Britain.

☆ The authors wish to thank Knick Harley, Jacob Weisdorf, Richard Sylla, Bob Allen, Stephen Broadberry, Greg Clark, Bob Lucas, Matthias Morys, Paul Warde, Jan Luiten van Zanden, Michael Best, Joe Rowsell, Charlie Brendon, Nick Howarth, Nick Juravich, Nico Voigtländer, Hans-Joachim Voth, Alan de Bromhead, and Stefan Bache for helpful consultations and insightful comments. The views expressed in this paper are those of the authors and are not necessarily reflective of views at the Federal Reserve Bank of New York or the Federal Reserve System. Any errors or omissions are the responsibility of the authors.

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http://dx.doi.org/10.1016/j.jmacro.2015.01.006

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We apply the model to the breakout that occurred in Britain at the time of the Industrial Revolution, which was characterized by an unprecedented rise in maximum sustainable population growth (MSPG). In the years from the late 17th century to the early 19th century, MSPG increased from firmly Malthusian levels to levels that exceeded not only the peak of British population growth but also any rate of population growth that has ever been recorded. This vast increase in the amount of population growth that the British economy could absorb without engendering declining living standards was possible due to a set of economic changes associated with the Industrial Revolution. We will see that while many of the factors that have been cited by other authors—technology, structural change, coal, and capital—made a contribution to lifting the Malthusian constraint, the process was dominated by technology and structural change.

In addition to solidifying the link between the Industrial Revolution and rising living standards, we make four main contributions to the economic history literature. First, this research reconciles the gradualist and limited Crafts–Harley view of the Industrial Revolution with a dramatic and rapid change in Britain's macroeconomic character. Second, it estimates, in an accounting sense, the contributions of various economic factors to the ability of the economy to sustain income growth. Third, it shows that the link between the Industrial Revolution and the economy's ability to sustain a rise in living standards is robust to a wide variety of estimates for the various components of economic growth. Although the pace of transition varies, the qualitative story stays the same. Finally, along the way to compiling MSPG estimates we come up with new estimates for total factor productivity during the Industrial Revolution. These generally follow Crafts and Harley but employ improved estimates of factor shares and natural resource growth. The new estimates point to a somewhat larger role for TFP than the most recent estimates put forth by Crafts and Harley.

This article makes also three contributions to the growth theory literature. First, it develops the sustainable population growth framework and shows how it acts as a "common currency" in measuring contributions to takeoff. Second, we believe it represents the most elementary possible model in which takeoff can occur. Third, it identifies a heretofore underappreciated channel through which change in the structure of the economy is an important cause of takeoff, in addition to being simply a symptom of it as many authors have assumed.

The MSPG estimates presented here also carry two further implications that are at variance with the conventional wisdom. First, the effect of trade on the ability of the British economy to transition to modern growth is probably exaggerated. Second, we will see that short- or even medium-term economic growth is a different phenomenon than the ability to sustain a breakout in living standards. If we want to understand the end of the Malthusian era, just asking which factors contributed to growth does not necessarily shed light on this question. Rather, the question we must answer is "What allowed the British economy to transition, possibly fairly abruptly, from a regime where per capita income was trendless to one where it was growing at 1% per year?" The difficult thing to understand is not the "growth" but the "transition."

Finally, it is important to recognize that this analysis does not purport to investigate the ultimate causation of the Industrial Revolution. Rather, it is an accounting exercise in the spirit of Solow, linking the economic changes that were part of the Industrial Revolution to the accompanying rise in living standards. While it would be correct to consider the factors identified in this paper as the direct causes of a breakout, they are likely to be linked to each other as part of the broader underlying process of the Industrial Revolution. Although some cursory thought is given to these links here, a thorough examination of them is beyond the scope of this research.

Section 2 lays out our basic framework for modeling transitions from Malthusian regimes to modern growth. Section 3 explains data sources and estimation methods for the various components of MSPG. Section 4 combines the data to estimate MSPG in Britain. Section 5 discusses some implications of the results and how they relate to the previous literature. Section 6 concludes.

2. The basic model

The three most prominent contributions towards the literature modeling growth in a unified way are Kremer (1993), Galor and Weil (2000); and Hansen and Prescott (2002).[1] The model presented here has several advantages over previous attempts to model the transition process. First, it is much simpler and allows easy access to the intuition that can be obscured by a more complex model. Our model could be thus viewed as a prequel both to the modern "Unified Growth" literature, which is reviewed by Galor (2011), and to the previous generation of literature of which Sato and Niho (1971) is an example.[2] While

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[1] Kremer assumes and empirically tests a simple relationship between essentially global population size and the global rate of technological progress and shows how this relationship depends on initial population size. Galor and Weil construct a complex model that includes assumptions similar to Kremer's as well as Beckerian assumptions about child quality–quantity tradeoffs to generate an endogenous demographic transition as societies grow richer. Hansen and Prescott assume exogenous technical progress and fertility decisions but include shifting from a Malthus sector that relies on land for production to a Solow sector that does not. The shift is an equilibrium phenomenon driven by diminishing returns to land as the population grows concurrently with technical progress. The model introduced here shares with those papers an emphasis on a phase change generated by a demographic shift and an increase in sustainable population growth, although this is not their terminology.

[2] Sato and Niho (1971) employ a framework of sustainable population growth in a two-sector model of emergence from Malthusian stagnation in a closed economy, concluding that only technological progress in agriculture leads to breakout. More recently, Voigtländer and Voth (2006) introduce a probabilistic two-sector model and argue that the English economy in 1700 was more likely to see an industrial revolution than other countries. Strulik and Weisdorf (2008) point out that technology growth in industry has a very different impact on population growth and living standards than technology growth in agriculture. In particular, much of the new technology that arrived before the industrial revolution helped agriculture rather than industry. Voigtländer and Voth (2013) show how a major shock to population, such as the Black-Death, has increased wages and urbanization rates in Europe. In our approach we will be able to continuously observe how the English economy changed in the very long-run from 1300 to 1860.

Sato and Niho, and Hansen and Prescott require two sectors, which essentially doubles the number of variables, and Galor and Weil employ four simultaneous difference equations, the present model combines one production function and one differential equation governing population growth in a simple, intuitive way. It thus highlights the most important and fundamental dynamics of the transition from a Malthusian regime to a Solovian one, showing that the many assumptions and complexities of the literature are not necessary to generate both a qualitatively and quantitatively correct story. From a pedagogical perspective, the concept could become a useful tool in introductory teaching of the unified-growth theory.

Second, unlike Galor and Weil, and Kremer, this model's assumptions do not dictate that takeoff can only occur in societies of a certain size or level of technological advancement. Given that the first takeoff actually did occur in Britain, rather than in much larger France or China, this result is to be viewed as an advantage.

Third, in this model, most of the underlying causes of growth are exogenous. This approach is more flexible, allows investigations that a model with more endogeneity would not, and highlights key insights that a more complex model might obscure.

