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Published in:
Explorations in Economic History

DOI:
10.1016/j.eeh.2021.101437

Publication date:
2022

Document version:
Final published version

Explorations in Economic History 84 (2022) 101437

Contents lists available at ScienceDirect

Explorations in Economic History

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

Arresting the Sword of Damocles: The transition to the post-Malthusian era in Denmark[☆]

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ARTICLE INFO

JEL classification:
J1
N33
O4

Keywords:
Cointegration
Denmark
Malthusian
post-Malthusian

ABSTRACT

The Malthusian model is the subject of a fierce debate within economic history. Although the positive causal relationship postulated from living standards to population growth is relatively uncontroversial for preindustrial societies, this cannot be said for the other key relationship, diminishing returns due to fixed supplies of land. We argue that Denmark, which was characterized by extreme resource and environmental constraints until the final decades of the eighteenth century, provides an ideal setting for testing whether any society was ever truly Malthusian. We employ a cointegrated VAR model on Danish data from 1731 to 1800, finding evidence for diminishing returns until ca. 1775. Yet this relationship disappears in the late-eighteenth century, consistent with an increasing pace of technological progress and the emergence of what Unified Growth Theory has termed the "post-Malthusian" era.

1. Introduction

> *"Thanks to coal and iron, the energy and raw materials crisis was overcome, and the sword of Damocles hanging over Denmark and the whole of Europe was removed. The pessimists, who had preached that Denmark would freeze to death and that the country would have to be abandoned as uninhabitable, were put to shame… In the* 1820s*, the gloomy prophecies abounding in books and periodicals vanished like the morning dew. Even the memories of the energy and raw materials crisis that had threatened society with slow strangulation disappeared."*
>
> - Kjærgaard 1994, p. 128

Malthusian concerns are nothing new, as witnessed by historical fears about shortages of land, coal, oil or more generally today about the capacity of the planet to sustain economic growth. Malthus was not even the first to raise such concerns, with another priest from the Danish island of Lolland, Daniel Huusfeld, even claiming in 1771 that Martin Luther had prophesized the end of the world due to a lack of wood centuries earlier: "Our blessed and - in his time - perspicacious Lutherus has foreseen that a shortage of wood would lead to the end of the world, and no doubt cause great suffering to the human race, mostly towards the globe's North Pole" (Huusfeld 1771, p. 30, quoted by Kjærgaard 1994). Such concerns were, however, not perhaps unfounded, since a growing body of

☆ We would like to thank conference and seminar participants for helpful comments and suggestions. This work was made possible by a grant from Independent Research Fund Denmark (grant no. DFF - 1327-00069).
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https://doi.org/10.1016/j.eeh.2021.101437
Received 22 March 2021; Received in revised form 10 December 2021; Accepted 10 December 2021
Available online 13 December 2021

work within economic history, growth, and development explicitly assumes Malthusian constraints to be a main reason – if not *the* main reason – for why rates of growth were low in preindustrial times. Foremost among those theories is Unified Growth Theory (UGT, Galor 2005, 2011, Galor and Weil 2000), which argues that for most of human existence the world has indeed been characterized by constraints which were only truly overcome with the demographic transition and the industrial revolution. The present work seeks to test the validity of the first of the transitions predicted by UGT – from a Malthusian to a post-Malthusian regime, at which point such constraints, which manifest themselves in diminishing returns to labor, are offset by an increasing pace of technological change. We do this in a setting which, as we will explain below, is uniquely fit for purpose: eighteenth century Denmark, which was experiencing an extensive ecological crisis at that time.

Malthus, starting with his 1798 essay "An Essay on the Principle of Population," explained how the preindustrial world could be understood through three assumptions: the first is that an increase in wages causes an increase in birth rates because people marry earlier and so they have more children ("the preventive check"); the second effect is that an increase in wages causes a decrease in death rates because people will live in better conditions ("the positive check"); and the third assumption is that an increase in labor leads to diminishing returns, because the amount of land that can feed the population is fixed. These assumptions combined imply that an improvement in technology, while initially leading to an increase in wages, will simply cause population to grow and wages to decrease again. The Malthusian model is at the core of much work in economic history. Thus, Clark (2008) puts Malthus at the core of his theory for why the Industrial Revolution occurred in eighteenth-century England and not elsewhere, as the preventive check ensured that the richest and most successful – those with middle-class values – out-reproduced the rest of society, and due to economic stagnation came to dominate both upper and lower tiers of the social spectrum.[1] By contrast, a large part of Persson and Sharp's (2015) textbook on European economic history is devoted to arguing that one of the fundamental bases of the Malthusian model, land constraints, have little bearing on reality, largely because technological progress can effectively be "land augmenting". They argue that empirical studies have generally found no evidence of sustained diminishing returns to land, and that growth could be positive in preindustrial times, something which has found increasing evidence in recent reconstructions of GDP (see for example Broadberry et al., 2015).

Nevertheless, a central pillar of the theoretical approach provided by UGT is that societies began to escape Malthusian stagnation through the gradual accumulation of technological knowhow prompted by the expansion of the population (so-called 'scale effects' - see Boserup 1965 and Kremer 1993), which in turn was made possible by the productivity advances due to technological progress. This weakened the power of diminishing returns, leading to a post-Malthusian regime. Ultimately, the demographic transition led to the disappearance of the preventive and positive checks, leading to modern economic growth. Such formal theory has inspired more rigorous econometric testing, made possible by the increasing availability of relevant data in recent decades. Much of these analyses have considered England, which of course is something of an historical outlier, and have generally found evidence for a transition from a Malthusian or post-Malthusian regime to a modern growth regime sometime in the nineteenth century. Thus, for example, Møller and Sharp (2014) build on earlier work by Nicolini (2007), who first suggested that the Malthusian model should be estimated as a VAR model, and contribute to this literature by formalizing the Malthusian model within the framework of UGT and demonstrate how it can be tested within a Cointegrated Vector AutoRegressive (CVAR) framework. This approach has the advantage that it allows a focus on what can be interpreted as long run equilibrium relationships rather than the emphasis on short run effects which had previously been common in the literature (see for example Lee 1981), or on non-classical estimation techniques with only loose theoretical underpinnings (Lee and Anderson 2002; Rathke and Sarferaz 2010).

