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Technological Change and Inequality in the Very Long Run[*]

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Abstract. In this paper we investigate the impact of technological change on inequality in the presence of a landed elite using a standard unified growth model. We measure inequality by the ratio between land rent and wages and show that, before the onset of the fertility transition, technological progress increased inequality directly through land-biased technological change and indirectly through increasing population growth. The fertility transition and the child quantity-quality trade-off eventually disabled the Malthusian mechanism, and technological progress triggered education and benefited workers. If the elasticity of substitution between land and labor is sufficiently high, the rent-wage ratio declines such that inequality is hump-shaped in the very long run. We use the publication of new farming book titles as a measure of technological progress in agriculture, and provide evidence for technology-driven inequality in Britain between 1525 and 1895. We confirm these results for a panel of European countries over the period 1265–1850 using agricultural productivity as a measure of technology. Finally, using patents in the period 1800–1980, we find a technology-driven inequality reversal around the onset of the fertility transition.

Keywords: Inequality, Malthus, Unified Growth Theory, Agriculture, Human Capital.

JEL: O40, O30, N30, N50, J10, I25.

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1. Introduction

In this paper we develop and test a new theory of the evolution of inequality from Malthusian times to the 20th century. In a unified growth model, we consider technological progress that increases the productivity of land and labor, potentially in a factor-biased way. In the Malthusian regime, population growth responds positively to improvements in income such that technological progress benefits the income of landowners in steady state. The income of workers rises temporarily but ultimately returns to subsistence level, as the population growth triggered by the higher income decreases the marginal returns to labor. The resulting increase of the labor-land ratio reduces the marginal product of labor relative to that of land and the rent-wage ratio increases. Landowners benefit twice from technological change, indirectly through increasing population density and directly if technological change is land-biased. Technological and economic development are thus associated with increasing inequality.

Eventually, however, technological progress initiates mass education and a fertility transition. This is the central mechanism of unified growth theory (Galor and Weil, 2000; Galor, 2011). The negative response of fertility to technological progress potentially breaks the increasing inequality path: Education and human capital accumulation increase wages while population growth declines. The impact of technological progress on inequality depends on the elasticity of substitution between labor and land in production. If the elasticity is greater than one, inequality, measured by the rent-wage ratio, declines in response to human capital accumulation. In the very long-run, technological progress thus motivates a hump-shaped pattern of inequality (a Kuznets curve) with a peak around the time of the onset of the fertility transition (Kuznets, 1955).

The use of the rent-wage ratio as a measure of inequality is mostly motivated by data availability. It is the only aggregate measure of income distribution that is available at relatively high frequencies over a long historical timespan. Alternatively, scholars have inferred inequality prevailing at a particular time and place from social tables. Milanovic et al. (2010) find that income inequality was positively associated with economic development up to the early 19th century when it reached a level much above inequality in contemporaneous currently advanced countries. This is exactly the phenomenon that we want to address in our theoretical and empirical analysis. A distinct literature investigates the evolution of inequality since the late 19th century and, in particular, the rise of inequality since the 1970; a phenomenon that we do not address in our paper (e.g. Piketty and Saez, 2014; Roine et al., 2009).

The functional income distribution measured by the rent-wage ratio provides a good approximation of the personal income distribution in a largely agricultural environment with a landed elite and a homogeneous low-skilled working population. In an extension of the model, we show that our results are robust to the introduction of capital accumulation and a rising capital share, which could be conceptualized as "industrialization". With industrialization, however, the rent-wage ratio loses power as an approximation of the personal income distribution. The rise of a new class of capitalists (Doepke and Zilibotti, 2008), democratization (Acemoglu and Robinson, 2000) and the gradual abolition of primogeniture (Bertocchi, 2006) weakens the informative quality of the rent-wage ratio as a measure of personal income inequality. However, it has also been argued that these processes were very gradual, and that, by the 1860s, the rich were still by and large the descendants of the landed aristocracy (Clark, 2008). According to Lindert (1986), the top 5% of English households held 73% of all wealth in 1670 and 74% in 1875.[1]

The use of the rent-wage ratio (or the reverse) as a measure of long-term inequality trends has been established by O'Rourke and Williamson (2005) who offer an alternative hypothesis for the decline of inequality in England in the 20th century. They argue that globalization decoupled the price of food from domestic supply such that land rents declined because of declining agricultural prices. Our argument, in contrast, is based on the demographic transition that reduced population growth and induced mass education and therewith increased the wages of workers. Their paper is complementary to ours in that they stress the importance of trade, which we have not explicitly considered in our analysis. Most importantly, we identify technological progress as the driver of rising inequality, and the onset of the fertility transition as the turning point, and we provide a dynamic general equilibrium theory that explains our results.

In the theory section we set up a model of long-run development with endogenous fertility, education, and technology. The model can be conceptualized as a simplified unified growth model based on Galor and Weil (2000) that takes the existence of a landed elite into account and that relaxes their assumption that the elasticity of substitution in production is equal to one. We take this model and analytically derive the association between technology and inequality before and after the fertility transition, as outlined above. We use a numerically specified version of

[1]A rising rent-wage ratio is compatible with a constant or declining share of land in total income. As shown in greater detail below, the land share falls with a rising rent-wage ratio when the elasticity of substitution between land and labor is larger than one and the increase of the labor share is driven by population growth. Inferences from the land share on inequality can thus be misleading since they depend on the elasticity of substitution and on whether an increase in the aggregate labor income is due to higher wages or an expanding workforce.

the model and investigate the transition from Malthusian stagnation to modern growth. Along the transition, the model predicts a hump-shaped association between the rent-wage ratio and economic development (the level of technology). Extensions of the basic model show robustness of these results by taking into account physical capital in production (as a complement to human capital and a substitute for land) and by allowing for a time-varying elasticity of substitution.

Our paper contributes to the field of unified growth theory (Galor and Weil, 2000; Galor, 2011), which emphasizes the fertility transition and the expansion of mass education and human capital formation as the prime forces behind the transition from stagnation to growth. We focus on a side-effect that has had little attention in this literature, namely how technological progress contributed to the evolution of inequality before and after the fertility transition. A related literature investigates how inequality affects the timing of the transition and how cross-country differences in pre-industrial inequality contribute to differences in contemporary development (Galor and Moav, 2004; 2006; Galor et al., 2009). These papers focus on the emergence of mass education in the process of development and how this process is causally related to inequality. These studies consider a stationary population (and thus no Malthusian dynamics) and omit technological progress. Furthermore, agricultural land plays no role in Galor and Moav (2004, 2006). Galor et al. (2009) discuss how the distribution of land affects the timing of educational transition but, again, how the role of technological progress, directly and through its impact on population growth, affects the evolution of inequality in the long run, is not investigated .

Another related literature investigates the interaction between agriculture and population growth in a unified growth context but does not address inequality issues (Kogel and Prskawetz, 2001; Strulik and Weisdorf, 2008; Vollrath, 2011). Here, we set up a more stylized model that ignores impediments to human capital formation as well as details of structural change and focus on the interaction of population growth and technological progress in the long-run and the evolution of inequality. In this regard, our model can also also be conceptualized as an extension of the canonical Malthusian model of pre-industrial development (Ashraf and Galor, 2011). This model typically assumes a Cobb-Douglas production function and that workers earn their average product, which thereby shuts down the two channels through which technological progress affects inequality in pre-industrial times, the marginal product of labor and factor-biased technological change.

We contribute to the empirical literature on inequality and development by using a data set on technological progress in agriculture, the publication of new farming books in Britain over the period 1525–1895. This direct measure of agricultural technology in pre-industrial times and beyond allows for a structural estimation of the rent-wage ratio as a function of technological progress and population growth. Aside from a quantitative assessment of the drivers of inequality, the results also allow us to make inferences about the elasticity of substitution between land and labor and about the factor-bias of technological change. Using agricultural productivity as a measure of technology, our main results are confirmed for a panel of European countries 1265–1850. Finally, we use patents over the period 1800–1980 and provide evidence for a technology-driven inequality reversal around the onset of the fertility transition.

The paper is organized as follows. In the next section we set up the model and derive the main results on the state-dependent association between technology and inequality. In Section 3, we present the results from testing the theory using three different samples and three different measures of technology, as outlined above. Section 4 concludes the paper.

2. Technology and Inequality in the Very Long Run: Theory

2.1. **Production.** Consider an economy populated by a landed elite and (landless) workers. Aggregate production of output Y_t at time t takes place with the CES technology,

$$Y_t = A_t \left[\alpha(A_t^X X)^\psi + (1-\alpha)(A_t^L H_t)^\psi\right]^{1/\psi} \tag{1}$$

and the production factors land, X, and quality-adjusted labor or human capital, H_t. Increases in the technology level A are conceptualized as (Hicks-) neutral technological progress that equally benefits both production factors. Increases in A^X are land-augmenting technological progress, and increases in A^L are labor-augmenting technological progress. Human capital is the human capital per worker h_t times the number of workers L_t, $H_t \equiv h_t L_t$. The elasticity of substitution is given by $\sigma \equiv 1/(1-\psi)$ and $\psi < 1$. The supply of land is fixed. Suppose both factors earn their marginal product. Then the land rent, R_t, and the wage per unit of physical labor, L_t, are given by

$$R_t = \alpha(A_t^X)^\psi X^{\psi-1} A_t \left[\alpha(A_t^X X)^\psi + (1-\alpha)(A_t^L H_t)^\psi\right]^{1/\psi-1} \tag{2}$$

$$W_t = (1-\alpha)(A_t^L)^\psi h_t^\psi L_t^{\psi-1} A_t \left[\alpha(A_t^X X)^\psi + (1-\alpha)(A_t^L H_t)^\psi\right]^{1/\psi-1}. \tag{3}$$

From (2) and (3) we obtain the rent-wage ratio R_t/W_t, our main measure of inequality:

$$\frac{R_t}{W_t} = \frac{\alpha}{1-\alpha} \cdot \left(\frac{A_t^X}{A_t^L}\right)^{\frac{\sigma-1}{\sigma}} \cdot \left(\frac{L_t}{X}\right)^{\frac{1}{\sigma}} \cdot h_t^{\frac{1-\sigma}{\sigma}}, \tag{4}$$

where we have used $\psi = 1 - 1/\sigma$ from the definition of the elasticity of substitution. The main mechanics of the model can be read off from equation (4). Suppose the economy is in a Malthusian state: Human capital per person is constant (at a low level $\bar{h}$) and the population density of workers, L/X, increases due to technological change. This means that the rent-wage ratio increases because land becomes relatively more scarce.[2]

Moreover, inequality is affected by factor-biased technological progress. Technological progress is defined as land-biased if it increases the relative price of land. How labor- and land-augmenting technological progress translates into biased technological change depends on the elasticity of substitution (Acemoglu, 2009, Ch. 15.2) For example, suppose $\mathrm{d}(A^X/A^L) > 0$ such that technological change is relatively more land-augmenting than labor-augmenting. The relative increase in the productivity of land implies an increase of the rent-wage ratio for $\sigma > 1$. In this case the increase in relative productivity increases the demand for land by more than the demand for labor and induces a higher relative price of land. For $\sigma < 1$, the relative increase in the productivity of land increases the demand for labor by more than the demand for land, which implies a lower rent-wage ratio.