We view as highly suspect the suggestion that simply adding an additional equation or two would suffice to satisfactorily explain complex interactions between wealth and technological innovation, or to permit a credible estimate of fertility functions derived from pre-specified preferences. Surely political institutions are one of the dominant influences on these issues, as argued, for example, by Acemoglu et al. (2005) or North (1991). It should be uncontroversial to state that marriage and fertility are highly influenced by cultural and religious institutions (e.g. Greif, 2006). The study of Economics is not a substitute for the study of History: it is a complement.

Moreover, should we even wish to derive everything from first principles, as some would suggest is ideal, our current models of preferences have well-known weaknesses. The empirical evidence against expected utility theory is extremely strong (e.g. Kahneman and Thaler, 1991; Kahneman and Snell, 1992). Any insistence that models be grounded in expected utility maximization is therefore a demand to adhere to a dogmatic framework that is rife with empirical shortcomings.

Finally, we are not making unsupported arbitrary assumptions. Economics, like other disciplines, is collaborative and cumulative, and we rely on the past work of others, which we cite to inform our assumptions about the relationship between population growth and fertility. Our assumptions are consistent with both theory (e.g. Galor and Weil, 2000) and empirical evidence (e.g. Lucas, 2004).

In any event, by remaining agnostic about the relationships between the elements of a breakout, the model can accommodate a rich array of development strategies and can apply to a wider range of societies. Once again, our simple framework shows that the essence of the dynamics associated with a takeoff are not different than those derived from complex approaches using a variety of assumptions about endogeneity.

We employ a very simple Malthusian model, with a production function of population and resources.[3] Resources are fixed and population is endogenous. Technology is exogenous, for we wish to examine the role of technology in the transition from a Malthusian economy to a growth economy, and to do this we would like to exogenously vary the rate of technological progress.

We begin with a Cobb–Douglas production function in order to enable a convenient visualization of the main implications of our model. The birth and death rates are taken to be exogenous functions of per capita income:

$$Y = AL^{\alpha}R^{1-\alpha} \tag{1}$$

$$\frac{\dot{L}}{L} = b - d \equiv g(Y/L) \tag{2}$$

The birth rate rises with income until income reaches some critical level and subsequently falls, while the death rate falls with income. Defining per capita income $y = Y/L$, the functions $b(y), d(y)$, and $g(y)$ look like Fig. 1. The justification for the qualitative functional form of $g(y)$ in Britain is discussed in some detail in Appendix A, but is consistent with Lucas' (2004) results on the relationship of population growth to per capita GDP for five regions of the world. While this functional form facilitates an intuitive illustration of the transition process, it is not a strict requirement for the results. Our conclusions would not change if the function was not hump-shaped but monotonically increasing instead.

To solve the model, we rewrite it in per capita terms, take logs, and differentiate, which yields:

$$\frac{\dot{y}}{y} = \frac{\dot{A}}{A} + (1-\alpha_t)\frac{\dot{R}}{R} - (1-\alpha_t)\frac{\dot{L}}{L} \tag{3}$$

Noting that resources are fixed and substituting for population growth, we have simply that:

$$\frac{\dot{y}}{y} = \frac{\dot{A}}{A} - (1-\alpha_t)g(y) \tag{4}$$

This has a simple interpretation: if technological growth is faster than population growth times the resource share, per capita income is rising, and otherwise it is falling.

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[3] The basic results do not change if endogenous accumulation of capital is included in the model.

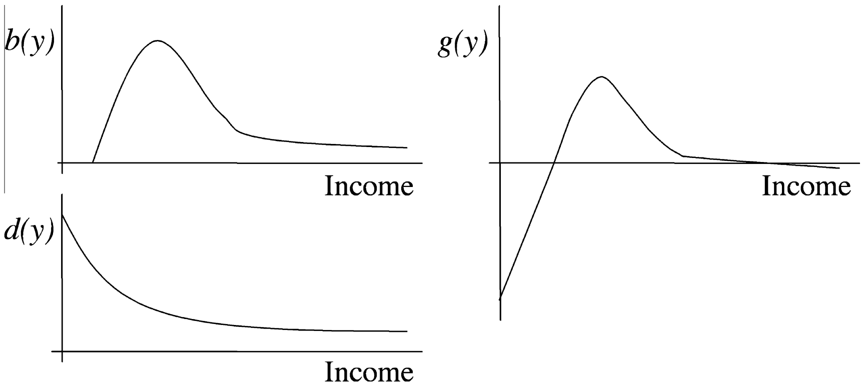

Fig. 1. Functional forms of birth rate, death rate, and population growth.

$\frac{\dot{A}}{A}(1-\alpha_t)^{-1}$ thus defines the *maximum sustainable population growth*, i.e. the fastest rate at which the population can grow without falling incomes.[4] MSPG can be thought of as the carrying capacity of the economy. If per capita income starts at a low level, then it will eventually rise to a Malthusian equilibrium at point M in Fig. 2, where the MSPG is precisely equal to $g(y)$: i.e. sustainable population growth equals actual population growth. This equilibrium is stable: if per capita income is hit by a positive shock, the population will grow faster and income will fall again; if hit by a negative shock, population will grow more slowly and income will rise. The same analysis holds for population shocks.[5]

The mechanism is classically Mathusian: A technology shock leads to higher incomes, causing population growth to rise and encountering diminishing returns to land. Diminishing returns combined with a population that is growing faster than the maximum sustainable population growth cause falling incomes and a return to a Malthusian equilibrium.

In this economy the *level* of income is determined by the *growth rate* of technology. The situation is analogous to pouring water into a leaky bucket—the faster the water is poured in, the higher the steady-state level of water in the bucket, but if the faucet is turned off, the water leaks out to a lower level. This leads to a prediction that in pre-modern societies, higher income levels should be associated with periods of technological advancement (or high MSPG for other reasons) but should dissipate once the technological advancement ends.

In essence, maximum sustainable population growth is a reservoir that can be used to support a growing population or rising living standards. In a Malthusian society, the maximum sustainable population growth rate is below the peak population growth rate. All growth in productivity is used to support a larger population, fully exhausting the reservoir. But once MSPG rises above that peak, people do not want to reproduce fast enough to "use up" all the productivity advances being discovered in the economy. Some of these advances can be used to increase per capita income, effecting the transition to modern growth. Returning to the leaky bucket analogy, modern growth is equivalent to pouring water into the bucket so fast that, despite the leaks, the bucket overflows.

These results do not depend on the Cobb–Douglas functional form or on having just two factors of production. Consider the very general production technology or, even more generally, an income function:

$$Y = F(L, R_i, X_j, s_k) \tag{5}$$

which is assumed to have constant returns to scale in the extensive inputs L, R_i, and X_j. Here, R_i are different types of fixed resources, X_j are variable factors of production such as capital or human capital, and s_k are parameters of the economy, such as the terms of trade and level of technology.[6] Then, if we take logs and differentiate, per capita income growth is given by:

$$\frac{\dot{y}}{y} = \sum_i \eta_i \frac{\dot{R}_i}{R_i} + \sum_j \eta_j \frac{\dot{x}_j}{x_j} + \sum_k \eta_k \frac{\dot{s}_k}{s_k} - \eta_R g(y) \tag{6}$$

where η_i and η_j are the elasticities of income with respect to each of the fixed resources and variable factors of production, and η_k are the elasticities of income with respect to the parameters s_k. Lowercase letters denote per capita amounts or

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[4] If the resource base of an economy is expanding, then MSPG $= \frac{\dot{A}}{A}(1-\alpha_t)^{-1} + \frac{\dot{R}}{R}$.