We argue that the case of Denmark can shed light on the question of whether *any* society was Malthusian in the UGT sense, since according to the historical narrative it appears to have experienced an extreme Malthusian crisis in the run up to the eighteenth century. We combine the formalized testable hypothesis of UGT with the structural approach of Møller and Sharp (2014) and apply this to data from Denmark, which, according to Kjærgaard (1994), was characterized, among other issues, by the overexploitation of the land and an acute shortage of wood for fuel and other uses. This was only solved by a variety of measures around the turn of the eighteenth and nineteenth centuries. We know from the evidence presented by Klemp and Møller (2016), who used the same methodology as us, that Denmark was post-Malthusian for much of the nineteenth century, and that modern economic growth was only experienced later in that century. This followed major institutional reforms such as the first democratic constitution of 1849, the industrialization of town and country (the latter particularly through cooperative butter factories and slaughterhouses from 1882), and a fertility transition from around 1880 (see for example Henriksen 1993 and Lampe and Sharp 2018). We add evidence from the eighteenth century, and investigate whether Denmark at that time was purely Malthusian, consistent with the historical narrative presented by Kjærgaard (1994).[2] In Fig. 1, we describe how the theory corresponds to the findings of a number of other studies on technological and institutional advances at that time which we discuss more in the following sections.

Thus, according to UGT, societies, in order to escape Malthusian stagnation and enter a regime of modern growth, should first go through a post-Malthusian phase. This phase is characterized by a level of technological progress able to offset the negative effects from population on wages, while the two checks are still in place. The timeline shows events which have contributed to the technological progress and the transition from Malthusian stagnation to modern economic growth.

[1] See also the empirical investigation of his theory by Boberg-Fazlic et al. (2011), as well as the debate in the *European Review of Economic History*'s twelfth volume (McCloskey 2008, Voth 2008, Grantham 2008, Persson 2008), which also included a response from Clark himself (Clark 2008).

[2] Kjærgaard's work is somewhat controversial among Danish historians (see for example the debate in the Danish journal *Fortid og Nutid* in the volume for 1993). Our analysis lends support to his story of stagnation and crisis, followed by recovery in the late 1700s, however.

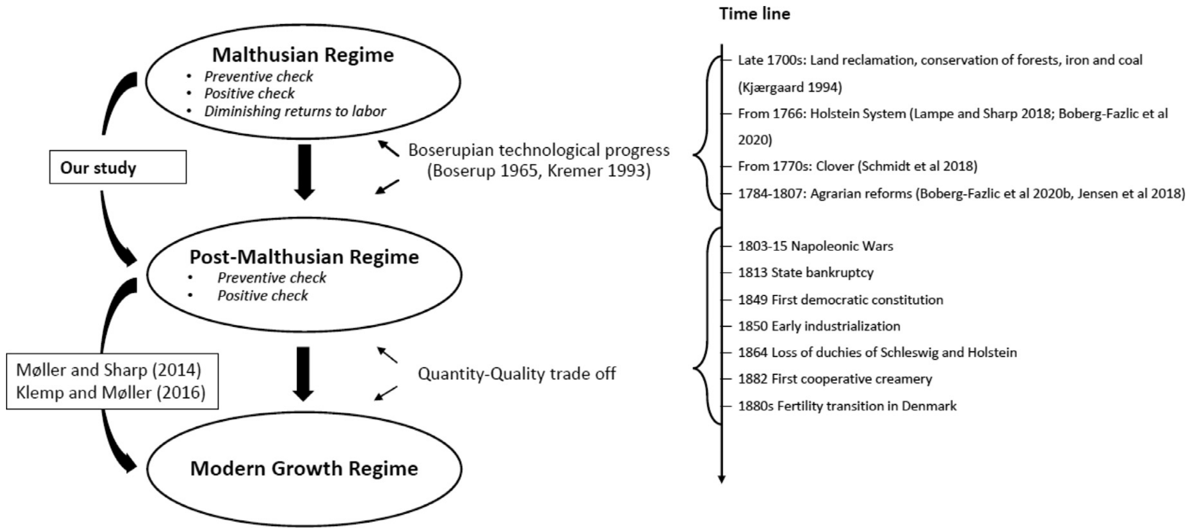

Fig. 1. The Historical background and our study within the context of UGT.

2. Literature review

The present work relates to the considerable body of literature that takes inspiration from UGT and seeks to understand the transition from stagnation to growth, the differential timing of this around the world, and thus the massive difference in living standards between countries we observe today. Fundamental to this literature is the interaction between human evolution and economic development (see also the survey by Ashraf and Galor 2018): the Malthusian preventive check, by implying greater fertility of more economically successful individuals, meant that their share of the population gradually increased. This success might be due to innate (genetic) preferences for the quality rather than quantity of offspring, resistance to infectious diseases, human body size, time preference, and more (see for example Galor and Moav 2002, 2007; Lagerlöf 2015; Galor and Özak 2016). Beyond the evidence for Malthusian and post-Malthusian regimes we contribute to here, there is in fact growing empirical support for UGT. For example, Ashraf and Galor (2011) have found evidence that population density was determined by productivity, and Galor and Klemp (2019) using historical population registers from Quebec, have offered convincing evidence for changes in preference regarding quantity and quality of children.

In terms of tests of the Malthusian model itself, an early contribution considering the English case was provided by Lee and Anderson (2002), who used data on real wages collected by Phelps Brown and Hopkins (1956) along with vital statistics from Wrigley and Schofield (1989) to find evidence for a preventive and positive check as well as an elasticity of the real wage with respect to the size of the population very close to −1. In his aforementioned work, Nicolini (2007) found weak positive checks that disappeared before the middle of the seventeenth century and stronger preventive checks disappearing before the middle of the eighteenth century. Similar results were found by Crafts and Mills (2009), who however used data on real wages from Clark (2007) which, they argue, represent living standards in a more accurate way. Finally, Kelly and Ó Gráda (2014) gathered data on inheritances, extending mortality estimates far back to 1250 and find that even if real wages were falling, the positive check had lost strength by 1650. They based this on the emergence of public charity in the same period, thus highlighting the role of government actions for the impact of harvest failure on mortality.

A disadvantage with the focus on England, however, has been that it was certainly an historical outlier in many ways. Important in this context is of course its early industrialization, which Møller and Sharp identify as central to the disintegration of the Malthusian mechanisms already in the late eighteenth century. Thus, other scholars have recently attempted tests using data from other countries: France (Murphy 2010), Germany (Pfister and Fertig 2010), and Northern Italy (Chiarini 2010; Fernihough 2013; Pedersen et al., 2021a). Notably, Murphy (2010) and Pedersen et al. (2021a) apply Møller and Sharp's method and conclude that France and Italy respectively appear more Malthusian in the eighteenth century due to the presence of diminishing returns to labor, although unlike the present work they do not seek to identify the transition to a post-Malthusian regime. Most relevant for the present work is the analysis by Klemp and Møller (2016). They again apply Møller and Sharp's approach (although without marriage rates) to Scandinavian data, finding results similar to those for England. For Denmark, Norway and Sweden, they find evidence for post-Malthusian dynamics until around 1900, at which point the preventive check flips sign, consistent with a quantity-quality trade off. Thus, for Scandinavia at least, the timing of the transition from the post-Malthusian to the modern regime has been established, but what about the transition from the Malthusian to the post-Malthusian regime? This should be associated with the disappearance of the negative relationship between population and living standards (diminishing returns) as it is offset by productivity gains. Although we will of course test for this formally, we start by considering the historical record, which suggests that Denmark was suffering from Malthusian constraints in the eighteenth century, but that reforms were undertaken which counteracted these from the 1770s and 1780s.