The same intuition applies to the ambiguous affect of human capital accumulation on the rent-wage ratio. Higher human capital increases the productivity of labor. This increases the demand for labor by more than the demand for land and implies a relative increase of wages (a decline of the rent-wage ratio) if the elasticity of substitution is greater than one. If the elasticity of substitution is less than one, land demand responds more strongly to human capital accumulation than labor demand, and the rent-wage ratio increases.

By combining these mechanisms we observe the following picture. Before the onset of the fertility transition and modern growth, inequality rises driven by increasing population density and this is (perhaps) further amplified by land-biased technological change. With the onset of

[2] Notice that the rent-wage ratio is influenced by inheritance norms for land only through the population density of workers, i.e. through the influx of descendants of landlords into the workforce. This influence is relatively small since the landed elite is a small fraction of the total population. Other measures of inequality, which we do not consider in our study, such as the ratio of income per landlord vs. income per worker, could be influenced much more strongly by inheritance laws than the rent-wage ratio. In particular, the gradual abolition of primogeniture (Bertocchi, 2006) weakens the informative quality of the rent-wage ratio as a measure of personal income inequality.

the fertility transition and of mass education, the growth of L declines and h increases gradually. Then, if $\sigma < 1$, inequality rises further. If, however, $\sigma > 1$, inequality eventually declines as fertility converges to the replacement level (of a stationary population) and human capital continues to increase. This means that inequality, measured by the rent-wage ratio is hump-shaped over time (see the literature cited in the Introduction; O'Rourke and Williamson, 2005). We explore the inequality dynamics in detail below. Applying Occam's razor, we abstain, for the basic model, from introducing physical capital accumulation. In an extension we show that all qualitative results are robust to the introduction of physical capital.

2.2. **Households.** We focus on the decision about fertility and child education of worker households. This means that we consider the influx into the workforce of descendants of landlords as being negligible.[3] Following the basic setup in the unified growth literature (Galor and Weil, 2000), parents are assumed to maximize utility from consumption c_t, the number of their (surviving) children n_t, and human capital per child h_{t+1}, as a measure of the children's expected income as adults. The utility function is logarithmic and reads

$$u_t = \log c_t + \gamma \log n_t + \eta \log h_{t+1}. \tag{5}$$

We assume that $\gamma > \eta$ in order to ensure that parents want to have children (see below).

Child rearing costs τ units of income. Furthermore, parents may decide to invest $e_t \geq 0$ units of income into education per child. This means that the budget constraint is given by

$$c_t + (\tau + e_t) n_t w_t = w_t. \tag{6}$$

Following Galor and Weil (2000), we assume that there is a subsistence constraint, $c_t \geq \bar{c}$.

Human capital is produced from education via a linear production function,

$$h_{t+1} = \nu A_t e_t + \bar{h}, \tag{7}$$

[3]The approximation of the actual workforce is exact when there is no population growth (in the Malthusian steady state). With population growth a small approximation error emerges. For example, if descendants of workers grow at 0.1 percent per year and descendants of landlords at twice this rate and initially 1 percent of the population belongs to the landed elite, then the approximation error for the size of the workforce grows from zero initially to 1 percent after 500 years under primogeniture. The approximation error is largest for primogeniture (since it produces the greatest influx of descendants from landlords into the labor force) and smaller for other inheritance norms. It is zero when landownership is split between all descendants of landlords.

such that the return on education increases in the level of technology, A_t; thus, capturing the idea that it is more worthwhile to learn when there is much to learn. The structure of human capital production is a simplification of Galor and Weil (2000). It allows for simple closed-form solutions for all variables (see Strulik et al., 2013; Strulik, 2017). In the present context neither the linearity in A_t nor the linearity in e_t is decisive for the (qualitative) results. It is, however, important that there exists some human capital, $\bar{h} > 0$, that can be acquired without investment in (formal) education. This minimum level of skills is obtained, for example, by observing parents and peers working in the fields. The presence of $\bar{h}$ implies a threshold for the level of technology below which there will be no investment in education.

Specifically, the first order conditions for maximizing (5) subject to (6) and (7) are given by

$$1/c \leq \lambda, \qquad \text{with } = \text{ for } c_t > \bar{c} \tag{8}$$

$$\gamma/n_t = \lambda(\tau + e_t)w_t \tag{9}$$

$$\frac{\eta\nu A_t}{\nu A_t e_t + \bar{h}} \leq n_t w_t \qquad \text{with } = \text{ for } e_t > 0, \tag{10}$$

in which λ_t denotes the shadow price of income. The left hand sides of (8)–(10) show the marginal utility from consumption, having a child, and education and the right hand sides show the marginal costs. From (9) and (10) we obtain optimal education:

$$e_t = \max\left\{0, \ \frac{\eta\tau\nu A_t - \gamma\bar{h}}{(\gamma - \eta)\nu A_t}\right\}. \tag{11}$$

Notice that, as in Galor and Weil (2000), education is independent of income and whether or not the subsistence constraint binds. Instead it depends on the state of technology. For

$$A_t \leq \bar{A} \equiv \frac{\gamma\bar{h}}{\eta\tau\nu}, \tag{12}$$

education is not worthwhile. If there is education, e_t increases with technological advancements and converges asymptotically (for $A_t \to \infty$) to the constant $\eta\tau/(\gamma - \eta)$.

For fertility and consumption we obtain from (6), (8), and (9):

$$\left.\begin{aligned} n_t(\tau + e_t) &= \frac{\gamma}{1+\gamma} \\ c_t &= \frac{w_t}{1+\gamma} \end{aligned}\right\} \qquad \text{for } w_t > (1+\gamma)\bar{c} \tag{13}$$

and otherwise $c = \bar{c}$ and

$$n_t(\tau + e_t) = 1 - \frac{\bar{c}}{w_t}. \tag{14}$$

2.3. **Population and Technology Dynamics.** The workforce evolves over time as

$$L_{t+1} = n_t L_t. \tag{15}$$

Following Galor and Weil, we assume that technological progress is driven by education as well as by population size, capturing learning-by-doing effects, which provide technological advances before the onset of mass education and human capital accumulation. For simplicity, and without the loss of generality, we assume the functional form suggested by Lagerloef (2006) for Hicks-neutral technological progress in the Galor-Weil model:

$$g^A_{t+1} \equiv \frac{A_{t+1} - A_t}{A_t} = \delta(e_t + a) \cdot \min\left\{L_t^\theta, \;\; b\right\}. \tag{16}$$

The assumption $a > 0$ provides growth without education; the assumption $b > 0$ limits the gains from learning by doing through increasing population size. Without the loss of generality we assume that factor-augmenting technological progress is proportional to neutral technological progress: $g^{Aj}_{t+1} \equiv (A^j_{t+1} - A^j_t)/A^j_t = \Gamma^j g^A_{t+1}$, $\Gamma^j \geq 0$ and $j \in \{X, L\}$.

2.4. **The Three Regimes.** Assuming that the subsistence constraint is resolved before the education constraint is resolved, and that $a > 0$ and $b > 0$, any economy evolves through three distinguished periods (Galor, 2011): 1) The Malthusian regime, in which the subsistence constraint binds and fertility is increasing in income, see (14); 2) the post-Malthusian regime, in which income is above subsistence level but the demographic transition and mass education have not yet set in, such that fertility stays constant at a level above replacement level, see (13) with $e_t = 0$; and 3) the modern growth regime with education rising and fertility declining. To see that fertility is declining, solve for n_t in (13) with $e_t > 0$ from (11) to obtain:

$$n_t = \frac{(\gamma - \eta)A_t}{(\nu\tau A_t - \bar{h})(1 + \gamma)}. \tag{17}$$

With technological advances, fertility declines and, at the end of the fertility transition, it converges towards the constant $n^\infty \equiv (\gamma - \eta)/[\nu\tau(1 + \gamma)]$.

2.5. **Inequality in the Malthusian Regime.** At the Malthusian steady state, wages stay constant at subsistence level. From (3) this implies

$$G = (1-\alpha)A_t^L A_t \left[\alpha\left(\frac{A_t^X}{A_t^L}\right)^{\psi}\left(\frac{L_t}{X}\right)^{-\psi} + (1-\alpha)\right]^{\frac{1-\psi}{\psi}} - \frac{\bar{c}}{1-\tau} = 0. \tag{18}$$

We first investigate the impact of *discretionary* technological change, i.e. occasional improvements of technology without a continuous trend.

Proposition 1. *(i) In the Malthusian regime with discretionary technological change, population density increases with Hicks-neutral and land-augmenting technological progress. (ii) Inequality, measured by the rent-wage ratio, increases with increasing population density and land-biased technological change.*

For the proof we differentiate (18) implicity and obtain

$$\frac{\mathrm{d}(L_t/X)}{\mathrm{d}A_t} = -\frac{\partial G/\partial A_t}{\partial G/\partial(L_t/X)} > 0, \qquad \frac{\mathrm{d}(L_t/X)}{\mathrm{d}A_t^X} = -\frac{\partial G/\partial A_t^X}{\partial G/\partial(L_t/X)} > 0.$$

This is a generalization of the well-known result, that at the Malthusian steady state, technological improvements are used to fuel population growth such that technologically more advanced regions are more densely populated (Ashraf and Galor, 2011). The response of population growth to labor-augmenting technological progress is ambiguous and depends on the elasticity of substitution. The second part of Proposition 1 follows from inspection of (4) and recalling that human capital is constant in the Malthusian regime.

Our empirical section is confined to a sample of Western European countries, i.e. countries that were not characterized by strong institutions of labor coercion since the early modern period. Nevertheless, a legitimate question is to which extent the results from the propositions above depend on the assumption that labor earns its marginal product. In Appendix A, we show that the results are independent of coercive institutions defined by the feature that labor earns less than its marginal product.[4]

In order to scrutinize the role of labor-augmenting technological change, we follow Kremer (1993) and additionally assume that fertility adjusts infinitely fast to income changes such that

[4]A recent paper by Ashraf et al. (2018) argues that the decline of coercive labor institutions has been an inevitable by-product of industrialization due to an intensification of capital-skill complementarity in the production process.

labor income stays constant at the Malthusian steady state despite continuous technological change. This allows us to obtain the following result.

Lemma 1. *In a Malthusian regime with perpetual technological change, the population grows asymptotically at the rate*

$$g^L_{t+1} = \sigma g^A_{t+1} + g^{AX}_{t+1} + (\sigma - 1) g^{AL}_{t+1}. \tag{19}$$

For the proof we acknowledge that with technology and population perpetually growing, the term $(1-\alpha)$ in the square brackets of expression (18) vanishes asymptotically such that, asymptotically, the equation reads

$$(A^H_t A_t)^{\frac{\psi}{1-\psi}} \left(\frac{A^X_t}{A^L_t}\right)^{\psi} \left(\frac{L_t}{X}\right)^{-\psi} = constant.$$

The result in (19) follows from logarithmically differentiating this expression. It shows that the population growth rate, g^L, increases with labor-augmenting technological change, g^{AL}, if the elasticity of substitution is larger than one and declines otherwise.