[5] Point G in the figure is also an equilibrium, albeit an unstable one. If the economy finds itself to the right of point G, income will rise, causing fertility to fall resulting in further income rises, fertility falls, and sustained growth. In practice, however, point G tends to occur at a high enough income that it is not attainable by pre-industrial societies (Lucas, 2004). If the economy is to the left of G, it will fall back to the Malthusian equilibrium at point M.

[6] Even though in the quanitative framework, due to data availability, we will not be able to disentangle capital from human capital issues, the role of each can be captured by the model. Galor (2011) explains how technological progress increased the incentive to invest in the education of children, at the cost of a reduced number of births. The existence of a historical child quantity-quality trade-off has been shown also in recent empirical studies by Becker et al. (2010), Klemp and Weisdorf (2012) and Fernihough (2011).

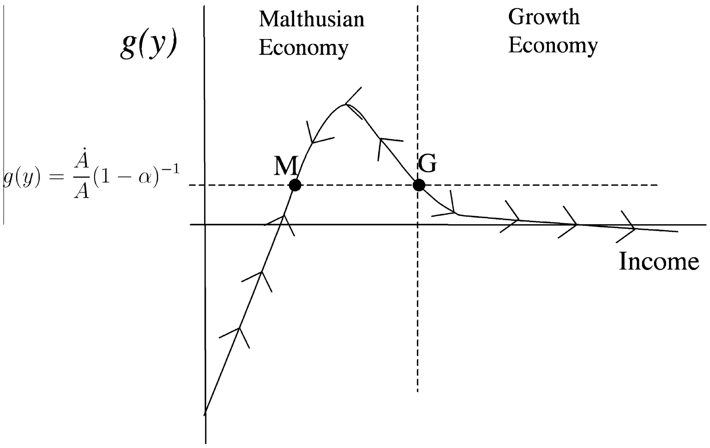

Fig. 2. The dynamics of the economy.

intensive properties of the economy, and $\eta_R = \sum_i \eta_i$ is the total share of output paid to fixed factors. Maximum sustainable population growth is then determined, as before, as the rate of population growth giving rise to constant per capita income:

$$\text{MSPG} = \frac{1}{\eta_R} \cdot \left[\sum_i \eta_i \frac{\dot{R}_i}{R_i} + \sum_j \eta_j \frac{\dot{x}_j}{x_j} + \sum_k \eta_k \frac{\dot{s}_k}{s_k} \right] \tag{7}$$

$$= \frac{1}{\eta_R} \frac{\dot{y}}{y} + \frac{\dot{L}}{L} \tag{8}$$

The R_i terms in line (7) are familiar and represent the contribution from an expanding resource base. The terms in x_j are new. They represent the contributions of deepening in other factors of production, particularly capital. Growth in these factors contributes to MSPG proportionately to their shares in output, and inversely with the share of fixed resources in output. Thus, structural change away from land-intensive production and into capital-intensive production raises MSPG by increasing the multiplier on the capital deepening term of Eq. (8).

The formulation in Eq. (8) offers a very general reduced form for MSPG that applies to any constant-returns-to-scale economy. Note that this is not a causal relationship but an observational one that allows us to calculate MSPG from economic observables.

Eq. (8) highlights the difference between income growth and MSPG. The concepts are related but not identical, and changes that increase one may decrease the other. To see this, let us consider the effect of a small change in the structure of the economy by differentiating Eq. (8):

$$d(MSPG) = d\left(\frac{\dot{y}}{y}\right) \cdot \frac{1}{\eta_R} + d\left(\frac{1}{\eta_R}\right) \cdot \frac{\dot{y}}{y} + g'(y)dy \tag{9}$$

Eq. (9) makes explicit that changes that increase instantaneous income or income growth may or may not increase MSPG depending on what happens to the resource share. If a structural change increases the resource share, it may decrease MSPG even though it increases income or income growth. If it decreases the resource share, it may increase MSPG even in the face of a decline in income or income growth. The intuition is that a lower resource share raises the ultimate steady-state income level even as it decreases the rate of growth toward that equilibrium.[7]

3. Estimating the building blocks of MSPG

We now estimate MSPG in Britain during the period 1300–1850. For this purpose we utilize Eq. (7), which allows us to include capital in the model as follows:

$$\text{MSPG} = \frac{1}{\gamma}\frac{\dot{A}}{A} + \frac{\beta}{\gamma}\frac{\dot{k}}{k} + \frac{\dot{R}}{R} \tag{10}$$

where γ is the resource share in the economy and β is the capital share. We will thus require estimates of total factor productivity A, the factor shares β and γ, effective land area R, and capital intensity k.

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[7] In Appendix B we provide a detailed theoretical account of the effect of an opening to trade on the economy.

3.1. Total factor productivity

Estimates of TFP growth prior to the advent of modern statistics are quite unreliable and difficult to come by. The estimates that have been used in this paper are based on those by Allen for the years prior to 1700 and by Crafts for the years after 1700. Allen (2005) estimates total factor productivity in agriculture in 1300, 1500, and 1700, and he also estimates labor productivity for 1400 and 1600 (Allen, 2000). In order to estimate TFP for these latter two years, we assumed that TFP followed a similarly shaped path to labor productivity.[8] Table 1 shows Allen's estimates for TFP and labor productivity, and our interpolated estimates for 1400 and 1600. There is assumed to be no TFP growth outside of agriculture prior to 1700,[9] so the agricultural TFP growth rate is multiplied by the share of GDP in agriculture, which is estimated as described in Section 3.2. The top three rows of the table present index numbers in the turn of the centuries; the bottom three rows are averages over the century beginning with the date at the column heading.

For the years from 1700 to 1860, we use the residual approach of Crafts (1985, p. 78), making use of Crafts (1985, 1995) and Crafts and Harley's (1992) estimates of real GDP growth, Wrigley and Schofield's (1981) population estimates, Feinstein's (1988) estimates of capital stocks, and our own estimates of natural resource growth and factor shares as described in Sections 3.2 and 3.3 below. Combining these figures with the numbers from Allen gives estimates of TFP growth from 1300 to 1860. This time series is shown in Table 2, and it will serve as our estimate of TFP growth for the rest of this paper.

These estimates of TFP growth are close to Crafts' original (Crafts, 1985) estimates and are generally somewhat higher than Crafts and Harley's revised figures. This does not stem from any fundamental disagreement with Crafts and Harley over the progress of the economy but rather reflects the need to treat land and capital as separate factors.

The results indicate that prior to the scientific revolution in the mid-17th century TFP growth was extremely slow and may have been dominated by exogenous events like climate change. The 150 years from 1650, including the agricultural revolution, saw modest but consistently positive rates of TFP growth in England. Then, beginning with the Industrial Revolution in the first half of the 19th century, TFP growth slowly accelerated to modern levels.