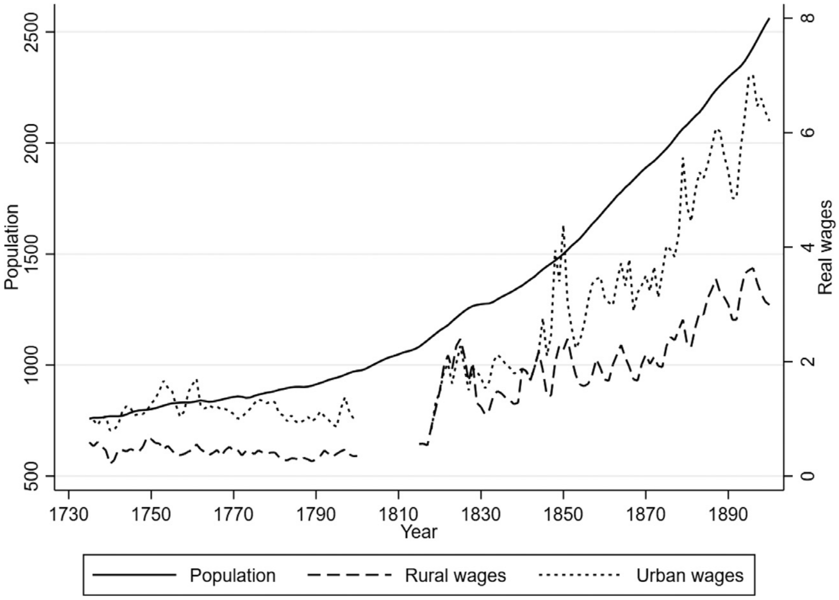

Fig. 2. Population and real urban and rural wages.
Sources: Population: Gille (1949); Urban wages: Khaustova and Sharp (2015); Rural wages: Jensen et al. (2021).

3. Historical background

According to Kjærgaard's (1994) ecological account of the history of Denmark, before the Black Death, Danes lived "in a state of misery without parallel in the country's history" (quoted by Kjærgaard 1994, from Paludan 1977). However, in true Malthusian fashion, and in common with much of the rest of Europe, living standards peaked after the population decline precipitated by the pandemic. Historical accounts mention deserted farms and general shortage of population in mid-fourteenth century Denmark,[3] combined with a recovery of the ecosystem during the fifteenth and sixteenth centuries, as forests expanded, moorlands contracted, and sand dunes stabilized. Then the population began to recover. In 1650 it was around 550,000, probably around half the level in 1300. By 1735 it had grown to 715,000, in 1774 to 815,000, and by 1800 it was 925,000, and was thus back, according to Kjærgaard, to where it had been 500 years earlier. Fig. 2 illustrates the stagnation in real wages during the 1700s combined with modest population growth, as well as the movement towards modernity in the nineteenth century. Note that real wages are not available for the period of the Napoleonic War, which in Denmark led to a collapse of the currency and state bankruptcy.

Alongside this population growth, continuous wars with Sweden meant that there was enormous pressure on resources from the growth of the fiscal-military state on the basis of taxation in the seventeenth and eighteenth centuries. This showed itself both through civilian and military expenditure. For example, the construction of Christiansborg Palace in 1731–45 required ten thousand beech trunks for its foundations alone, and the firing of around thirty million bricks required close to ten thousand tons of wood as fuel. This was an extreme example, of course, but timber and bricks were also in demand for the construction of for example lighthouses and other purposes, although this was moderate compared to the rest of Europe. What was not, however, was consumption for military purposes. During the seventeenth century, Denmark became the strongest militarized nation in Europe, with the building of naval vessels playing a central role. This, supplemented by consumption for ground forces, used vast quantities of timber and led to massive ecological destruction. Moreover, this was funded by extremely high taxes on the countryside which led to increased agricultural production and an overproduction crisis.

According to Kjærgaard, this Malthusian crisis showed itself in four ways. First, through the devastation of the forests. Around 1600, 20–25 percent of Denmark was covered by forest. By 1750 this had fallen to only 8–10 percent, a catastrophe for an economy in which wood was fundamental, as fuel in households and all kinds of industries, and as timber for the construction of ships, houses, and fences. Alongside this, forest hunting disappeared. Second, sand and mould drift became an increasing problem. This began in the sixteenth century, and by the seventeenth and eighteenth centuries, dunes were spreading deep into the countryside. Forests and fertile arable land were transformed into "sandy desserts or windswept surfaces almost devoid of topsoil" due to overexploitation by forestry and agriculture so that for example by 1750 as much as five percent of Jutland was no longer cultivated due to sand and mould drift. Contemporaries had to suffer through the massive sandstorms which this precipitated. Third, the water level was affected. Tree felling and soil erosion led to more flooding, acidification of the soil, increased peat formation, and a shortened growing

[3] We refer to Denmark as being the "Kingdom of Denmark", which did not include Greenland, Iceland, Norway and the Duchies of Schleswig and Holstein. Northern Schleswig constitutes part of modern Denmark today, but otherwise the "Kingdom of Denmark" was similar in geographical extent to modern Denmark.

season. Finally, levels of nitrogen were extremely low practically everywhere. This meant that production was low and what was even worse unsustainable. It was not even possible to rely on a stable supply of manure for fertilizing the land: both animal fodder and manure was burned as fuel due to lack of wood. The lack of fodder meant that livestock was malnourished, meaning that when cattle plague struck in the 1740s, around half the national cattle herd, around 250,000 head, were killed in just a few years.