Using (19) and (3) we obtain the (asymptotic) impact of technological progress on inequality:

Proposition 2. *In the Malthusian regime with perpetual technological change, the rent-wage ratio grows (asymptotically) one-to-one with Hicks-neutral and land-augmenting technological change and it is (asymptotically) independent of labor-augmenting technological change,*

$$g^{RW}_{t+1} \equiv \frac{(R_{t+1}/W_{t+1}) - (R_t/W_t)}{(R_t/W_t)} = g^A_{t+1} + g^{AX}_{t+1}. \tag{20}$$

For the proof, we logarithmically differentiate (4) and obtain

$$g^{RW}_{t+1} = \frac{\sigma - 1}{\sigma} \left(g^{AX}_{t+1} - g^{AL}_{t+1}\right) + \frac{1}{\sigma} g^L_{t+1}. \tag{21}$$

The result (20) follows from substituting g^L_{t+1} from (19). Interestingly, the impact of labor-augmenting technological change is neutralized. For example, if the elasticity of substitution is smaller than one, labor-augmenting technological change has a direct positive impact on the rent-wage ratio as well as a negative impact on population growth. Population growth affects the rent-wage ratio positively and exactly counterbalances the direct effect from labor-augmenting technological change. In other words, there is no way by which technological progress could reduce the rent-wage ratio in the Malthusian regime.

These results are useful for the empirical analysis. They suggest that, in reduced form, the rent-wage ratio is solely positively dependent on technological progress. A great part of technological progress, however, works through population growth. In fact, only biased technological progress affects the rent-wage ratio independently of population growth. If the elasticity of substitution is greater than one (less than one) then land-biased technological progress exerts a positive (negative) impact on the rent wage ratio beyond its impact through population growth. These effects can be tested via linear regression by taking logs of (4):

$$\log(R_t/W_t) = \frac{\sigma - 1}{\sigma} \log(A_t^X/A_t^L) + \frac{1}{\sigma} \log L_t + constant. \tag{22}$$

The coefficient of $\log L_t$ provides an estimate of the elasticity of substitution. The coefficient of (A_t^X/A_t^L) provides an estimate of whether technological progress is more labor- or more land-augmenting.

2.6. **Inequality in the Post-Malthusian Regime.** When the subsistence constraint is not binding but there is still no mass education, the fertility rate is constantly above its replacement level, $n_t = \gamma/[(1+\gamma)\tau] > 1$. Fueled by technological progress, wages and the population are growing perpetually such that the rent-wage ratio (4) is increasing with population growth and land-biased technological progress. However, further improving technological progress eventually initiates the fertility transition, investments in education, and the transition to the modern growth regime.

2.7. **Inequality in the Modern Growth Regime.** After education is initiated when the technological threshold has been crossed, education is gradually rising and converging towards the constant $\eta\tau/(\gamma - \eta)$, see (11). Using this result in (16), we find that the rate of neutral technological change is converging towards the constant

$$g = \delta a \cdot \frac{\eta\tau}{\gamma - \eta}.$$

Using (7) and (11), we see that human capital converges towards

$$h_{t+1} = \frac{\nu\eta\tau}{(\gamma - \eta)} A_t. \tag{23}$$

It is thus growing at the rate of neutral technological progress. This is a reasonable result: while (years of) education converge towards a constant, the value of education, measured by human capital is perpetually growing.

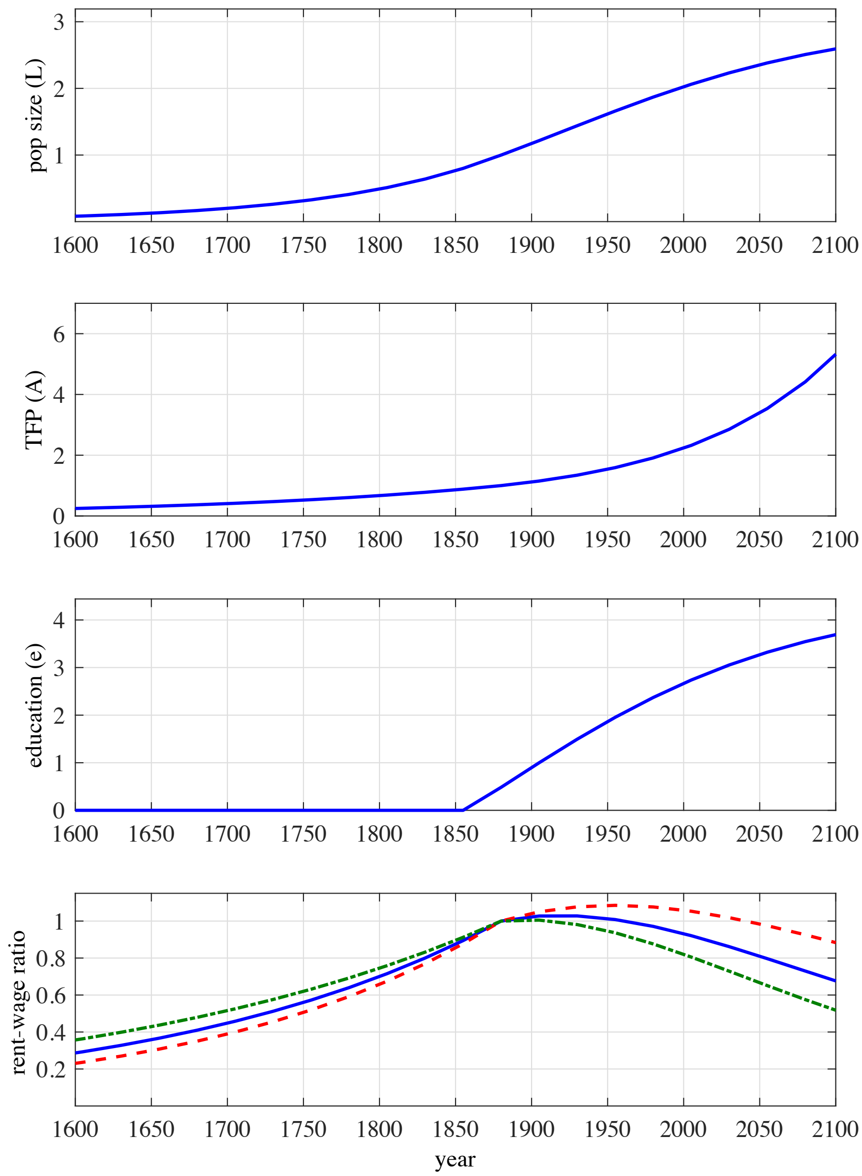
From the theory, long-run growth after the demographic transition could be associated with positive or negative population growth, depending on whether n^∞ exceeds or falls short of 1. In the long-run, however, for mere physical reasons, any steady state needs to be associated with a stationary population (otherwise humans die out or the population increases exponentially to infinity). A rare unified growth theory that renders this result as an endogenous outcome of the process of development is provided by Strulik and Weisdorf (2008). Here, we just assume that at the end of the demographic transition n^∞ is at or close to unity.

Proposition 3. *In the modern growth regime in steady state, along which the population is stationary and human capital, h_t, is growing, inequality is declining (increasing) if the rate of human capital accumulation exceeds the rate of land-biased technological progress and $\sigma > 1$ (and $\sigma < 1$).*

The proof follows from inspection of (4).

2.8. **Inequality Along the Transition to Modern Growth.** While Propositions 1-3 focus on steady states, we next explore the productivity – inequality nexus off the steady state, i.e. along the transition to modern growth. For this purpose we specify a typical Western European country undergoing a fertility transition. Naturally, this attempt provides only a rough approximation of any particular country, given the simple structure of the model. We set child rearing costs, τ, to 0.15, following Haveman and Wolfe (1995), normalize ν to 1, and assume that a generation takes 25 years. We then calibrate the remaining parameters such that the economy grows at an annual rate of 2 percent in the steady state of the modern growth regime, that fertility per adult approaches unity in the modern economy (convergence towards a stationary population), and that the population increases tenfold between 1800 and 2000. We start in the year 1600 and set $\bar{c} = 0.05$ such that the economy starts in the Malthusian regime. We begin with the case of an elasticity of substitution larger than one and set $\psi = 0.5$, i.e. $\sigma = 2$. We set $\alpha = 0.8$, implying an initial land share of income of about 0.25. We set initial L to 1000 and X to 10 and adjust the initial value of A such that the fertility transition starts in 1880. For the benchmark run we ignore biased technological change ($\Gamma^j = 0$). This leads to the estimates $\gamma = 0.23$, $\eta = 0.046$, $a = 0.27$, $b = 1.03$, $\theta = 0.3$, $\delta = 4.0$.

Figure 1: Long-Run Productivity and Inequality



Blue (solid) lines: benchmark run; red (dashed) lines: 30% land-biased technological progress ($\Gamma^X = 0.3$, $\Gamma^L = 0$); green (dashed-dotted) lines: 30% labor-biased technological progress ($\Gamma^X = 0$, $\Gamma^L = 0.3$). The variables are normalized such that $L(j) = A(j) = R(j)/W(j) = 1$ and $e(j+1) = 1$, where j is the year of the onset of the fertility transition.

The implied economic transition for population size, TFP, education, and the rent-wage ratio are shown by blue (solid) lines in Figure 1. The variables are normalized such that $L(j) = A(j) = R(j)/W(j) = 1$, in which j is the year of the onset of the transition, and $e(j+1) = 1$ (to avoid division by zero). In the bottom panel we see that as productivity grows, inequality (the rent-wage ratio) increases, as long as the economy is in the Malthusian regime. Around the onset of the fertility transition inequality stays approximately constant, indicating that the inequality-increasing force of population growth and the inequality-reducing force of human capital accumulation are roughly balancing each other. Later in the 20th century, the rent-wage ratio declines, rendering an overall hump-shaped inequality pattern (a Kuznets-curve). Inequality rises about fourfold from 1600 until peak inequality is reached at the onset of the fertility transition.[5].

The red (dashed) lines in Figure 1 show the evolution of inequality when 30 percent of technological progress is land-augmenting ($\Gamma^X = 0.3$, $\Gamma^L = 0$). This feature amplifies the inequality gradient (the increase of the rent-wage ratio with technological progress) in the (post-) Malthusian regimes and slows down the decline in inequality after the onset of the fertility transition. The opposite holds if 30 percent of progress is labor-augmenting ($\Gamma^L = 0.3$, $\Gamma^X = 0$), as shown by green (dash-dotted) lines. Inequality rises less steeply before the fertility transition and declines faster afterwards.

While the assumption of an elasticity of substitution greater than one is irrelevant for the motivation of increasing inequality during the Malthusian and post-Malthusian regime (see Propositions 1 and 2), it is decisive for declining inequality in conjunction with human capital accumulation in the modern growth regime (see Proposition 2). It is thus reassuring that studies focusing on contemporary economies confirm an elasticity of substitution larger than one (e.g. Nordhaus and Tobin, 1972; Weil and Wilde, 2009). For pre-industrial economies, the results are conflicting. Wilde (2017) estimates an elasticity smaller than one by assuming that there exists no biased technological progress. In Section 3 of this paper, we apply a similar estimation strategy and confirm the Wilde (2017) results when we omit technological progress (measured by farming book titles). However, after controlling for technological change, the estimated elasticity of substitution becomes greater than one.