3.2. Structural change

Structural change is linked to breakout because it reduces the dependence of the economy on land and other natural resources that are constrained in the Malthusian sense.[10] While there are many measures of structural change, the one that matters for breakout is the factor shares in the economy. Specifically, the inverse resource share acts as a multiplier on MSPG, so that reducing the importance of fixed factors in the economy can have a large effect on sustainable population growth.

Structural change may encompass not only a shift to less resource-intensive production but also a shift to more capital-intensive production. In Eq. (10) we observe that as the resource share, γ, falls (if the move is into capital-intensive production), then β increases at the same time, magnifying the effect. Estimating the production elasticities β and γ is fraught with pitfalls. The simplest way to do so, and the approach taken by most authors, is to assume that the pre-Industrial and Industrial Revolution British economy was approximately competitive and to proxy the elasticity of production by the share of GDP paid to each factor. That is the approach taken here, although it is recognized that this is a strong assumption.

We construct our own rent share coefficients prior to 1700. For the rent share after 1700, we obtain two separate series: using Clark et al.'s (2012) and Allen's (2009) estimates or Broadberry et al.'s (2013) figures.

The estimation methodology is as follows. We assume that all land rents derive from agriculture prior to the 18th century, as rents paid on coal mines even in 1860 were at most 4% of agricultural rents, and were negligible before this time.[11] We then combine data on the share of agricultural income paid to land (Allen, 2005),[12] share of labor force in agriculture (Broadberry et al., 2013; Clark, 2013; Clark et al., 2012), and the productivity differential of agriculture and other sectors (Broadberry et al., 2013) to determine the share of output paid as land rents.

Data on the share of agricultural income paid to land is fairly straightforward but there is a range of estimates for the share of English labor force engaged in agriculture prior to 1760. Previous estimates by Wrigley (1985) and Overton and

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[8] See Appendix C for details of this calculation.

[9] This may appear to be an extreme assumption, but in the absence of data we believe it to be the most appropriate. First, it avoids repeating Deane and Cole's (1967) error of assuming that the sector with notable productivity growth (in their case textiles, in this case agriculture) was representative. Second, Crafts' (1985) estimates that industrial and commercial output grew at an annual rate of 0.70% from 1700 to 1760, while the population outside agriculture grew at a rate of 0.64% (Wrigley and Schofield, 1981). This leaves little room for productivity growth even in the 18th century, and there was probably less in earlier times.

[10] Although it is not modeled as part of the main paper, it is easy to create a feedback loop so that structural change is endogenous in the model. Intuitively, if agricultural productivity increases slowly, then the entire productivity growth is absorbed into supporting a larger population. However, if agricultural productivity increases more quickly, then as incomes rises, people consume more non-agricultural goods (the income elasticity of food demand is less than one). This leads to people moving off the land, decreasing the rent share, which increases per capita income growth, leading to a lower share of agriculture in GDP and more people moving off the land, which leads to a lower rent share, in other words a virtuous circle.

[11] See Clark and Jacks (2007) for data on coal rents.

[12] We obtain from Allen (2005) estimates of the agricultural income paid to land for 1300, 1500, and 1700. The share of agricultural income to land in 1400 is assumed to be the same as the estimate for 1500, as all the change in economic structure between 1300 and 1500 is assumed to be due to the Black Death in 1348–51. We further use the share from 1700 for 1650, as it is the closest available estimate. The later assumption is further motivated by the observation that the share of agricultural income to land remains remarkably stable at around 50% throughout the 17th and 18th centuries.

Table 1
Calculation of total factor productivity pre-1700. *Sources:* See text.

	1300	1400	1500	1600	1700
Allen TFP	0.83		1.00		1.38
Allen labor productivity	0.8	0.92	1.00	0.76	1.15
Interpolated TFP		0.94		0.83	
Estimated Ag TFP CAGR for Century	0.12%	0.06%	−0.18%	0.51%	
Proportion of GDP in agriculture	46%	43%	41%	35%	
Present TFP estimates	0.06%	0.03%	−0.08%	0.18%	

Table 2
Annual growth rates of total factor productivity (%). *Sources:* see text.

	1300–1400	1400–1500	1500–1600	1600–1700	1700–1760	1760–1780	1780–1800	1800–1830	1830–1860
Crafts/Harley TFP					0.20	0.00	0.10	0.35	0.75
Present TFP Estimates	0.06	0.03	−0.07	0.14	0.31	0.04	0.41	0.57	0.88

Campbell (1996) have been contested by recent scholarship (Broadberry et al., 2013; Clark, 2013; Clark et al., 2012). However, the estimates provided by Broadberry et al. (2013) differ quite significantly from those reported by Clark et al. (2012). Broadberry et al. (2013) reconstruct the labor force in the three principal sectors—agriculture, industry and services—for benchmark years using the poll tax returns of 1381, the Muster Rolls of 1522, and re-worked social tables for 1696, 1759, 1801 and 1851. Clark (2013) also uses the poll tax returns of 1381 to reconstruct the share of English labor force engaged in agriculture, but for later dates (1560–79 and 1651–60) uses occupation statements in wills.

The estimated share of the labor force in agriculture for 1381 is essentially the same according to both groups of researchers, which is unsurprising since they rely on the same primary source. Broadberry et al. (2013) find that 57% of the workforce was engaged in agriculture, while Clark (2013) provides figures of 56–59%. The next available estimate is provided by Broadberry et al. (2013)—58.1% in 1522, which suggests that the farm share in employment remained fairly stable over the course of the 15th century. The agreement ends however here and the estimates provided for the following years diverge. While Clark et al. (2012) report consistently high figures for 1560–79 and 1652–60, which are 61% and 59%, respectively, Broadberry et al. (2013) provide significantly lower estimates for 1700, equal to 38.9%, and further decreasing numbers for later periods. If both sets of figures are right, it would imply an implausibly rapid structural change in the English economy from 1660 to 1700. Until new and better evidence becomes available, it is not clear which point of view will stand the test of time (Leunig, 2013), and as such, it is not obvious which estimates are the right ones. Therefore, we construct two separate rent share series for the period of the disagreement.

Based on the earliest estimates, which are provided for 1381 and come closest to 1400, we calculate the average agricultural share in employment for 1400. Since there is no estimate available for the share of workforce in agriculture in 1300, we approximate it with the estimate from 1400, an assumption supported by the near-constant share of agricultural employment from 1381–1650. Broadberry's figure for 1522 is used for 1500 and Clark's estimate for 1652–60 is employed for 1650. From then on their estimates diverge significantly and we construct two separate series for the period post 1700. The first one takes rent share estimates directly from Allen (2009) for the period after 1760 and calculates the rent share for 1700 as the average between Allen's figure for 1760 and our estimate for 1650. The second series is based on Broadberry's estimates that are closest to 1700, 1760, 1800 and 1841. Table 3 summarizes the calculations.