Kjærgaard argues that a crisis was averted by a number of innovations. The central administration only took measures to stop sand drift in the late 1700s, making use of a massive conscription of men and vehicles, with a network of officials appointed to oversee the work. Once the formation of deserts was halted, new land needed to be reclaimed through damming, draining, marling, and from the sea. There were also major developments in agriculture, see Boberg-Fazlic et al. (2020a,b) and Lampe and Sharp (2018). These included new crop rotation techniques (from 1766), increased efforts to retain manure, with the spread of stall feeding, and the introduction of domesticated clover (after 1801, see Schmidt et al., 2018), as well as institutional changes such as the abolition of serfdom (from 1788, see Jensen et al., 2018). The end result was that agricultural production became greater than ever before. As for fuel, first, various ways were found to economize on wood consumption. For example, new building materials were used, and more efficient means of heating were developed. Wooden fences were replaced by stone walls and hedges, or by turf or seaweed. Ways were found to reduce the use of timber for shipbuilding, and stone was used for surfacing roads instead of wood. Second, laws were passed to protect the forests. Third, peat, waterpower and wind power were increasingly used for fuel. Finally, there was an increased use of imported wood substitutes: iron and coal. Kjærgaard somewhat controversially argues that the driving forces behind what he terms the “Danish Revolution” were not the agrarian reforms of the late 1700s, which he claims were mostly about the redistribution of political power within the elite. Rather, it was the consequence of growing technological potential through science and the printed word. Whatever the case, the end result was that, as stated in the opening quote, the ecological and Malthusian crisis was soon forgotten. It remains, however, to be shown whether the data supports an end to the Malthusian era and a transition to the post-Malthusian era in the late 1700s – which is what the remainder of the present work seeks to test.

4. The theoretical model

Before turning to the empirical analysis, we first recap the basic Malthusian model as formalized by Møller and Sharp (2014). The model assumes a closed economy with no trade and migration, fixed land supply, labor supply to be proportional to total population, fully flexible prices, and supply determined output. The Malthusian system can then be characterized by the following system of five equations:

$$w_t = c_0 - c_1 \ln N_t + \ln A_t \tag{1}$$

$$b_t = a_0 + a_1 w_t + \varepsilon_{bt} \tag{2}$$

$$d_t = a_2 - a_3 w_t + \varepsilon_{dt} \tag{3}$$

$$\ln A_t = \ln A_{t-1} + \varepsilon_{At} \tag{4}$$

$$\ln N_t \equiv \ln N_{t-1} + b_{t-1} - d_{t-1} \tag{5}$$

Here w_t represents the natural logarithm of real wages, N_t the total population, A_t represents aggregate technology/arable land or capital per worker and finally b_t and d_t are the crude birth and death rates respectively. The error terms are all stochastic and normally distributed with mean zero and constant variance. The shocks represent unsystematic influences on the variables, not explained by the model. Eq. (1) describes the relationship between real wages and population growth, with c_0 being the intercept, and $c_1 > 0$ the diminishing marginal returns to labor, this latter being a crucial assumption of the Malthusian model and important for our empirical analysis. Eq. (2) describes the preventive check, where real wages are expected to affect birth rates positively. a_0 is the intercept and a_1 captures the preventive check itself. Eq. (3) describes the positive check, where the death rate is expected to be negatively affected by increases in real wages with a_2 being the intercept and $-a_3$ capturing the positive check. The rationale behind the two checks has been discussed extensively in the literature. The positive check can be motivated through biology and the impact of low incomes on nutrition and infant mortality. For the preventive check more rational, forward-thinking economic behavior has been invoked – see for example Cinnirella et al. (2017), who find evidence that English couples in the period 1540–1850 planned childbirth according to economic conditions.

Technology is described by Eq. (4) and is modeled as a non-stationary stochastic process, specifically a random walk (Møller and Sharp 2014). In the case of Malthusian stagnation technology is assumed to be exogenous and persistent. Finally, Eq. (5) describes population growth (or labor supply). $b_{t-1} - d_{t-1}$ represents the difference between the birth rate and the death rate (the rate of population growth) which in turn is determined by the previous equations.

The short-run equilibrium results from solving the above system of equations with respect to $\{w_t, N_t, A_t, b_t, d_t\}$. When technology A_t is held fixed the steady state values of the economy can be obtained where population growth $b_{t-1} - d_{t-1} = 0$ and there are no shocks. This is illustrated in Fig. 3 together with the short-run equilibrium. Here, for period t, the short-run equilibrium is represented by the dashed lines, while the steady state, given a fixed level of technology, is represented with arrows.

The steady state values of real wages, birth rate and death rate (w^*, b^*, d^*) do not depend on time while the steady state level of population, $\ln N_t^*$, depends on A_t. In the right panel it is apparent that the short-run equilibrium level of real wages is determined by the stocks of population and technology. In the left panel the birth and death rates are determined adding their respective shocks,

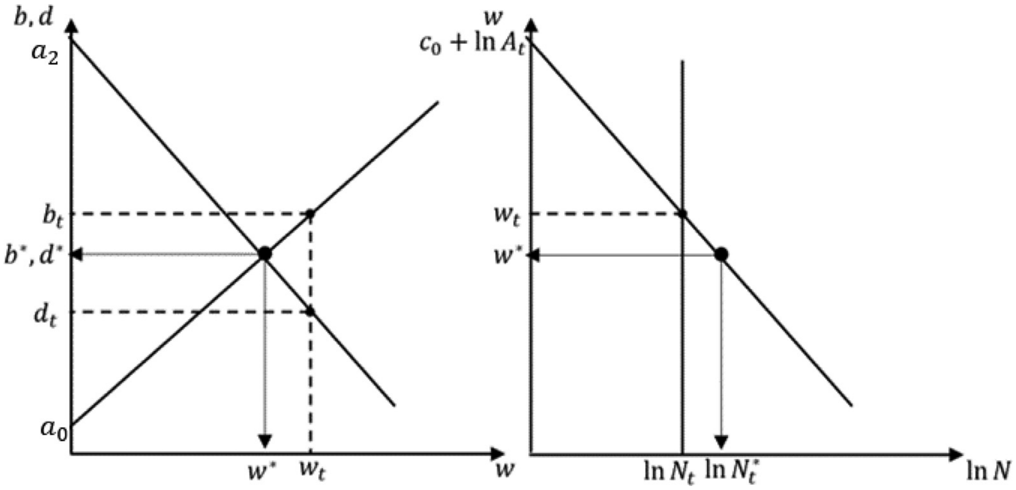

Fig. 3. The Malthusian model, based on Møller and Sharp (2014) and Eqs. (1)–(5).
Note: The preventive check relation (upward sloping) and the positive check relation (downward sloping) are presented in the left panel. The downward sloping labor demand and vertical labor supply are presented in the right panel. The short-run equilibrium is shown by the dotted lines, while the steady state, given A_t is represented by arrows.