Given these conflicting results, it may be regarded as useful to demonstrate that the theoretical predictions are indeed independent of the size of the elasticity of substitution in pre-industrial times. Since $\sigma > 1$ is needed at the modern steady state in order to explain declining inequality along with the human capital accumulation, we consider a model where the size of the elasticity of

[5] Inequality declines with a small delay after the onset of the fertility transition and mass education. This is so because the newly educated need time to enter the work force and because the population is still growing (albeit at a lower rate) after the onset of the fertility decline. Thus it takes a while until the impact of rising human capital overrides the impact of continuing population growth on rising inequality. Furthermore, human capital accumulation fosters technological progress. If technological progress is land-biased, then the decline of inequality is further delayed (cf. solid and dashed lines in Figure 2)

substitution changes along the adjustment path of the economy, $\sigma < 1$ in pre-industrial times and $\sigma > 1$ in the modern steady state. In order to allow for an endogenous elasticity substitution, we assume that σ increases with technological progress. This implements in "reduced-form" the intuition that human capital driven industrialization reduces the importance of land in production. Formally, we assume that ψ is a positive function of the level of technology:

$$\psi(A) = \psi_L + \frac{\psi_H - \psi_L}{1 + \mathrm{e}^{-\phi \cdot A}}. \tag{24}$$

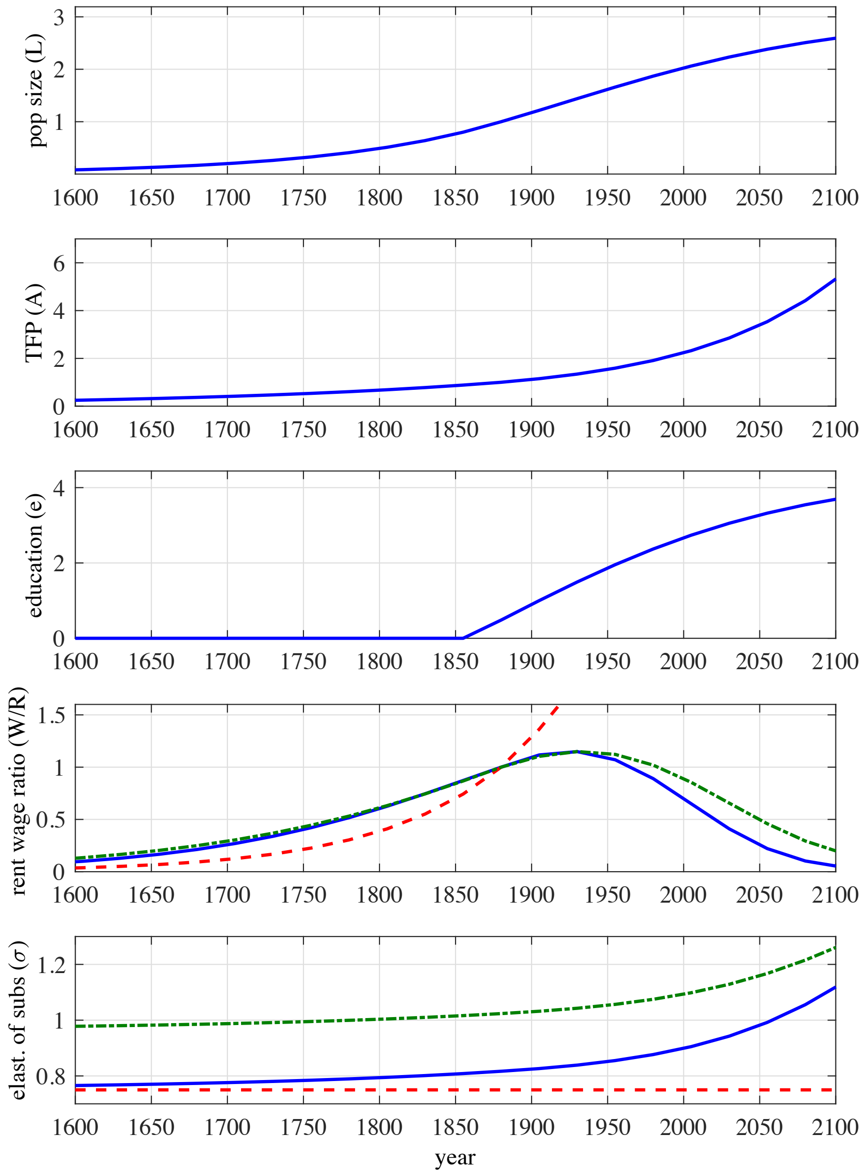
In Figure 2, the blue (solid) lines show an example for $\psi_L = -1$ (implying a minimum elasticity of substitution of 0.5 in the Malthusian regime) and $\psi_H = 0.33$, implying convergence towards an elasticity of substitution of 1.5 in the modern regime. We set $\phi = 0.015$ such that the elasticity of substitution exceeds 1 for the first time in the year 2050. The initial value of A is adjusted such that the fertility transition begins in 1880. All other parameters are kept from the benchmark run of Figure 1. The implied evolution of the elasticity of substitution is shown in the lower panel of Figure 2. Interestingly, the rent-wage ratio starts declining in the early 20th century, before the elasticity of substitution exceeds 1. Apparently, an increasing elasticity of substitution is sufficient for the the onset of mass education to generate a Kuznets-curve.

In order to illustrate that an increasing elasticity of substitution is also necessary for these results, we consider the case of a constant elasticity of substitution below one (by setting $\phi = 0$ in the example from above). In this case, shown by red (dashed) lines in Figure 2, the rent-wage is further increasing with human capital accumulation and converging towards infinity.

Green (dash-dotted) lines in Figure 2 show the case where the elasticity of substitution is close to one in the Malthusian regime. For this case, which approximates the frequently made Cobb-Douglas assumption, we set $\psi_{min} = -0.4$ and $\phi = 0.015$. We see that this has hardly any effect on inequality evolution in the Malthusian regime and slows down the decline of inequality in the modern growth regime.

Another (theoretical) way to induce a declining rent-wage ratio in the 20th century with an elasticity of substitution below one forever, is to assume a sufficiently high rate of labor-biased technological change that overcompensates the upward pressure on the rent-wage from human capital accumulation (see equation (4)). Such a scenario would necessarily require that A^X grows at a higher rate than A^L. In this case, labor-augmenting progress would be land-biased and vice versa.

Figure 2: Long-Run Productivity and Inequality: Improving Elasticity of Substitution



Blue (solid) lines: the elasticity of substitution increases from below one to above one with technological change; red (dashed) lines: constant elasticity below one; green (dashed-dotted) lines: Increasing elasticity of substitution around the value of one (Cobb-Douglas). The variables are normalized such that $L(j) = A(j) = R(j)/W(j) = 1$ and $e(j+1) = 1$, where j is the year of the onset of the fertility transition.

Finally, consider how these results would be affected by relaxing the assumption of a closed economy. For the open economy case, we additionally need to assume that there is at least one other sector such that goods can be traded. Such a model could combine the present model with the two-sector model of Strulik and Weisdorf (2008) and the North-South trade model of Galor and Mountford (2008). Suppose that agricultural technology initially advances at a higher speed in the North (perhaps because of a geographical advantage (Diamond, 1998)). This means that in the North there is a greater push of labor out of agriculture and into manufacturing (Matsuyama, 1992), and thus, there is more learning-by-doing opportunities and faster technological progress in manufacturing (Strulik and Weisdorf, 2008). When the economy opens, the North specializes in manufactured goods, which are assumed to be produced skill-intensively, while the South specializes in unskilled-intensive agriculture (Galor and Mountford, 2008). This means that, in the North, the demographic transition develops faster and R_t/W_t–inequality declines faster than predicted by the basic model, whereas in the South, the demographic transition is delayed and inequality keeps on rising after the introduction of trade until it finally declines when the demographic transition is accomplished in the South. In the empirical section, we consider a sample of the OECD countries that were assigned by Galor and Mountford (2008) to belong to the North. For these countries, we would expect that, ceteris paribus, the demographic transition happens faster and inequality declines faster than predicted for the basic one-sector economy. Structurally, we expect no change in the results for the open economy.

3. Empirical Analysis

In this section we test the empirical predictions of the theory, viz., that technological progress in the pre-industrial period increased land rent per hectare, R, while wages, W, were kept close to subsistence level in the long run through the Malthusian check; thus increasing income inequality. We then address the impact of productivity advances around the onset of the fertility transition and during the 20th century until the 1980s. Following the predictions of our theory and the lead of Williamson and his collaborators, see e.g. O'Rourke and Williamson (2005), we measure inequality by the rent-wage ratio, denoted by R–W, throughout the empirical section. The R-W ratio is an excellent measure of inequality in the pre-industrial society and during most parts of the industrialization era since the elite, including the clergy, derived most of their income from land, while agricultural workers, representing the low-income class, lived almost entirely from their labor. Rent is measured as land rent per hectare of agricultural land and wages are measured as daily wages or, alternatively as annual wages of agricultural labor when available. Data construction and sources are detailed in the online Appendix.

Four sets of estimates are carried out to test for the nexus between the R-W ratio and technological progress in the three distant regimes covered in the theory section: 1) The Malthusian regime; 2) the post-Malthusian regime; and 3) the modern growth regime. In the first set of estimates, carried out for Britain over the periods 1525-1895, 1525-1850, 1600-1820, technological progress is measured by the growth in farming book titles, which captures the dissemination of innovations, and new techniques and methods in agriculture (Sullivan, 1984).

In the second set of estimates, carried out over the period 1265-1850 for five countries (Malthusian regime), technology is approximated by agricultural labor productivity, which is a good measure of TFP under the assumption that the cultivated land area is fairly constant and that the agricultural capital stock is a negligible or, at least, a relatively constant fraction of agricultural output.[6]

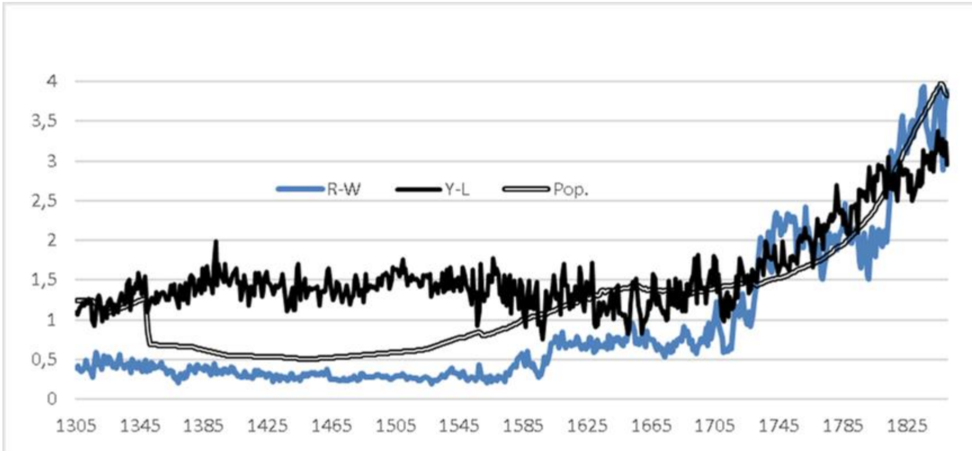
The third and fourth sets of estimates are undertaken for seven OECD countries over the periods 1800-1920 (post-Malthusian regime) and 1920-1980 (modern growth regime) and technological progress is measured by the number of patent applications of residents. In order to overcome potential feedback effects from the outcome variables to technology and population growth, we use instruments for technology in some of the post-1800 regressions. Instruments are not used in the other estimates because it is unrealistic to find good instruments that are available annually for the centuries prior to 1800.