We turn next to the estimation of productivity differences between the agricultural sector and the rest of the economy. Broadberry et al. (2013) estimate that productivity outside agriculture was higher than productivity in agriculture by a factor 1.6 in 1381, 2.11 in 1522, and 1.74 in 1700. We use these figures to translate our agricultural share in employment into GDP share estimates for 1400 and 1500, and interpolate the productivity difference for 1650. We then multiply the share of GDP in agriculture by the share of agricultural production paid as rent to obtain the share of GDP paid to land. To determine the rent share in 1600, we use Clark's (2002) rent index combined with the assumption that gross land area under cultivation was constant over the half-century from 1600 to 1650. Linked with data on population growth and the rent share in 1650, this uniquely determines GDP per capita growth, which is estimated to have been 0.02% per annum from 1600 to 1650.[13] Broadberry et al. (2012) report a comparable figure for annual GDP per capita growth rate of −0.04%. Our estimates imply a rent share of 29% in 1600 and, by taking the average of the rent share for 1650 (based on Clark's estimates) and Allen's estimate for 1760, we find a rent share of 23% in 1700. Calculating the rent share using Broadberry's numbers, one would end with a low estimate of 14%.

As a check on these figures, one could conduct a bottom-up approach: multiplying the rent per acre by the number of acres (Clark, 2002) and dividing by nominal GDP (Lindert and Williamson, 1982). This yields a rent share in GDP of 23% in 1700, 24% in 1760 and 13% in 1800. The 1700 estimate is practically the same as the rent share coefficient obtained in

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[13] See Appendix C for the details of this calculation.

Table 3
Rent share in national income estimates. *Sources:* Rent share in agricultural income from Allen (2005). Share of population in agriculture from Broadberry et al. (2013), Clark (2013), Clark et al. (2012). Share of GDP in agriculture and rent share in GDP own calculation based on Broadberry's et al. and Clark's et al. data on share of population in agriculture. See text for calculation methods.

	1300	1400	1500	1600	1650	1700	1760	1800	1841
Allen:									
Rent share of ag. inc.	0.39	0.19	0.19		0.51	0.51	0.48	0.51	0.48
Clark/Broadberry/Allen:									
Share of pop. in ag.	57%	57%	58%		59%				
Share of GDP in ag.	46%	46%	40%		46%				
Rent share in GDP	0.18	0.09	0.08	0.29	0.23	0.23	0.22	0.17	0.11
Broadberry:									
Share of pop. in ag.						39%	37%	32%	24%
Share of GDP in ag.						27%	30%	31%	19%
Rent share in GDP						0.14	0.14	0.16	0.09

our framework when Clark's agricultural share in employment is used; the estimates for the following years come very close to Allen's rent share.

To get averages over a period, we simply average the endpoints of the period. The final rent share series for use in the MSPG calculation are reported in Table 4, along with Allen's figures for capital shares after 1700. Both series show a large reduction of the rent share—by over a factor of two—from the 17th century to the middle of the 19th century. Because many components of MSPG are inversely proportional to the rent share, this structural change in the economy approximately doubled sustainable population growth over the period.

A further check could be conducted by calculating the sum of incomes derived from land, based on the social tables from Lindert and Williamson (1982). We assume that 80% of the incomes of the high titles comes from land, 20% for secular professions, 50% for farmers, cottagers and paupers. We also assume that 80% of the excess of income of freeholders over farmers was derived from landholdings.[14] These estimates translate into a rent share of 28% in 1688. The calculation is summarized in Table 13.

Both checks support the series based on Clark's and Allen's estimates over Broadberry's. For this reason we shall use this series in the baseline specifications when estimating MSPG. We use the rent share based on Broadberry's estimates to demonstrate the robustness of our results.

3.3. Coal and land improvements

MSPG was also influenced by growth in England's natural resource base. This took two forms. First, as England grew, more land was brought under cultivation and cleared, increasing effective land area. Second, and more importantly, the explosion of coal production up to the mid-18th century substituted for timber, which freed up land to be used for other purposes and similarly expanded England's natural resource base. We rely on Allen (2005) for estimates of increases in effective land area, while deriving our own estimates for coal.

Coal increased MSPG in two ways. Most significantly, it substituted for timber, which required land, i.e. the Malthusian fixed factor, for its cultivation.[15] Second, because rents on coal producing land were proportionately lower than rents on agricultural land, it reduced the factor share of land in the economy.[16] The substitution for timber meant that coal increased the effective amount of land that Britain had to support its population; land that previously was needed to grow timber could be used to grow food, and the demand for energy that would have needed to be met by additional timberland could be met by coal. Determining the effective easing of the land constraint, however, can be slightly more complicated. Coal energy is recognized to have been of a lower quality than charcoal (coal sold at a discount to charcoal), and coal mines are not as versatile as land in production of final goods. Additionally, because coal mining is a different production process than agriculture, rent typically made up a much lower share of gross produce. Exactly what adjustments should be made for these differences is open to debate.

The baseline approach taken here aims at determining the acreage necessary to produce timber of the same value as British coal output. This methodology has the advantages that it implicitly takes into account a measure of land quality,

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[14] These shares are based on Holmes (1977, pp. 54–55), Mingay (1963), Mimardiere (1963, p. 98), Stone (1965, p. 562), Thompson (1966, p. 509) and Cooper (1967, p. 431).

[15] It may be argued that once nearly all energy came from coal, coal mines could no longer substitute for agricultural land because people cannot eat coal. However, coal could be and was exported and thus held down prices of land-intensive goods on the world market, goods which Britain imported.

[16] Adam Smith comments on this in *The Wealth of Nations* (p272): "Rent, even where coals afford one, has a generally smaller share in their price than in that of most other parts of the rude produce of land. The rent of an estate above ground commonly amounts to what is supposed to be a third of the gross produce…In coal mines a fifth of the gross produce is a very great rent; a tenth the common rent…Thirty years' purchase is considered as a moderate price for the property of a landed estate, [but] ten years' purchase is regarded as a good price for that of a coal mine." Clark and Jacks (2007) also figure that coal rents were typically just 7–10% of the pithead production.

Table 4
Factor shares in national income. *Sources:* See text.

	1300–1400	1400–1500	1500–1600	1600–1700	1700–1760	1760–1780	1780–1800	1800–1830	1830–1860
Clark/Broadberry/Allen:									
Rent share in GDP	0.13	0.08	0.18	0.25	0.23	0.22	0.19	0.16	0.11
Broadberry:									
Rent share in GDP				0.22	0.14	0.15	0.15	0.14	0.11
Allen:									
Capital share in GDP					0.20	0.19	0.20	0.32	0.39

and it reflects Britain's ability to trade coal for timber on the world markets. Appendix D discusses three alternative estimation strategies:

1. a simple calculation of the amount of woodland that would be required to produce the same quantity of energy as British coal;
2. a comparison of the total output of the coal industry to the agricultural output; and
3. a comparison of land rents in agriculture to site rents for coal mines.

We will later use the results from these methods to estimate the range of possible estimates of MSPG, but now we return to our baseline approach.

According to Clark's price indexes, coal sold for about 4.1 shillings/ton in 1800, which agrees with Crafts' (1985) estimate that British coal production was worth £2.7 million in 1800. A cord of firewood sold for 31 s. At 1 cord/acre (Allen, 2009), an acre's worth of firewood production cost as much as 7.6 tons of coal.[17] Combined with improvements in land quality as discussed by Allen (2005, Table 1), coal increased the effective land area of England and Wales from 17.5 million acres in 1300 to 45 million acres in 1860. Table 5 summarizes the contributions of coal and land improvement to effective land area growth.