$\varepsilon_{b,t}$ and $\varepsilon_{d,t}$. In the absence of further shocks all variables will converge to their steady-state values in the subsequent periods, $\{w^*, \ln N_t^*,\ b^*, d^*\}$.

In conclusion, fundamental to Malthusian stagnation are diminishing returns to labor and a positive effect from real wages on population growth with the additional assumption that technology is exogenous. In the empirical framework we will be testing directly for a post-Malthusian regime where the diminishing returns are offset by technological progress. Exactly how to test for a post-Malthusian regime is discussed in the following section, but intuitively c_1 should be found to be statistically insignificant.

5. The data and the econometric approach

5.1. Data[4]

We take vital rates from Johansen (2002) for the years 1731–1775 and Gille (1949) for the period 1776–1800[5], allowing us to take advantage of the early official reporting of these statistics in Denmark.[6] The demographic data is considered to be of superior quality, since official statistics of births and deaths were kept from the 1730s, which although sometimes of dubious quality, are more reliable than the samples of church records of christenings and funerals used to provide estimates of the vital rates of other countries (see for example Wrigley and Schofield 1989).

For the real wages, we mostly rely on series for unskilled day laborers in Copenhagen constructed by Khaustova and Sharp (2015). Nevertheless, we complement this with agricultural wages from Jensen et al. (2021) for the rural sector as originally collected by the Danish Price History Project (Andersen and Pedersen 2004). Our motivation for so doing is twofold. First, they might be more representative of living standards for the country as a whole, which was of course mostly agricultural. In fact, Jensen et al. (2021) base their series on a microlevel database of wages from workers on nineteen manorial estates (corrected for example for payment-in-kind, which is also recorded in the database), which are then “condensed” into a single series using the regression method suggested by Clark (2005). Second, the Malthusian model is reliant on the idea of land scarcity, which might be more relevant for the countryside rather than in a city like Copenhagen which was also more dependent on trade. A downside to the rural series, however, is that most people in the rural economy would not have been earning money wages, and there is a debate about the extent to which the wages recorded by the manor corresponded to what we might consider a modern labor market. Nevertheless, as we demonstrate below, our results are largely qualitatively unchanged if we use the rural rather than urban wages. Moreover, the latter aids comparability with other work, which largely focuses on urban wages. In our empirical analysis we use the natural logarithm of real wages.

Table 1 shows summary statistics for our four variables of interest, i.e. crude birth rates (*cbr*), crude death rates (*cdr*), the log of real urban wages (w_{urban}) and the log of real rural wages (w_{rural}). We show statistics for three different periods the first covering the entire sample (1731–1800). The other two periods are of interest for the analysis in the next section, where we split our sample in

[4] Data and replication files are published in Pedersen et al (2021) and available through open-ICPSR at the following link: https://doi.org/10.3886/E156781V1
[5] Johansen (2002) and Gille (1949) overlap, and for the years for which we have both, they follow each other very closely.
[6] This unfortunately precludes using marriage rates as in Møller and Sharp (2014), but these do not seem to be available for Denmark.

Table 1
Summary statistics for crude birth and death rates and the log of urban and rural wages.

Variable	Mean	SD	Min	Max	No. observations
			Sample 1731–1800		
cbr	30.740	1.295	27.105	33.600	70
cdr	28.292	3.277	22.400	39.540	70
w_{urban}	0.057	0.071	– 0.099	0.229	70
w_{rural}	– 0.371	0.121	– 0.669	0.048	70
			Sample 1731–1775		
cbr	30.669	1.230	27.105	32.603	45
cdr	29.959	3.516	22.522	39.540	45
w_{urban}	0.070	0.075	– 0.099	0.229	45
w_{rural}	– 0.325	0.117	– 0.669	0.048	45
			Sample 1776–1800		
cbr	30.868	1.421	28.100	33.600	25
cdr	27.092	2.426	22.400	32.900	25
w_{urban}	0.033	0.059	– 0.647	0.139	25
w_{rural}	– 0.454	0.076	– 0.590	– 0.333	25