3.1. **Graphical Analysis.** Figure 3 shows the long-run evolution of the rent-wage ratio, agricultural labor productivity (denoted by *Y-L*), and population size (denoted by *Pop*) for Britain over the period 1305-1850. The reduced population pressure caused by the continual outbreaks of the Black Death starting from the 1348 shock, resulted in an approximately 50% reduction in inequality that continued well into the 16th century. Over the period 1573-1850, technological advances in agriculture and population pressure jointly resulted in a remarkable 15-fold increase of the rent-wage ratio. Since real wages were relatively flat over the period 1573-1850, the productivity advances and the increasing population pressure created a marked increase in inequality, and by the first half of the 19th century inequality in Britain was rampant.

Figures 4 and 5 show the evolution of the rent-wage ratio over the period 1800-1980 and agricultural productivity over the period 1800-1900 for the OECD countries of our sample. Agricultural productivity is not shown beyond the 19th century because it increases exponentially during the 20th century and movements during the 19th century would be difficult to visualize in a Figure for

[6]TFP equals the growth in labor productivity when land is fixed and the agricultural capital-output ratio is constant or negligible. Formally, for any production with constant returns to scale to labor, L, and fixed factors X and with multiplicatively separable technology A, $Y = F(A, X, L)$, we have $\mathrm{d}\log(Y/L) = \mathrm{d}\log(A) - \mathrm{d}\log(L/X)$. Labor productivity thus measures technology when population is controlled for.

Figure 3: Rent-Wage Ratio, Productivity, and Population: Britain 1305–1825

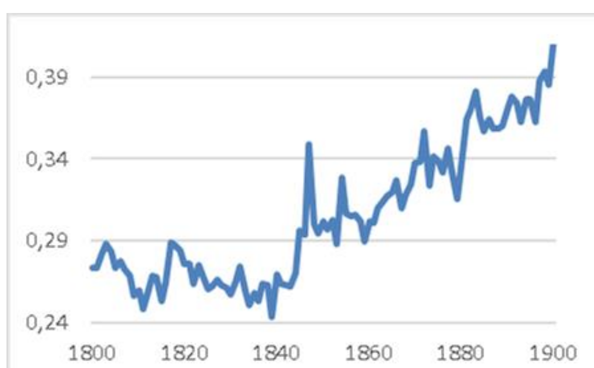


Notes. The data are indexes normalized to have the same mean over the period 1750-1850. R-W: land rent-wage ratio; Y-L: agricultural labor productivity; Pop: population.

the whole series. The evolution of the R-W and Y-L ratios are consistent with our theory. The R-W and Y-L ratios move in parallel fashion up to circa 1880; however, they show no systematic relationship after the onset of the fertility transition, which started, on average, in 1880 in the OECD countries considered here (Madsen et al., 2018a). Productivity grows at a positive rate while the rent-wage ratio declines alongside with the fertility transition over the period 1914-1980 (fertility is not shown in the figure). Our analysis does not address the increasing R-W ratio in the late 20th century (for that see Piketty, 2014 and, with emphasis on land prices, Grossmann and Steger, 2017). Here, we focus on inequality trends before post-modern times and their reversal around the onset of the fertility transition.

Figure 4: Rent-Wage Ratio: OECD Countries 1800–1989

Figure 5: Agricultural Productivity: OECD Countries 1800–1989



Notes. The data are measured as unweighted averages for Belgium, Denmark, France, Ireland, Spain, Britain and the US. The data are standardized to have a mean of one over the period 1850-1980 for each individual country.

3.2. **Farming Book Titles and Inequality in Britain, 1525-1895.** Our main analysis focuses on Britain for which farming book titles, as a direct measure of technological opportunities in agriculture, are available from Sullivan (1984) over the crucial period 1525-1895, representing a period in which technological progress gradually increases in importance while the economy is predominantly in the Malthusian regime. Sullivan (1984) argues that the number of titles of published farming books is a sound measure of agricultural innovations and, particularly, the dissemination of new technology as well as the description of the implementation of new methods and the utilization of contemporary mechanical devices of technologies. In the next section we discuss why farming book titles are good indicators of technological opportunities.

Agricultural wages are measured as daily wages (from Clark, 2010) and, alternatively, as annual wages (from Humphries and Weisdorf, 2019). Daily wages are better measures of labor productivity (and in this sense closer to the theoretical model) while annual wages better capture actual income and the associated R-W ratio captures better actual inequality. Land rents, which are estimated by Clark (2002), are derived from land held by charities in England, including adjustments for tithes and taxes, and cover nearly 2% of farmland holdings in England and Wales. Clark (2002) corrects the data for regional spread, plot size, share of common land, and distribution across parishes to ensure representativeness. The data measures rental values from competitive market rates, not the average rents paid by land occupiers, which are often below the market rates (Clark, 2002).

Figure 6 shows the R-W ratio, accumulated titles of farming books, and population size for Britain over the period 1525-1895. We observe a relatively tight positive long-run relationship between accumulated book titles and the R-W ratio. In the short run, however, the R-W ratio fluctuates around the long-run trend because of short- and medium-run influences such as weather-induced output fluctuations and price changes induced by effective prices of agricultural import prices.[7]

[7]Fueled by the Corn Laws, effective over the period 1815-1846, the macro tariff rates were a whopping 50% during this period, noting that macro tariff rates underestimate the effective tariff rates because of substitution away from products most affected by the tariffs. Similarly, capitalizing on the widening trade deficit after the wars between France and Britain in the period 1689-1713, protectionists engineered the imposition of high tariffs on a range of imports from France during and after the war (Fletcher, 1961). The repeal of the Corn Laws, effective from 1846, and the Great Agricultural Depression over the period 1873-1896, driven by the grain invasion from the New World and a series of crop failures, put strong downward pressure on land rents despite the technological advances in agriculture (Fletcher, 1961).

The following models are estimated to test for the influence of the number of farming books and manuals on income distribution and land rent:

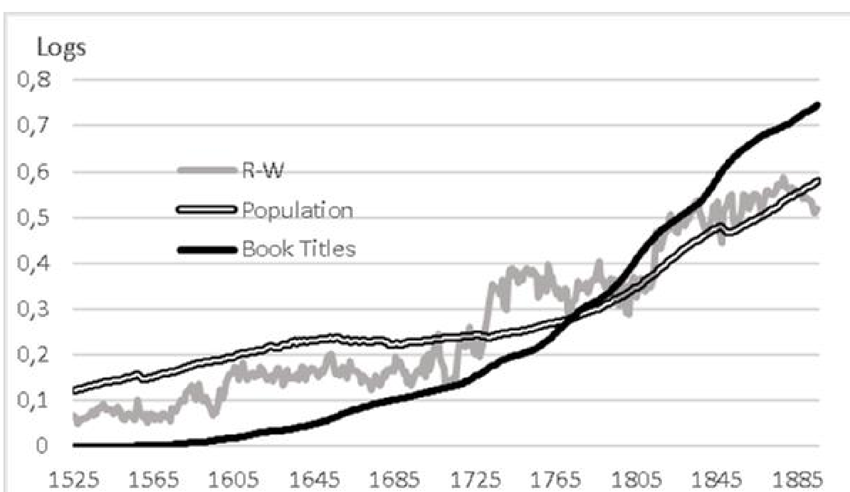
$$\ln(R/W^D)_t = a_0 + a_1 \ln(Book_t^X) + a_2 \ln Pop_t + v_{1t} \tag{25}$$

$$\ln(R/W)_t = b_0 + b_1 \ln(Book_t^X) + b_2 \ln Pop_t + v_{1t} \tag{26}$$

where R is land rent per hectare; W^D is daily wages of agricultural labor; W is annual wages of agricultural labor; Pop is population size and equals L (from theory section); $Book^X$, $X \in \{P, S\}$, $Book^P$ is the number of new published titles of farming books per year (a flow variable), $Book^S$ is the stock of farming book titles, and v is a stochastic error term. We expect the coefficients of book production and population to be positive. The stock of book titles is the accumulated flow of new titles without depreciation. Results are quite similar if we allow for 2-5% depreciation using the perpetual inventory method.

The regression results can be interpreted as the structural estimation of (4), the core equation from the theory section, displayed in logs in (21). The inverse of the coefficient on Pop then provides an estimate of the elasticity of substitution and the sign of the coefficient on $Book^X$ provides the direction and the strength of biased technological progress. Moreover, theory suggests that $a_1 = 1 - a_2$ and $b_1 = 1 - b_2$.

Figure 6: Rent-Wage Ratio, Productivity, and New Farming Book Titles: Britain 1525-1895



Notes. Book titles are the accumulated number of new book titles. Wages are measured as daily wages of agricultural labor.

The models are estimated over the periods 1525-1895, 1525-1850, and 1600-1820. The year 1850 signals the beginning of a period in which the share of British agriculture in total nominal GDP declined from 44% in 1850 to 27% in 1860 and further to 17% in 1890 (Madsen and Murtin, 2017). Furthermore, 1850 is shortly after the repeal of the Corn Laws in 1846. The period 1600-1820 represents the period under the Malthusian regime in which technological progress become more systematic and persistent; facilitated by the scientific revolution and the enlightenment (Mokyr, 2018).

3.3. **Farming Book Titles as Indicators of Technological Opportunities.** Farming books were potentially effective media of transmission of agricultural knowledge as a large fraction of the adaptors were writing literate and, presumably, even more would have been reading literate, as reading was traditionally taught before writing. Based on early surveys for England, Schofield (1973) finds that the gentry were 100% literate and 81% of yeomen and farmers were literate around 1770. Over the period 1580-1730, Cressy (1977) finds 98% of the gentry and 65% of the yeomen to be literate.[8]

Many of the books were practical treatises, giving explicit instructions of the implementation of new methods and utilization of contemporary mechanical devices of technologies (Sullivan, 1984, Overton, 1985). Some seedsmen even prepared instructions on cultivation technique (Overton, 1985) and it is widely observed that the introduction of new crop types was promoted mainly by agricultural books (Sullivan, 1984).

Farming books are an excellent medium of efficiency gains that are driven by knowledge, effectively acquired by a continuous flow of books. Agricultural productivity advances were predominantly promoted by 1) the introduction of new growing methods that could increase yields such as crop rotation, draining, and irrigation (land-biased technological progress); 2) the introduction of new crops, such as clover, turnips, and potatoes (product variety innovations); 3) a more efficient use of labor/draught animals driven by improvements of the plough (draught animal saving technological progress); and 4) the adaptation of the seed drill in 1701 and mechanization (land-biased technological progress). Brunt (2003) shows that several of these factors contributed

[8]In 1590, the writing literacy rate for yeomen was 61%; thus close to the literacy covering the period 1580-1730, suggesting a high degree of literacy even among owners or cultivators of small plots back in the late 16th century. While we do not have literacy data for the gentry in 1590, the fact that literacy did not change much for the gentry from 1590 to the average over the period 1580-1730, does give some indication that the literacy of the gentry was widespread and close to the 1580-1730 average.

to increasing crop yields in England around 1770; particularly effective crop rotations, growing turnips, management techniques, and the use of fertilizer, seed drills and horse hoeing.