Effective land area growth contributes to sustainable population growth on a one-for-one basis, so while coal and land area growth contributed moderately to MSPG, they were not sufficient to cause a dramatic breakout. Appendix D conducts a number of estimates based on different methodological approaches. We present the low and high estimates from those alternative calculations in table 10. It is only at the very highest end of the estimates, and even then only beginning in the mid-19th century, that coal could itself have been sufficient to raise MSPG above the threshold for breakout. Even then, other contributions to MSPG were of equal or greater magnitudes.

3.4. Capital deepening

The technological change of the Industrial Revolution brought with it an increase in investment and therefore significant capital deepening. We use estimates of capital stocks from Feinstein (1988) post-1760 and follow Crafts (1985) in assuming that prior to 1760 the capital-to-GDP ratio was constant. This assumption, however, still allows some role for capital deepening, since GDP generally grew faster than the population in the 18th century. Table 6 shows the figures on capital growth, both in aggregate and per capita, that we use in our MSPG calculations.

Prior to 1700, capital per worker is assumed to be constant outside of agriculture. In agriculture, any GDP changes due to capital per worker show up as increases in TFP.

4. Calculating MSPG in Britain

An important question about the Industrial Revolution is how British industrialization relates to the beginning of the sustained rise in living standards that occurred at approximately the same time. To the extent that the Industrial Revolution refers to a shift in production away from agriculture into industry, and into more technologically advanced industrial production processes requiring higher capital intensity and relying on coal for energy, we are now able to draw a clear link between these economic changes and the beginning of a sustained rise in living standards.

Using the estimates made in the previous section we now plot British MSPG (Fig. 3), calculated according to Eq. (10), and population growth. In Appendix E we report alternative estimates based on the rent share derived from Broadberry's data.[18] In post-medieval British history, we can see that it was not until the last two decades of the 18th century that sustainable population growth significantly exceeded the peak in the population growth function for any sustained period, but by the middle of the 19th century, the economy was able to sustain a population growing at around 13% per year—nine times the maximum

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[17] We assume 82 cu. ft. of solid wood per cord after accounting for air space, which is what is implied by figures in Allen (2005).

[18] As we will see, the qualitative story is not sensitive to which estimates one chooses. We also show this in this section by estimating low, best and high estimates of MSPG.

Table 5
Effective p.a. land area growth. *Sources:* See text for sources and calculation method.

1300–1500	1500–1700	1700–1750	1750–1775	1775–1800	1800–1830	1830–1860
0.04%	0.16%	0.26%	0.37%	0.39%	0.18%	0.53%

Table 6
Growth in capital stock and capital per worker. *Sources:* See text.

	1700–60	1760–80	1780–1800	1800–30	1830–60
$\Delta K/K$	0.7%	0.63%	1.30%	1.73%	2.48%
$\Delta k/k$	0.37%	−0.05%	0.26%	0.29 %	1.30%

observed rate of population growth and more than six times the rate that could have been sustained at any time prior to the Industrial Revolution.

These results naturally explain Crafts and Mills' (2009) empirical finding that the British economy exhibited strong homeostasis prior to 1645 and extremely weak homeostasis thereafter. Crafts and Mills' result is likely a consequence of their having tested an equilibrium version of a Malthusian model where wages and population are always in their Malthusian equilibrium. By contrast, the present model is a dynamic one that explains the behavior of the economy even in out-of-equilibrium states. Prior to 1645, MSPG was close to zero, so a traditional Malthusian model linking wages to population should perform relatively well. After 1645, MSPG was near the threshold for breakout, meaning the traditional Malthusian mechanism operated only very weakly.

The chart also suggests that from the 17th century onwards the British economy was slowly and smoothly building toward the ability to achieve breakout, with the "knee" of the curve reached at the Industrial Revolution. While at first glance the chart shows a dramatic change at the end of the 18th century, it could just as easily be interpreted as a smooth curve from 1600 onwards with technological progress in agriculture flowing into technological progress in industry as part of a single phenomenon, save only for a depression from 1760 to 1780. That depression was characterized by a slowdown in TFP growth that may have been related both to the Seven Years War from 1756 to 1763 and the American Revolution from 1775 to 1781.

In any event, by the beginning of the 19th century, the Malthusian constraint had been completely and—depending on which view of the 1760s and 1770s one takes—suddenly eliminated. This finding is consistent with Lee and Anderson (2002, p217), who find a "very sharp and discontinuous rise in the rate of increase [of labor demand] starting around 1810." Their definition of the rate of increase of labor demand is the rate at which new labor can be absorbed by the economy; this is MSPG viewed through the econometrician's lens.

Maximum sustainable population growth is the only measure of capacity we are aware of that shows such a dramatic change over precisely the time period of the Industrial Revolution and the beginning of the increase in living standards. TFP growth, for example, did not reach truly unprecedented levels until the middle of the 19th century. The MSPG framework thus reconciles the Crafts–Harley limited view of the Industrial Revolution with a large and discontinuous change in the carrying capacity of the economy, which was linked to the beginning of a sustained increase in living standards.

Viewing the takeoff through the lens of MSPG also reconciles the timing of the economic change and expansion in output—the last two decades of the 18th century—with the timing of real wage growth, which did not begin in earnest until a few decades later.

The estimates upon which MSPG is based are open to debate and measurement error. Fortunately, the broad, qualitative story of breakout and how and when it occurred does not change if different estimates are used. Fig. 4 plots a low, high, and best estimate of MSPG from 1300 to 1860. The high estimate uses the highest estimates of GDP growth (Deane and Cole's), assumes that productivity growth in the non-agricultural part of the economy mirrored productivity growth in agriculture prior to 1700, employs the energy-equivalent method for coal mining (see Appendix D) with Warde's figure of 0.38 tons of coal per acre, and uses the lowest rent share estimates (based on Broadberry et al.'s share of agriculture in employment). The low estimate uses the lowest estimates of TFP growth we found (from Antras and Voth, 2003), the rent-equivalent method for coal mining (implying an equivalence of 50 tons per acre), and the highest rent share estimates available (based on Clark et al.'s share of agriculture in employment and Allen's rent share for post-1760). It should be recognized that the range presented does not represent a confidence interval in any sense. Rather, it is intended to show that the overall story is not sensitive to which "view" of the Industrial Revolution one takes. The narrow interval in the early years of the chart is indicative not of strong confidence in the figures but of a paucity of varying estimates in the literature.

Fig. 5 plots the contributions of each of the factors we consider to MSPG. These are also shown in Table 7. The figure shows that during the Industrial Revolution, MSPG was largely attributable to technological advances and structural change in the economy and, by the middle of the 19th century, to a shift to more capital-intensive production. The shift to more capital-intensive forms of production played a rather minor role prior to 1830. At least in an accounting sense, coal played only a minor part in the takeoff.