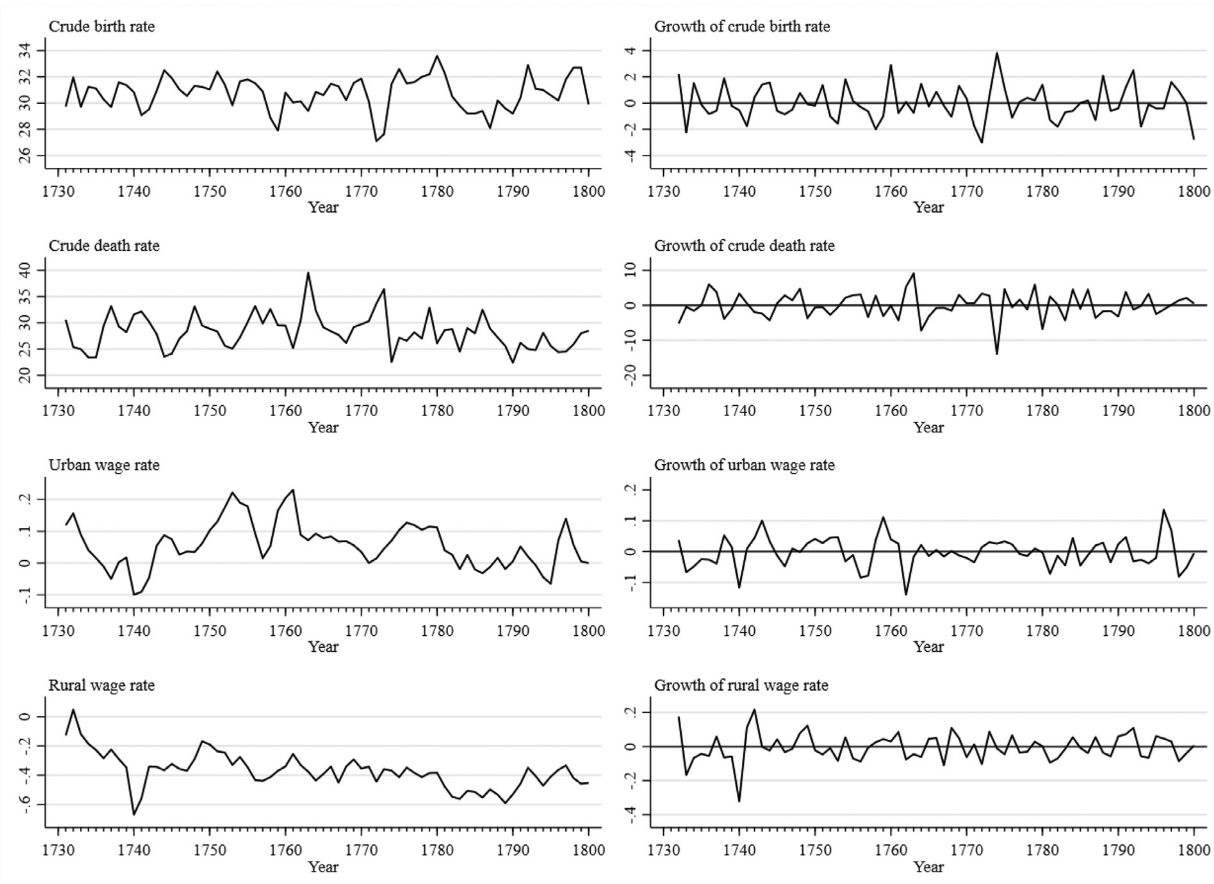

Fig. 4. Crude birth and death rates and log of real wage indices (urban wage index=1 in 1800) for Denmark, 1731–1800.
Sources: Johansen (2002), Gille (1949), Khaustova and Sharp (2015), Jensen et al. (2021).

two: 1731–1775 and 1776–1800. As we explain below, this is motivated by both the historical and empirical evidence of a transition from a Malthusian to a post-Malthusian in the late eighteenth century.

The data is then illustrated in Fig. 4 in their levels and growth rates. It is apparent that wages are if anything declining over this period during which fertility usually exceeds mortality, giving rise to the population growth apparent in Fig. 2, and on the face of it consistent with a Malthusian interpretation. Even though we have wage data going back to 1705, we only have vital rates from 1731 and our analysis thus considers the period 1731–1800. They reflect nicely known historical events such as the (re-)introduction of serfdom in 1733, and the aforementioned severe outbreak of cattle plague in 1740.

An important assumption behind the use of the cointegrated VAR model, which we turn to below, is non-stationarity of the variables, since cointegration as a property implies that there is a linear combination of two or more series which is stationary, and thus allowing for standard statistical inference. Table A1 in the appendix demonstrates that both rural and urban wages are non-stationary, while the vital rates are more sensitive to the number of included lags, even though there is some indication that they might be non-stationary. However, univariate tests such as ADF and KPSS are only one way of testing for stationarity. Alternatively, one can determine this using a system-based approach where all variables are tested jointly. Thus, one of the first steps in the cointegration approach is to test for the rank of the system, i.e. the trace test, which is a system-based test for stationarity. Given that the variables are interdependent, we follow Møller and Sharp (2014) and consider it to be more natural to perform a system-based test when determining the order of integration.

5.2. Econometric approach

According to Møller and Sharp (2014), whose work we refer to for a full account of the econometric details[7], the Malthusian model presented in Section 4 can be written as a cointegrated VAR model in the three variables $\{w_t, b_t, d_t\}$. In order to have a well-specified cointegrated VAR model there are several steps to follow and therefore the empirical analysis will be performed as follows. First, we estimate an unrestricted VAR model. Second, we analyze the residuals in order to be certain that the model is well specified, i.e. that the errors do not exhibit heteroskedasticity or autocorrelation and are normally distributed.[8] Third, if the unrestricted VAR model is well-specified, then we test for non-stationarity and for the cointegration rank. Dummies can be used to account for different types of outliers before testing for stationarity. If the trace test finds evidence for reduced rank, our variables are non-stationary and, we can apply the co-integrated VAR model and finally we can continue with robustness checks.

The unrestricted VAR model is written as:

$$\Delta x_t = \Pi x_{t-1} + \Gamma_1 \Delta x_{t-1} + \cdots + \Gamma_{k-1} \Delta x_{t-(k-1)} + \Phi D_t + e_t, \tag{6}$$

where $x_t' = (w_t, b_t, d_t)$, k represents the lags, $e_t \sim Niid(0, \Omega)$ and ΦD_t represents a $d \times 1$ vector of deterministic components. The matrix Π represents the long run restriction and contains the coefficients of interest. It can be found by solving the system of Eqs. (1)–(5) with respect to the three observed variables in their first differences and is as follows:

$$\Pi = \begin{pmatrix} 0 & -c_1 & c_1 \\ a_1 & -(1 + a_1 c_1) & a_1 c_1 \\ -a_3 & a_3 c_1 & -(1 + a_3 c_1) \end{pmatrix} \tag{7}$$

If the determinant, $\det(\Pi) \neq 0$ then x_t is stationary. Otherwise, if $\det(\Pi) = 0$ it means that x_t is non-stationary and the variables can cointegrate. In this case Π has reduced rank, $r < 3$, and it is possible to decompose the matrix Π in the following way:

$$\Pi = \alpha \beta', \tag{8}$$

where α and β are $3 \times r$ matrices with $r < 3$. When the variables cointegrate we obtain $\beta' x_t \sim I(0)$ which is a stationary relation. β represents the cointegration coefficients and α represents the error correction coefficients (the so-called adjustment coefficients) which tell us which of the variables are error correcting whenever the system is out of equilibrium.

The determinant of Π is given by the equation:

$$\det(\Pi) = -c_1 (a_1 + a_3) \tag{9}$$

From Eq. (9) it is clear that the determinant will equal zero in one of two cases:

1) $a_1 + a_3 = 0$ or equivalently $a_1 = -a_3$. This hypothesis indicates that population is independent of income, because the effect on births is the same as on deaths. The restrictions on α and β' become:

$$\alpha = \begin{pmatrix} -c_1 & 0 \\ a_3 c_1 & -\rho_1 \\ 1 + a_3 c_1 & -\rho_2 \end{pmatrix} \quad \beta' = \begin{pmatrix} 0 & 1 & -1 \\ a_3 & 1 & 0 \end{pmatrix} \tag{10}$$

In β' the first row implies a stationary growth rate of population and the second is a 'check relation'. In this case we also observe c_1, diminishing returns, and its significance implies homeostasis, i.e. that any temporary increases in income for example due to a new technology will eventually be reversed.

2) $\bar{c}_1 = 0$, which is the post-Malthusian hypothesis stating that wages are no longer dependent on vital rates. Empirically this can be tested by imposing the following restrictions on α and β':

$$\alpha = \begin{pmatrix} 0 & 0 \\ -\rho_1 & 0 \\ 0 & -\rho_2 \end{pmatrix} \quad \beta' = \begin{pmatrix} -a_1 & 1 & 0 \\ a_3 & 0 & 1 \end{pmatrix} \tag{11}$$

[7] See also Johansen (1996), Juselius (2006) and Møller (2008).