Why were the farming books and manuals important for agricultural productivity advances? First, the productivity advances in agriculture were mostly not an outcome of the adoption of newly introduced technologies, but the adaptation of existing ones (van der Veen, 2010). While macro-inventions, such as radical new ideas did occur, micro-inventions such as changes or modifications to tools and practices made by skilled farmers, were more important promoters of agricultural productivity advances than macro-inventions in pre-industrial societies (van der Veen, 2010). Important inventions and knowledge, from overseas, or knowledge that might not have been passed on from earlier generations, could be effectively conveyed and stored by farming books and manuals.

Second, and related to the former point, farming books promoted new crops, such as the potato, clover and turnips; all of which enhanced crop yields directly or indirectly (Sullivan, 1984; Overton, 1996).[9]

A question is the extent to which ideas expressed in books were scientifically sound. Sullivan (1984) gives examples of poor ideas such as 1) beans should be planted when the moon is waxing; and 2) sails could be attached to the plough to increase the pulling power.[10] However, several useful ideas were promoted in the books, such as 1) the potato, turnips and clover as alternative crops; 2) techniques of how to operate the plough optimally; and 3) rotation technique (Sullivan, 1984). Overall, Sullivan (1984) finds that the net effect of farming books was positive. Using US data in the first half of the 20th century, Alexopoulos and Cohen (2009) find a causal relationship

[9] Clover is an example of crop that promoted agricultural productivity. The introduction of clover increased productivity directly by providing nitrogen to other crops, and indirectly through positive externalities (Overton, 1996; Schmidt et al., 2018). Adapting a differences-in-differences identification strategy, Schmidt et al. (2018), for example, find that the spread of clover in Denmark impacted positively on agricultural productivity and human capital accumulation. Furthermore, they find that the adaptation of clover increased the production of cows in Denmark in the first half of the 19th century, suggesting that clover contributed to the expansion of creameries in the second half of the 19th century; noting that the expansion of creameries is often considered to have been pivotal for the economic development of Denmark. In addition to the effects of increasing enclosure, Overton (1996), also attributes a large part of the pre-industrial advances in agriculture to the spread of clover and turnips starting from the 17th century or, perhaps, earlier. He finds that clover and turnips occupied only nine per cent of the sown area in 1660-1739, and as much as 49 per cent by 1836 in Norfolk. By contrast, Brunt (2003) finds that clover impacted negatively on crop yields across villages in England in 1770; however, he acknowledges that his results should be taken with a grain of salt.

[10] A misleading recommendation also came from Von Liebig (1840). Although Liebig was a strong advocate of replenishing the nitrogen that was used up in the soil for the next crop, he incorrectly believed that the nitrogen assimilated by plants came from precipitation. However, according to Brock's (2002) biography of Liebig, only a few farmers could accept Liebig's criticism of the humus theory, especially when his chemical fertilizers went against more than a century of tradition. Overall, like all scientific endeavors, some findings and recommendations are misleading.

from new farming book titles to TFP at the industrial level; thus giving further support for the use of farming books as an indicator of the introduction of new technology and new practices in British agriculture.

3.4. **Regression Results for Britain.** The results of estimating equations (25) and (26) are presented in the top panel (new farming book titles) and the lower panel (accumulated farming book titles) in Table 1. Since the variables included in the model are non-stationary, we perform a cointegration analysis to check for possible spurious correlations or omitted variables and to focus on the long-run relationship between the variables. The null hypothesis of no cointegration is rejected at the 1% level in almost all cases in which farming book titles are included in the regressions, suggesting that the significance of the coefficients is not driven by a common trend between the variables and, therefore, that the coefficients are super consistent. However, the variables are not cointegrated when farming book titles are excluded from the R-W regression (columns (6) and (7)), suggesting that the coefficient of population is biased because a variable driving non-neutral technological progress is missing from the model.

In the R–W^D regression in column (1), in which farming book titles is the only regressor, the coefficient of farming book titles is positive and statistically highly significant regardless of whether book titles are measured as flow (new book titles) or stock (stock of book titles). Since the null-hypothesis of no cointegration cannot be rejected at the 1% level, the results suggest that farming book titles captures neutral as well as non-neutral technological progress feeding through population.

The results of estimating the unrestricted equations (25) and (26) are presented in columns (2)-(5) in Table 1. The coefficients of farming book titles are all highly significant and positive regardless of whether $Book^P$ or $Book^S$ is used as the technology indicator, whether the estimation period ends in 1820, 1850 or 1895, and whether earnings are based on W or W^D. The coefficient of Pop is insignificant in the regression where the R-W ratio is based on annual wages, but highly significant in the regressions using daily wages; a result that is intuitive since the variation in the annual wage is, to a large extent, determined by variation in days worked per years (Humphries and Weisdorf, 2019) and, therefore, is not so much due to variations in the marginal productivity of labor.

TABLE 1. R-W Ratio, Population, and Farming Book Titles: Britain 1525-1895

	1	2	3	4	5	6	7
Dep. Var.	$\ln(R/W^D)$	$\ln(R/W)$	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$
Est. Period	1525-1895	1525-1895	1525-1895	1525-1850	1600-1800	1525-1895	1600-1800
New Farming Book Titles							
$\ln(Book^P)$	0.58***	0.37***	0.48***	0.39***	0.31***		
	(46.2)	(13.7)	(16.3)	(9.16)	(4.6)		
$\ln(Pop)$		0.07	0.26***	0.61***	1.07***	1.36***	2.26***
		(1.02)	(3.12)	(4.27)	(3.45)	(22.8)	(15.7)
R^2	0.88	0.82	0.88	0.88	0.68	0.78	0.64
$\chi^2(1)$		0.00	0.00	0.99	0.13		
DF	-4.17	-3.43	-4.1	-4.18	-4.23	-2.44	-3.89
ADF	-3.49	-3.57	-3.29	-3.3	-3.26	-1.50	-3.13
Stock of Farming Book Titles							
$\ln(Book^S)$	0.34***	0.22***	0.48***	0.24***	0.22***		
	(41.3)	(12.4)	(14.6)	(11.5)	(4.21)		
$\ln(Pop)$		0.07	0.22***	0.60***	1.07***		
		(0.91)	(2.67)	(6.53)	(3.56)		
R^2	0.91	0.82	0.89	0.91	0.68		
$\chi^2(1)$		0.00	0.00	0.02	0.78		
DF	-4.77	-3.44	-4.70	-4.18	-4.29		
ADF	-3.74	-3.27	-3.57	-3.29	-3.31		

The numbers in parentheses are absolute t-values, based on heteroscedasticity and serial correlation consistent standard errors. $Book^P$ = production of new farming books; $Book^S$ = accumulated number of farming book titles; R = agricultural land rent per hectare; W = is annual earnings of agricultural workers; W^D = daily wage rate for agricultural workers. $\chi^2(1)$ = p-value of test of the restriction $b_1 = 1 - b_2$ (see Eq. (25)), distributed as χ^2 with 1 degree of freedom. DF = Dickey-Fuller test for cointegration including a constant; ADF = Augmented Dickey-Fuller test for cointegration including a constant and one lag of the dependent variable. The critical values of the DF are -3.45 at the 1% and -2.88 at the 5% significance level. Significance at *10%, **5%, ***1% levels.

Economically, both farming book titles and population growth are influential for the inequality path; however, the increase in accumulated farming book titles is approximately twice as influential for the R-W path as population growth. Based on the average coefficient of the R-W ratio of 0.29, the fourfold increase in accumulated farming book titles during the 18th century contributed to a 116% increase in the R-W ratio. In the key period 1700-1850 during which the R-W ratio increased the most, farming book titles explain 45.9% of the increase in the R-W ratio, while the population increase explains 22.6%, where the coefficients in the lower panel of column (4), based on estimates over the period 1525-1850, are used because they match best the period 1700-1850.

Comparing the estimates with and without books as regressors gives an important insight. The coefficient of population is markedly higher when books are excluded from the regressions than when they are included, suggesting that the effects of increasing technological progress influences the R-W ratio directly and, indirectly, through population growth. We take up this idea in the IV-regression below. The feature that books exert a positive influence on the R-W ratio when population is controlled for, confirms that technological change as conveyed by farming book titles is land-biased. This seems plausible since the purpose of buying and reading new books on farming is likely to be motivated by the farmers' desire to increase yields of factors of production.

The size of the estimated coefficient of Pop suggests that the elasticity of substitution is larger than one or close to one. Only if Pop enters as a sole regressor (columns (6) and (7)), its coefficient is significantly greater than one, suggesting an elasticity of substitution that is less than one. However, these estimates are biased since the independent influence of books is missing from the model. An elasticity of substitution between land and labor of one is the implicit assumption in most economic theories of long-run development. An elasticity of substitution greater than one and perhaps close to two is in line with earlier studies of Nordhaus and Tobin (1972) for the US 1909-1958 and of Weil and Wilde (2009) for a sample of contemporaneous developed and developing countries.

As a final test of the theoretical consistency of the results, we test the restrictions $x_1 = 1 - x_2$, $x \in \{a, b\}$. The χ^2–test results are presented in the $\chi^2(1)$–row in Table 1. The restriction is rejected at any conventional significance level in the estimates covering the entire sample period, 1525-1895 (columns (2) and (3)); however, the restriction cannot be rejected in the regressions ending in 1800 or 1850 (columns (4) and (5)). Presumably, the restriction is rejected in estimates covering the period 1850-1895 because mass education and human capital accumulation are already underway during this period and, as such, derail the positive relationship between the R-W ratio and technological progress.

3.5. **Technological Progress and Population Growth.** As argued in the theory section, the size of the population is endogenous and its growth is largely determined by technological progress. In order to separate the independent influence of population growth from the one that is explained by technological progress, we use the following two-stage procedure:

$$\ln Pop_t = c_0 + c_1 \ln(Book_t^X) + v_{3t} \tag{27}$$

$$\ln(R/W^D)_t = d_0 + d_1 \ln(\widehat{Pop}) + v_{4t}. \tag{28}$$

By using the population size explained by the state of technology in (28), we follow the principle of 2SLS but we do not refer to it as an IV regression because we do not consider the exclusion restriction to be satisfied. If farming book titles comprise factor biased technological progress, this will impact on the R-W ratio independently of population pressure.