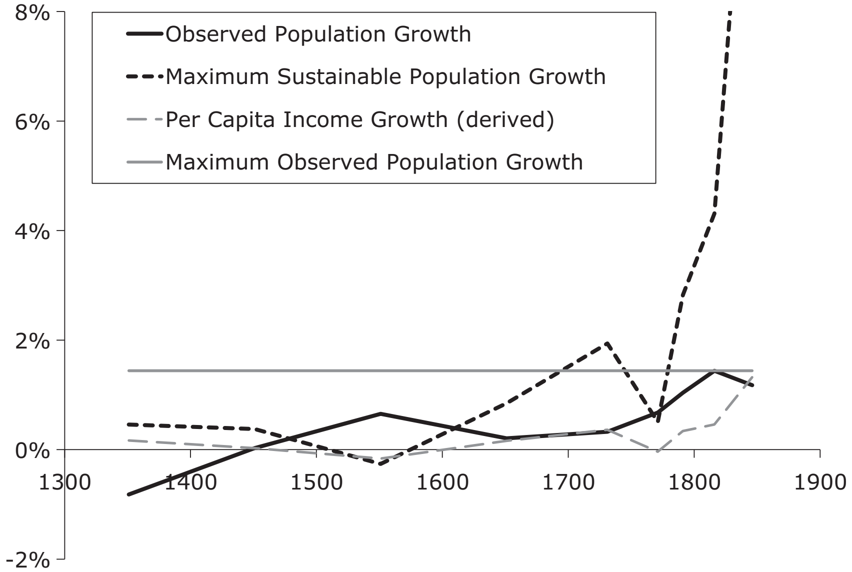

Fig. 3. Maximum sustainable population growth from 1300 to 1860.

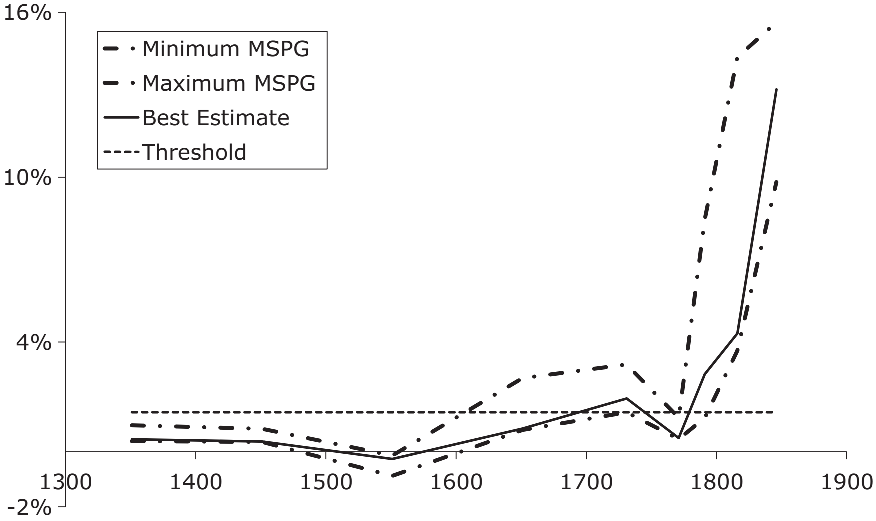

Fig. 4. Range of MSPG estimates, 1300–1860.

5. Discussion

The key to breakout is the ability to sustain non-immiserating population growth; MSPG is the measure of this ability. Fig. 6 illustrates that the Industrial Revolution, with its technological improvements and growth in less resource-dependent sectors, caused a clear and unprecedented increase in maximum sustainable population growth as early as 1780, well before a large effect was seen in wages and GDP per capita. The proposed framework explains how such a phase change can take place without unprecedented levels of per capita income growth. Indeed, even though the rates of income growth seen from 1780 to 1830 were at most a tenth of a percentage point greater than those seen a century earlier, the massive change in MSPG shows that the growth in the Industrial Revolution period was part of a new and unprecedented process of breakout.

Structural change, i.e. the movement of the labor force from agriculture into industry and from the country to the city, is often remarked upon as a feature of industrialization and the beginning of modern growth. Most of the literature, however, focuses on structural change as a *result* of the growth in living standards or of factors driving that growth.

The most obvious link between structural change and growth is that as agricultural productivity improves, fewer people are needed to produce the food supply for a society. The surplus labor that emerges tends to migrate to cities and towns and

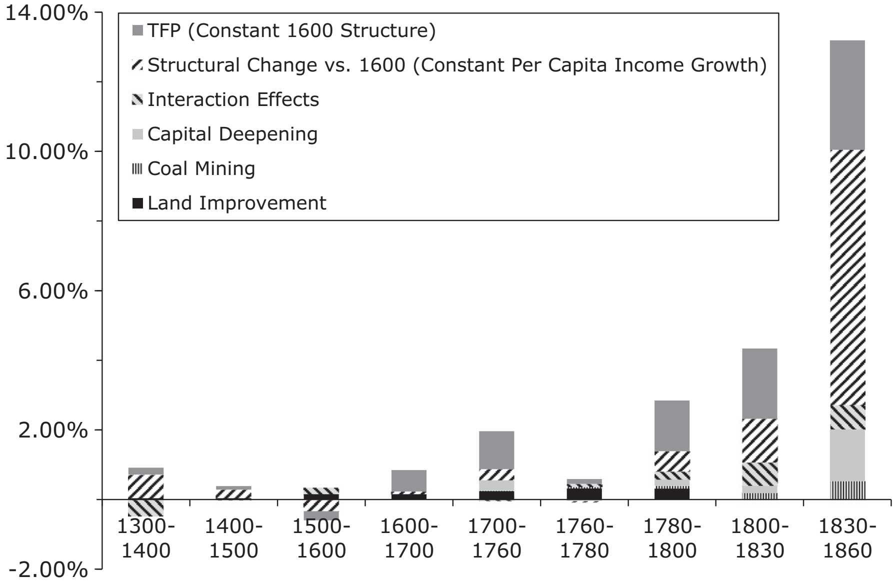

Fig. 5. Contributions of various factors to MSPG.

Table 7
Contributions to MSPG (Percentage Points Per Year). *Sources:* The utilized rent share estimates are based on Clark et al.'s share of workforce in agriculture. See text for remaining sources and calculation method.

	1300–1400	1400–1500	1500–1600	1600–1700	1700–1760	1760–1780	1780–1800	1800–1830	1830–1860
TFP (Constant 1600 structure)	0.20	0.10	−0.27	0.62	1.09	0.14	1.46	2.02	3.15
Structural change vs. 1600 (Constant Per Capita Income Growth)	0.68	0.25	−0.33	0.07	0.32	−0.04	0.58	1.24	7.32
Interaction effects	−0.47	−0.01	0.18	0.01	−0.03	0.08	0.24	0.69	0.72
Capital deepening					0.30	−0.04	0.18	0.21	1.48
Coal mining	0.00	0.00	0.01	0.01	0.02	0.06	0.08	0.17	0.52
Land improvement	0.04	0.04	0.15	0.15	0.24	0.32	0.31	0.01	0.01
MSPG	0.46	0.38	−0.25	0.83	1.94	0.51	2.83	4.31	13.19

find employment in less resource-intensive sectors. While there is debate about what exactly drives people off the land (see, for example, Weisdorf, 2006; Crafts and Harley, 2002, for different views on the topic), structural change is viewed as a consequence of or accompaniment to growth rather than an important ingredient in itself.