[8] Tests of the residual when estimating the unrestricted VAR can be found in Appendix A.

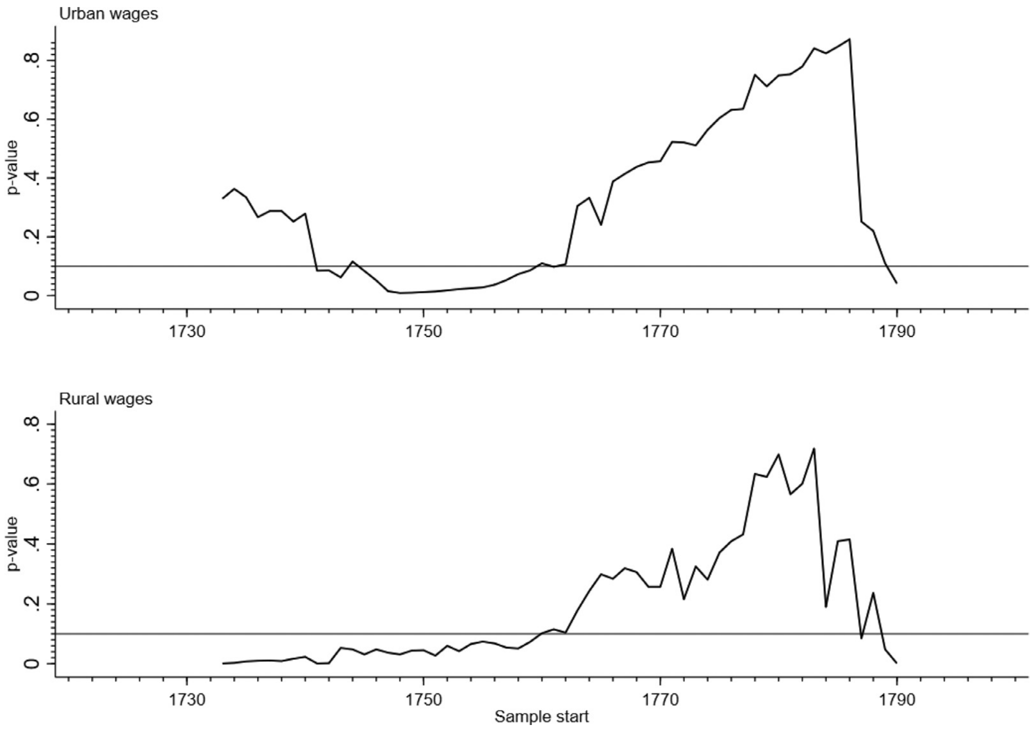

Fig. 5. The trace test calculated recursively.
Note: The top panel presents the *p*-values for the recursively calculated trace test for $H(2)$ against $H(3)$ using urban wages. The bottom panel presents the *p*-values for the recursively calculates trace test for $H(2)$ against $H(3)$ using rural wages. The horizontal lines represent the 10% significance level. The end point of the sample is fixed to 1800.

In β' it is possible to read the two parameters of the preventive and the positive check directly.

Theoretically ρ_1 and ρ_2 in Eqs. (10) and (11) both equal 1, indicating that adjustment towards equilibrium will take exactly one period (in case of annual data this would be equal to one year). However, empirically it is more realistic that adjustment will take longer and consequently that $\rho_1, \rho_2 < 1$. Furthermore, in the empirical version we also add a trend and a constant to each of the cointegrating relations in β'.

In case the data indicates that the matrix Π has reduced rank, we can impose the restrictions described in Eqs. (10) and (11) to test whether a reduced rank is consistent with one or both of the equations. Finding that Π has reduced rank contradicts Malthusian stagnation and testing the significance of the restrictions in (10) and (11) can assess in which way the system deviates from the theoretical equilibrium. In particular, accepting the restrictions in (11) is direct evidence for the post-Malthusian hypothesis. Finding the point in time for which (11) can be accepted, is evidence for the transition from a Malthusian to a post-Malthusian regime. Finding full rank, on the other hand, implies a stationary system and the full Malthusian model.

6. Results

6.1. Trace test

Before imposing the restrictions, it is first necessary to test the rank of the matrix Π using our two measures for real wages and the vital rates, and we thus proceed by testing the hypothesis of reduced rank, $H(2)$, against the hypothesis of full rank, $H(3)$.[9] Reduced rank implies that we can proceed with the analysis by imposing the restrictions from Eqs. (10) to (11). The historical account might lead us to expect a transition from a Malthusian regime to a post-Malthusian regime at some point towards the end of the 1700s, when technological progress began to take off, and an environmental catastrophe was averted. In Fig. 5 we illustrate the results of recursively calculated *p*-values for the trace test of $H(2)$ against $H(3)$ (full rank). In the recursive analysis we perform the trace test repeatedly holding the end year fixed but changing the starting year. Higher *p*-values indicate that we cannot reject the hypothesis of reduced rank, and consequently that the system deviates from the theoretical Malthusian equilibrium. In this case we can impose the restrictions from Eqs. (10) to (11). From the recursive analysis we can see when the reduced rank becomes significant and based on this, decide whether the data should be split in more periods to be analyzed independently.

[9] More specifically, to impose the restrictions in (10) and (11), we test the hypothesis that has rank 2, $H(2)$, against rank 3, $H(3)$.

Table 2
Regression results for the period 1731–1775.

Panel A Homeostasis hypothesis (Eq. (10))		Panel B Post-Malthusian hypothesis (Eq. (11))	
Preventive check (a_1)	− 0.668	Preventive check (a_1)	1.242
	(2.093)		(2.684)
		Positive check ($-a_3$)	− 8.622
			(7.655)
Diminishing returns to labor ($-c_1$)	**− 0.006**		
	(0.002)		
		First adjustment parameter ($-\rho_1$)	**− 0.886**
			(0.177)
		Second adjustment parameter ($-\rho_2$)	**− 0.825**
			(0.174)
LR test of identifying restrictions $chi^2(2)$	**1.337**	LR test of identifying restrictions $chi^2(2)$	**8.660**
	[0.512]		[0.070]

Note: Standard errors are in parenthesis while *p*-value of the LR-test is in square brackets. Coefficients significantly different from zero at the 5% level are in bold.

Table 3
Regression results for the period 1776–1800.