Table 2. Parameter Estimates of Eqs. (27) and (28) for Britain

	1	2	3	4
		Second Stage		
Dep. Var.	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$
$\ln Pop^{IV}$	1.59 (46.3)***	1.48 (47.9)***	1.33 (16.3)***	1.40 (14.6)***
$\ln Pop$			0.26 (3.12)***	0.22 (2.67)***
		First Stage		
Dep. Var.	$\ln Pop$	$\ln Pop$		
$\ln(Book^S)$		0.26 (22.0)***		0.26 (22.0)***
$\ln(Book^P)$	0.36 (28.3)***		0.36 (28.3)***	
R^2	0.83	0.81	0.83	0.81
Est. Period	1525-1895	1525-1895		

See notes to Table 1. $\ln Pop^{IV}$ = population size is 'instrumented' by new farming book titles or the stock of book titles. Note that the R^2's are not shown in the second-stage regressions because they are invalid.

The results of estimating Eqs. (27) and (28) are presented in Table 2. The coefficients of the technology indicators are highly significant in the first-stage regressions and explain a large fraction of the variance in population. The coefficients of population in the regressions in the first two columns are significantly higher than that in the regressions in Table 1, indicating that technology-driven population growth is more influential for the R-W ratio than for population growth in general; thus giving further evidence in favor of our theory. When non-instrumented population is added to the model as a regressor, it exerts a significant independent positive influence on the R-W ratio. However, the bulk of the influence of population growth on inequality is driven by technological progress. The coefficient on Pop^{IV} is about five times larger than the coefficient of Pop.

Finally, we undertake Granger causality tests to ensure that the Malthusian mechanism acts as a mediator between farming book titles and the R-W ratio. Following the Malthusian paradigm, we have assumed in the regressions above that farming books enhance land rent because real wages are kept at subsistence levels. Fertility responds positively to wages that are, temporarily, driven above their subsistence level by technological advances and the introduction of new agricultural practices. We performed Granger-causality tests as checks on whether the impact of new farming book titles on the R-W ratio is mediated through the Malthusian mechanism. Specifically, we check for possible feedback effects from fertility to book production by means of Granger causality tests in which the general fertility rate, GFR, is regressed on lagged GFR, lagged crude mortality rates, and new farming book titles, $Book^{Tit}$. All regressors are lagged 10-20 years and the estimation period is 1545-1895. The same regression is then repeated, but with $Book^{Tit}$ as the dependent variable. The regression results, which are reported and discussed in detail in the online Appendix, show that $Book^{Tit}$ Granger causes the GFR ($t = 4.58$) and not the other way around ($t = 1.66$). These results 1) give support for the Malthusian mechanism; 2) suggest that it was the gravitation towards the subsistence wages that ensured that the gain from technological progress and better agricultural practices was accrued to the landholders; and 3) indicate that farming books were mediated to the R-W ratio through fertility.

3.6. **Placebo Tests.** The positive relationship between farming book titles and the R-W ratio found in the regressions above may, in the worst case scenario, not reveal any causal relationship from technological knowledge to inequality. Instead, the increasing numbers of farming book titles may be an outcome of economic development and, particularly, the agricultural enlightenment in which book publication and farming book titles may go hand-in-hand because they are both driven by a general interest in reading. If this is the case, then the R-W ratio should also be significantly positively related to the production of all kinds of others books (i.e. non-farming books). To check for this possibility, we include book titles of a non-farming nature as regressors in the R-W baseline regressions. The extended regressions will reveal whether the coefficients of farming book titles have captured the influence and progression of the enlightenment that encouraged the exchange of general ideas, reading and debates through the written word (Mokyr, 2009).

Of books of non-farming nature we consider the stock of all books, Tot^S, cook books, $Cook^S$, and religious books, Cle^S, as well as the stock of new book titles of all books $TotX^S$. None of these types of books are related to the diffusion of technology and new agricultural practices; however, total book and cookbook production are likely related to the Enlightenment and an increasing enthusiasm for reading. In contrast to most other book types, religious books are likely to capture a cultural trend that is unrelated to the Enlightenment in that the Enlightenment de-emphasized the authority of the Church (Mokyr, 2009). We include clergy books because they may capture the cultural aspects of the Enlightenment that are not captured by the other types of books.

The regression results, which are presented in Table 3, show that of the four book categories, the stock of farming book titles is the only robust determinant of the R-W ratio. Starting from columns (1) and (3), in which farming book titles, $Book^S$, are excluded from the models, the coefficients of Tot^S and $TotX^S$ are both significantly positive. The coefficients of Tot^S and

Table 3. Placebo Test of R-W Ratio and Books, Britain.

	1	2	3	4	5	6	7	8
Dep. Var.	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$
$\ln(Book^S)$		0.50***		0.87***		1.31***		0.70***
		(8.85)		(3.79)		(5.20)		(5.73)
$\ln(Pop)$	0.25*	0.80***	1.97***	-0.34	1.39***	-1.81***	2.11***	0.76***
	(1.84)	(8.47)	(10.5)	(0.62)	(4.52)	(3.19)	(9.17)	(2.86)
$\ln(Tot^S)$	0.63***	-0.61***						
	(9.28)	(5.39)						
$\ln(Cle^S)$					0.01	0.28		
					(1.56)	(1.21)		
$\ln(Cook^S)$							0.05	-0.50***
							(1.01)	(5.33)
$\ln(TotX^S)$			0.01***	-0.06***				
			(2.56)	(2.84)				
ADF	-1.82	-4.84	-2.29	-2.98	-2.53	-4.49	-2.21	-2.9
Est. Period	1525-1895	1525-1895	1600-1800	1600-1800	1660-1800	1660-1800	1600-1800	1600-1800

Notes. See notes to Table 1. $Book^S$ = stock of farming book titles Tot^S = stock of the total number of book titles; Cle^S = stock of religious books; $Cook^S$ = stock of cookbooks; $TotX^S$ = stock of total new book titles.

$TotX^S$ are rendered significantly negative when $Book^S$ is included in the regression (columns (2) and (4)), supporting the hypothesis that the R-W ratio is driven by productivity advances that are promoted by the spread of new technologies and methods through $Book^S$. The coefficients of religious books are insignificant regardless of whether farming book titles are included in the regression (columns (5) and (6)). The coefficient of cookbooks is significantly negative when the stock of farming book titles is controlled for and insignificant when the stock of farming book titles is excluded from the model (columns (7) and (8)). Finally, the null hypothesis of no cointegration is only rejected when farming books are included in the regressions, suggesting that farming books contain relevant information that is orthogonal to book publication in general. Stated differently, neither $TotX^S$, $Cook^S$, nor Cle^S embodies useful information that can explain the path of the R-W ratio. It is, therefore, unlikely that farming book publication has captured the general spirit of the Enlightenment, rather it has genuinely captured factors that have mapped the link between technological knowledge and agricultural production.

3.7. **Non-linear Effects of Farming Book Titles.** In column (1) in Table 4, we include the squared log of books to check for the possibility of diminishing returns to farming book titles, noting that we have not tested for this possibility for the stock of farming book titles because they are already accumulated over time in these estimates and, as such, allow for non-linear effects from new farming book titles. It is possible that a fraction of the increase in the number of new titles has content that has already been included in other books and, therefore, that new titles have declining effects on the R-W ratio. The coefficient of the farming book titles is highly significantly positive and close in magnitude to that of the baseline regression in Table 1. The coefficient of farming book titles squared is statistically significantly negative, which, coupled with the positive coefficient of the level of farming book titles, suggests that there are diminishing returns to book publication, i.e., that the useful new information per new title is diminishing in the number of new titles. The effects of book titles on the R-W ratio is, however, significantly positive during the whole estimation period even when diminishing returns are allowed for. The finding of diminishing returns may reflect a reduced number of new innovations and methods included in each new book or diminishing value of each new innovation.

TABLE 4. Robustness Checks: Britain

	1	2	3	4	5	6
Dep. Var.	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$	$\ln(R/W^D)$
$\ln(Book^S)$	0.53***	0.42***	0.41***	0.40***	0.41***	0.39***
	(10.74)	(10.1)	(9.68)	(9.37)	(10.1)	(8.18)
$\ln(Book^S)^2)$	-0.003***					
	(4.42)					
$\ln(Pop)$	0.21***	0.21***	0.22***	0.22***	0.22***	0.25***
	(3.00)	(2.76)	(2.80)	(2.90)	(2.93)	(3.24)
$\ln(Y^{Man}/Y^{Tot})$			-0.03			-0.08
			(0.30)			(0.78)
$\ln(Meet)$				0.05**		0.05**
				(2.49)		(2.35)
$\ln(Temp-Sep)$					0.03**	0.03*
					(2.03)	(1.71)
$\ln(Temp-Dec)$					0.02**	0.03**
					(2.26)	(2.54)
Oster			0.81	0.61	2.39	0.95
R^2	0.83	0.75	0.75	0.75	0.76	0.76
DF	-3.47	-2.92	-2.97	-3.04	-3.73	-3.93
Est. Period	1525-1895	1659-1895	1659-1895	1659-1895	1659-1895	1659-1895

Notes. See notes to Table 1. $\ln(Y^{Man}/Y^{Tot})$ = share of manufacturing in total income; $Meet$ = number of parliament meetings per year; *Temp-Sep*: average temperature in September; *Temp-Dec*: average temperature in December; $Book^S$: stock of farming books. *Oster*: Oster (2019) test for an omitted variable bias, where the reported number is the coefficient of proportionality, δ. A number larger than one signifies that the included control variables are explaining a larger share of the variance in the treatment variable (farming books stock) than the excluded control variables.

3.8. **Other Controls.** As other control variables we consider the manufacturing income share, parliamentary sessions, and temperature. The estimation period starts in 1659 instead of 1525 because the average monthly temperature is first available from 1659. Estimates of the baseline regression over the period 1659-1895 are presented in column (2) in Table 4. The parameter estimates of the stock of new farming book titles and population are both highly significant and close to those of the baseline regression in column (3) in Table 1. First, consider manufacturing income share. The emerging industrial entrepreneurial middle class has often been stressed as being influential for the industrialization by shaping the institutional landscape (Acemoglu et al., 2005, 2011). Including the share of manufacturing in total GDP in the baseline regression as a proxy for the potential influence of the industrial middle class yields the estimates in column (3) in Table 4. The coefficient of the manufacturing share is insignificant, where the insignificance may reflect that the manufacturing sector was relatively small over most of the estimation period and, therefore, contained only a small identifying variation.

As an institutional variable, we include the number of annual parliamentary sessions in England. Van Zanden et al. (2012), who constructed the data, argue that parliamentary activity reflects the potential impact of parliaments on the decisions of the sovereign and other important matters relating to governance. When a sovereign needed extra money to finance costly military operations, for instance, his request for financial support from the state had to be granted by the parliament. The influence of the parliamentary activity on the R-W ratio is ambiguous a priori: A high frequency of sessions may reflect a strong opposition to the sovereign's military ambitions as most wars had to be financed through land taxes or bonds issued to the landed class. Conversely, since, during most of the period considered here, the parliament acted in the interest of the landowners, we would expect a positive effect of parliamentary sessions on the R-W ratio to the extent to which the frequency of sessions reflected the influence of the parliament on economic matters. The coefficient of session frequencies is statistically significantly positive (column (3)), indicating that, on average, the parliamentary sessions financially benefited the landed class.