Some authors have discussed structural change as a driver of growth, but usually through more complex channels than those modeled here. While Mendels (1972) argued that "proto-industrialization", which is the move into handicrafts rather than (or in addition to) food production, set the stage for the growth of modern industry, his arguments are based on cost pressures spurring technological improvement. Mathias (1989) similarly argues that proto-industrialization allowed the development of industrial and entrepreneurial skills, a commercial infrastructure, and capital. Harley (1994) discusses how Britain's focus on rapidly-advancing industry became an engine of growth. These arguments, however, tend to be made in broad brush strokes and offer a tentative rather than firm link between structural change and growth. The nature of the hypotheses are difficult to support with hard evidence. More importantly, they do not make it clear whether these channels were an idiosyncrasy of the British experience or whether they somehow represent an integral part of the process. Here, we show how structural change is an important cause of breakout because it reduces the economy's dependence on resource-intensive production, raising MSPG.

Coal's importance in the Industrial Revolution remains a subject of debate. While the New Economic History tends to view coal as playing a smaller role (e.g. Clark and Jacks, 2007, who also provide a review of the current state of the debate), coal remains to be seen by many scholars as a major driver of industrialization. In fact the industrial revolution is sometimes defined through the lens of coal as "the escape from the constraints of an organic economy" (Wrigley, 2010, p. 239). According to Griffin coal was *the* factor that has mitigated the "age-old constraints which had placed a ceiling to the growth of industry and population" (Griffin, 2010, p. 107).

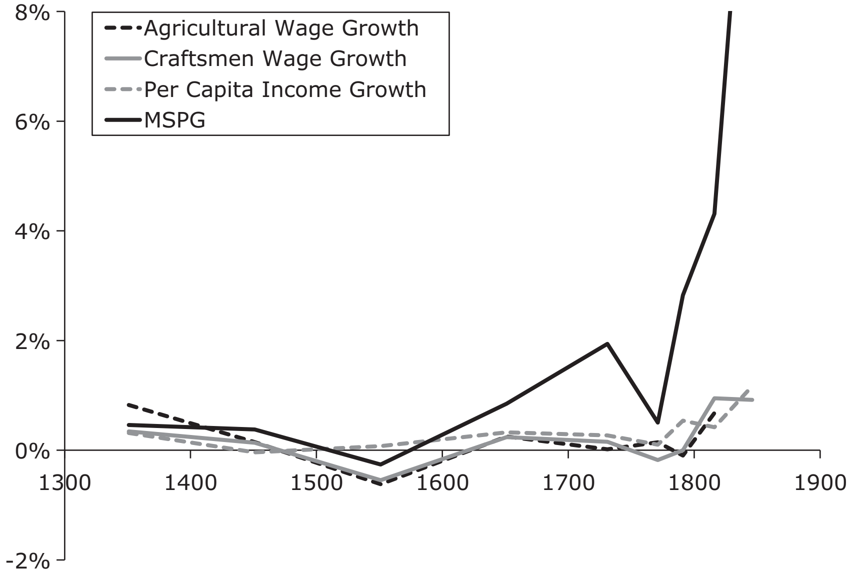

Fig. 6. MSPG, real wage and real GDP, 1300–1860. *Sources:* The utilized rent share estimates are based on Clark et al.'s share of workforce in agriculture. Real wage series for craftsmen from Clark (2005) and real GDP per capita series from Broadberry et al. (2012).

This analysis concludes that while coal could theoretically have played a large role in easing the Malthusian constraint, a quantitative investigation indicates that it probably did not do so, at least directly. However, coal may have contributed to the Industrial Revolution in ways beyond the scope of this model. In addition to easing the land constraint, the discovery of coal provided the areas of Britain in the vicinity of the coalfields with extraordinarily cheap energy because of the lower transport costs (Allen, 2009). It is thus no surprise that energy-intensive industry did in fact spring up around the coalfields. Independent of its contribution to increasing effective land area, economic growth, or import revenues, coal contributed to structural change in the British economy. This structural change was another significant factor in raising MSPG.

6. Conclusions

It seems obvious that there was a fundamental change in the British economy at the turn of the 19th century, a change that, at least in the popular imagination, has long been characterized by a small number of trends and inventions: the steam engine, cotton gin, coal, the reorganization of production into factories, and migration off the land and into cities. Yet one of the great mysteries of the New Economic History is that as prime causes of wealth, these icons of the Industrial Revolution have proved ethereal when investigated quantitatively (e.g. Harley, 2012).

The framework of sustainable population growth reconciles the older and popular notion of a cataclysmic, revolutionary change in the economy with the relatively limited changes in most economic variables. During the Industrial Revolution, the rate of population growth that the British economy could sustain without declining living standards increased from less than 2% to almost 13%. This change meant the virtually complete elimination of Malthusian constraints, so that technological advances and capital investments could be used to increase incomes rather than population. Interestingly, however, contributions to income growth and contributions to takeoff are not necessarily equivalent, which points to the importance of asking the right questions when we seek to understand what changed in the British economy.

In an accounting sense, the proximate causes of the increase in the carrying capacity of the British economy were the twofold increase of total factor productivity growth combined with an even greater decline in the economy's dependence on land from 1780 to 1860. The commonly cited factors of coal and trade, despite the drastic increases in volumes, do not appear to have nearly the same immediate impact on MSPG. Trade does not seem to have had a large effect until the middle of the 19th century, by which time the process of modern growth was well underway, while the direct contribution of coal to the economy never appreciably increased sustainable population growth. Those wishing to argue in favor of a strong role for coal must therefore argue that coal had an impact far in excess of what coal producers were compensated for.

An important corollary of this study is that there is no one prescription for development; an economy does not necessarily need to look a certain way, or have a certain quantity of capital, level of education, set of industries, nor arrangement of institutions to achieve takeoff. Rather, wherever the economy starts, modern growth is touched off by sustained but potentially temporary rapid productivity gains or other increases in maximum sustainable population growth. These gains can be achieved by capital accumulation, technological transfer, education, exploitation of natural resources, or structural change in any combination sufficient to raise maximum sustainable population growth above the peak in the Malthusian population-income function. They can be achieved in combination with factors like population control that act to lower the threshold.

While this paper demonstrates which proximate causes of the British breakout were most important and how those causes contributed to the ability of the economy to sustain population growth, it tells us little about the underlying causes of the broad change. The Industrial Revolution was a set of interrelated changes—the takeoff of coal mining, increases in capital per worker, rise in international trade, changing structure of the economy, and increases in TFP—that all occurred roughly contemporaneously; it is hard to think of this as a coincidence. This observation highlights some important open questions. What is the connection between the changes in the economy that occurred at the time of the Industrial Revolution? As the agricultural revolution enabled more efficient food production, what caused the new commodities not also to be land-intensive? And finally, what caused the acceleration of TFP growth around 1800, or around 1650 if the process is viewed as having been continuous with the agricultural revolution?

Appendices A–F. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jmacro.2015.01.006.

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