Panel A Homeostasis hypothesis		Panel B Post-Malthusian hypothesis	
Preventive check (a_1)	**22.465**	Preventive check (a_1)	**25.825**
	(3.533)		(4.177)
		Positive check ($-a_3$)	8.886
			(12.746)
Diminishing returns to labor ($-c_1$)	− 0.002		
	(0.004)		
		First adjustment parameter ($-\rho_1$)	**− 0.901**
			(0.204)
		Second adjustment parameter ($-\rho_2$)	**− 0.828**
			(0.254)
LR test of identifying restrictions $chi^2(2)$	**3.662**	LR test of identifying restrictions $chi^2(2)$	**4.322**
	[0.160]		[0.364]

Note: Standard errors are in parenthesis while *p*-value of the LR-test is in square brackets. Coefficients significantly different from zero at the 5% level are in bold.

Both for urban and rural wages we find a quite clear break at the beginning of the 1760s when the *p*-values start being consistently above the 10% significance level. Thus, we can conclude from the results of the trace test analysis, that our sample should be split into two subperiods: the first probably more Malthusian and the second possibly consistent with Eq. (10) or (11). We therefore proceed to split the sample at the year 1775[10], and analyze the periods 1731–75 and 1776–1800 for both rural and urban workers. Clearly, the choice of the year 1775 might be important for the analysis, and this is explored more carefully in Appendix C, although we would like to emphasize that the year itself is not of any particular importance beyond empirical necessity – in reality the transition from Malthusian to post-Malthusian was certainly gradual. For the sake of comparability with earlier work we focus here on the results using urban wages, but those using rural wages are given in Appendix D.[11]

6.2. Cointegrated VAR results

In this section we present the results of the cointegrated VAR when imposing the restrictions given in (10) and (11) using urban wages.[12] Table 2 show the estimates when imposing the restrictions from (10) to (11) using urban workers from 1731 to 1775. Panel A represents the homeostasis hypothesis (10), and panel B the post-Malthusian hypothesis, where for the former, the imposed restrictions cannot be rejected with a *p*-value of 0.512 while for the latter this is only 0.07. This means that the period 1731–1775 is much more consistent with homeostasis (Eq. (10)) rather than the post-Malthusian hypothesis (Eq. (11)), given that the former is accepted with a much higher *p*-value, 0.51 vs. 0.07. Furthermore, we find an estimate of $-c_1 = -0.006$, implying slow but significant diminishing returns. In Panel B, the preventive and the positive check, a_1 and a_3, both have the expected sign, even though they are not significantly different from zero while in Panel A the sign is inverted but also not significant.

Turning to the second period, 1776–1800, the results can be seen in Table 3. Now the homeostasis hypothesis (10) cannot be rejected with a *p*-value of 0.160 (Panel B) while for the post-Malthusian hypothesis (11) this is 0.364.

[10] The same analysis for the whole sample is in Appendix B. The results are largely insignificant.

[11] We also calculated a weighted average of the urban and rural wages, weighted using urbanization rates, to give a better representation of the national wage level. Our qualitative results are very similar, reflecting the fact that it makes little difference whether we use urban or rural wages.

[12] To make the exposition of the results in this section easily readable, we here present the main estimates of interest. The underlying tables are in Appendix B.

Table 4
Comparison with results in Klemp and Møller (2016).

	Klemp and Møller (2016)	Our study
Estimate	*1824–1890*	*1776–1800*
Preventive check (a_1)	**3.900**	**25.825**
	(1.133)	(4.177)
Positive check ($-a_3$)	**− 5.651**	− 8.886
	(2.514)	(12.746)
First adjustment parameter ($-\rho_1$)	**− 0.527**	**− 0.901**
	(0.125)	(0.254)
Second adjustment parameter ($-\rho_2$)	**− 0.429**	**− 0.828**
	(0.126)	(0.254)

Note: Standard errors are in parenthesis while *p*-value and coefficients significantly different from zero at the 5% level are in bold.

Now, although we cannot reject either hypothesis, the post-Malthusian explanation enjoys a much higher *p*-value (0.364 vs. 0.160). Moreover, we now see that the estimate of $-c_1$ is no longer significant, even though it keeps the expected sign. The preventive check is strong and highly significant in both panels ($a_1 = 22$ and $a_1 = 26$). The positive check also has the expected sign in Panel B but is not significant. For rural workers, the results in Appendix D reveal even stronger support for the post-Malthusian hypothesis in the period 1776–1800 with *p*-values of 0.06 vs. 0.27.

It is useful to compare the results in Table 3 with those found by Klemp and Møller (2016) for Denmark and the period 1824–90, which is given in Table 4.[13] Klemp and Møller (2016) find both checks to be significant with $a_1 = 3.9$ and $a_3 = 5.7$, although the elasticity of the preventive check and the adjustment coefficients are smaller, at roughly half those in Table 3. This implies a weaker preventive check, and indeed, after around 1890, they find evidence that the check mechanisms break down as Denmark moved towards a modern growth regime. Based on the evidence here, we can add to this conclusion: the post-Malthusian era began in Denmark around 1770 and lasted for a little over a century.

Finally, to confirm the relevance of the break point in 1775 identified above, in Appendix C we present the results of a backward and forward recursive analysis. The CVAR model relies on the assumption of constant parameters, so if the estimates are not constant over time the model is invalidated. The recursive analysis shows clear signs of parameter instability for the preventive check relation starting in the 1760′s and again in the 1770′s for both the specification with homeostasis and the post-Malthusian regime. This is also confirmed for the *p*-values associated with the acceptance for these specifications. Based on this, we can therefore conclude that the sample should indeed be split around 1775, consistent with the historical evidence.

7. Conclusion

Denmark faced massive and well-documented Malthusian constraints by the eighteenth century, which were solved by investments in new technologies and practices. This makes it an ideal testing ground for identifying the onset of the post-Malthusian regime as postulated by UGT – something which assuredly happened far earlier in more developed and well-documented countries such as England.

Using evidence from both the urban and rural sectors of the economy, we find strong evidence – the first of its kind for any country – for a transition from a Malthusian to a post-Malthusian regime in around the 1770s, consistent with the historical evidence. Combining this with a similar analysis for the nineteenth century, we can conclude that Denmark was post-Malthusian for a little over a century, when the demographic transition and rapid industrialization of the economy led to an onset of modern economic growth.

Supporting information

Appendix A: Tests for stationarity and on residuals from unrestricted VAR
Appendix B: Regression tables and results of the full sample 1731–1800 using urban wages
Tables A1–A3: ADF and KPSS tests for stationarity

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.eeh.2021.101437.

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[13] An obvious question would be why we do not merge their data with ours, and estimate the whole post-Malthusian era at once. The problem is that the Danish economy was destroyed by the Napoleonic Wars, and the currency collapsed, meaning that there are no meaningful real wages from around 1800 and into the 1820s, when a new currency was introduced.

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