Monthly average temperature is included in the regression in column (4) in Table 4. Overton (1989), for example, argues that warmer temperatures should have a positive effect on crop yields in Britain and finds that mild winters are associated with higher crop yields. Temperature for each month of the year was initially included in the regression and insignificant variables were sequentially deleted based on the general-to-specific model reduction procedure with the 10% benchmark significance level. We end up with a model in which the coefficients of temperature in September and December are significantly positive. Finally, all the control variables considered in Table 4 are included in the regression in the last column of the table except the squared R-W term. The coefficients of the R-W ratio, population, parliamentary meeting frequency, and temperature are all significantly positive, while the coefficient of manufacturing share remains insignificant.

Turning to the focus variables, the coefficients of book stock and population remain highly significant and close to those of the baseline regression in all the estimates that include control variables (columns (2)-(6) in Table 4), suggesting that the coefficients are insensitive to the inclusion of control variables. Checking for an omitted variable bias, the Oster (2019) δ-tests, where δ is the coefficient of proportionality, indicate that the coefficients of the stock of farming book titles are reasonably robust to the omission of unobserved control variables, noting that a test value greater than one signifies that the included control variables are explaining a larger share of the variance in the treatment variable than the excluded control variables. Finally, the Dickey-Fuller tests rejects the null hypothesis of no cointegration in all the estimates in Table 4. Overall, the significance and stability of the coefficients of the stock of farming stock titles and population, and the reasonably good diagnostic tests suggest that book publication and population have been important determinants of the R-W ratio during the British Industrial Revolution.

3.9. **Panel Estimates for the Pre-Industrial Period: 1265-1850.** In this section we extend the sample to five countries for which data on R, W, and agricultural labor productivity are available at least over the period 1534-1850: France (1386), the Netherlands (1500), Portugal (1534), Spain (1413) and Britain (1265), where the numbers in parentheses are the first year at which the data are available. As detailed in the online Appendix, employment in agriculture is based on population size before the early 19th century and agricultural employment thereafter. As explained above, agricultural labor productivity is a good measure of the evolution of technology. The relationship between relative factor payments and labor productivity in agriculture is tested as follows:

$$\ln(R/W)_{it} = e_0 + e_1 \ln(Y/L)^{Agr}_{it} + e_2 \ln Pop_{it} + CD + TD + v_{5it} \tag{29}$$

where $(Y/L)^{Agr}$ is real agricultural labor productivity; CD are country dummies; and TD are time-dummies, and the starting year is 1386, which is the first year in which at least two countries are included in the sample (Britain and France). Population is not only included in the regressions because of its independent effect on the outcome variables but also to deal with endogeneity. Technological progress increases wages and, through the Malthusian mechanism, population;

thus, resulting in a decrease in the Y-L ratio. This feedback effect is avoided when population is controlled for.

The results of regressing (29) are displayed in Table 5. In columns (1) and (3), we find that the coefficients of population are highly significant regardless of whether agricultural productivity is included in the model. The coefficient of population declines by 24% when agricultural productivity is added to the model, suggesting that neutral technological progress affects the R-W ratio through population pressure. The estimation period is narrowed down to 1600-1800 in the regressions in columns (3)-(4), during which period the technological progress in agriculture started to gain momentum in the pre-industrial period. The coefficients are slightly smaller than the estimates covering the full period 1265-1850. Again these estimates show that technological progress in agriculture creates inequality under the Malthusian regime; land owners gain from technological progress, directly and indirectly via population growth. Based on the coefficients of column (2) in Table 3, of the 129.5% increase in the R-W ratio in Britain during the 18th century, agricultural productivity advances explain 45.8% while population growth explains 36.9%, suggesting that technological progress in Britain was quantitatively influential for the increase in income inequality during this period.

In the regressions in the last three columns in Table 5 we allow for institutional factors that may have affected the evolution of the R-W ratio. In the regression in column (5) we include a shift-dummy that takes the value of one over the period 1808-1850 and zero elsewhere for the countries in our sample that adapted the Napoleonic Code, viz., France, the Netherlands, Portugal and Spain. Thus, Britain is the only country in our sample that did not explicitly adapt the Napoleonic Code. The imposition of the Napoleonic Code could potentially have influenced the trajectory of the R-W ratio because it undermined the aristocratic privileges and instituted equality before the law (Acemoglu et al., 2011).

The coefficient of productivity remains significantly positive at the 1% level, and the coefficient of Code is significantly negative at the 1% level, giving some indication that Napoleonic Code reduced income inequality. However, a potential problem with this result is that it may not have been the Code that differentiated Britain and the other countries after 1808 in our sample. Instead, the British Corn Laws, which were in effect over the period 1815-1846 imposed severe pecuniary penalties on corn imports to protect the interests of the British landowners. The coefficient of Code becomes insignificant at conventional levels if a dummy taking the value of

Table 5. R-W Ratio and Agricultural Productivity: European Sample 1265-1850

	1	2	3	4	5	6	7
Dep. Var.	$\ln(R/W)$	$\ln(R/W)$	$\ln(R/W)$	$\ln(R/W)$	$\ln(R/W)$ Nap. Code	$\ln(R/W)$ Atl. Trader	$\ln(R/W)$ Atl. Trader
Est. Per.	1265-1850	1265-1850	1600-1800	1600-1800	1600-1850	1600-1800	1600-1850
$\ln(Y/L)^{Agr}$		0.85***		0.70***	0.46***	0.73***	0.43***
		(10.2)		(10.4)	(6.10)	(5.04)	(4.51)
$\ln Pop$	1.58***	1.20***	1.26***	0.94***	0.44**	1.00***	0.42
	(16.3)	(12.6)	(6.04)	(4.98)	(2.21)	(3.34)	(1.60)
Code					-0.43***		
					(4.14)		
Oster		1.79		1.01	0.36	3.21	0.01
R^2	0.88	0.89	0.97	0.98	0.97	0.98	0.97
Obs.	2103	2103	1005	1005	1255	1005	1255

Notes. The data in parentheses are absolute t-values based on heteroscedasticity and serial correlated robust standard errors. Time and country fixed effects dummies are included in all the regressions. The following five countries are included in the estimates: France (1386), the Netherlands (1500), Portugal (1534), Spain (1413), and Britain (1265), where the numbers in parentheses are the first year at which data are available. *Code*: a dummy variable taking the value of 1 when the Napoleonic Code is adopted (1 for France, the Netherlands, Portugal and Spain after 1808 and zero before then). The regressions in the 'Atl. Trade' columns include the interaction between the time-dummies and the ratio of coastline and country area; however, the parameter estimates are not shown due to the abundance of coefficient estimates. *Oster*: Oster test for an omitted variable bias, where the reported number is the coefficient of proportionality, δ. The observed control variables are the time-dummies and the interaction between the time-dummies and Atlantic traders. Significance at *10%, **5%, ***1% levels.

one for the UK during the period in which the Corn Laws were in place and zero elsewhere is included in the regression. The Corn-Laws dummy, however, is significantly positive at the 5% level, signifying that such policies can be influential for income inequality (the results are not reported in the table). The insignificance of the coefficient of Code when a corn-law dummy is included, however, needs not to be regarded as evidence against the hypothesis of Acemoglu et al. (2011) of the positive impact of the institutional changes in the states that adopted the Napoleonic Code. Our sample is simply too limited to resolve this issue. All countries in our sample were affected by the Napoleonic Code to varying degree.

Thus far we have disregarded the influence of institutional variables on the R-W ratio. We allow for the influence of institutional factors on inequality by checking whether constraints on the executive (the monarch) reduced the exploitative power of the landed class and, hence, income inequality. Acemoglu et al. (2005), for example, argue that pre-industrial growth in Atlantic trade strengthened the merchant class by constraining the power of the monarchy, which in turn aided the adoption of institutions that protected property rights. Following Acemoglu et al. (2005), we allow for the effects of Atlantic trade on the R-W ratio by extending the baseline regression by the interaction between time-dummies and the coastline-to-land area ratio. The regression results, which are presented in columns (6) (1600-1800) and (7) (1600-1850), show that the principal results are unaffected by the inclusion of trader interaction effects.

Finally, to check for the possibility of omitted variables bias of the coefficient of agricultural labor productivity, we undertake the tests of Oster (2019). For the regression in column (6), Table 5, the Oster (2019) test gives the value of $\delta = 3.21$, suggesting that unobserved, omitted control variables would, under the proportionality assumption, have to be 3.2 times more important in explaining the variation in the agricultural productivity than the included control variables. Since the time-dummies and the interaction-terms have captured a large fraction of the variation in the data, it is reasonable to assume that these terms are at least as important as the unobservables. It is, therefore, unlikely that the positive productivity effects in this regression are driven by omitted variables bias. The coefficients of proportionality in the regressions in columns (2) and (4) in which the traders-interaction terms are excluded, are higher than 1; thus giving further support to the finding in column (6) that the coefficient of productivity is not significantly biased due to omitted variables.

However, the Oster-tests in the regressions covering the period 1600-1850 in columns (5) and (7), indicate that the coefficients of agricultural productivity are likely to be subject to an omitted variable bias. For the regression in column (5), in which the Napoleonic Code and time-dummies are the observed control variables, we obtain $\delta = 0.36$. In the regression in column (7), in which the time-dummies and the interaction between the time-dummies and Atlantic traders are the observed control variables, we obtain $\delta = 0.01$. The bias of the coefficient of agricultural productivity is likely to be in a downward direction as the coefficient is in the range of 0.70-0.85 in the regressions in which $\delta > 1$, while it is in the range of 0.43-0.46 in the estimates in which $\delta < 1$. In all events, the marked decline in the coefficients of proportionality when we expand the sample from the period 1600-1800 to the period 1600-1850, suggest that something is happening over the period 1800-1850 that is not captured by the political economy variables and the other variables included in the model.

3.10. **Panel Estimates for the Post-1800 Period.** In this sub-section we estimate the *R-W* model over the periods 1800-1920 and 1920-1980, where the benchmark year 1920 represents the year in which the fertility transition is well underway in most countries in our sample and is immediately after a sharp decline in the agricultural share in total GDP from 18% in 1910 to

10% in 1920. The period 1800-1920 represents the Post-Malthusian regime in which population growth is high but the transition towards the modern growth regime has started along with the fertility transition. The last year of the second period 1920-1980, signifies the entrance into the post-industrial regime; a period during which the manufacturing share of employment and GDP is on a declining trajectory.

The following models are estimated for seven OECD countries for the periods 1800-1920 and 1920-1980:

$$\ln(R/W)_{it} = f_0 + f_1 \ln S_{it}^{Pat} + f_2 D_i^{Fet} \ln S_{it}^{Pat} + CD + TD + v_{6it} \tag{30}$$

$$\ln(R/W)_{it} = g_0 + g_1 \ln(Y/L)_{it}^{Agr} + g_2 D_i^{Fet} \ln(Y/L)_{it}^{Agr} + CD + TD + v_{7it} \tag{31}$$

where S^{Pat} is the patent stock, based on the perpetual inventory method and a 15% depreciation rate; and D_i^{Fet} is a dummy variable taking the value of zero before the onset of the fertility transition of country i and one afterwards. The dates for the onset of the fertility transition are taken from Reher (2004). The country sample consists of Belgium, Denmark, France, Ireland, Spain, Britain, and the US.

Ideally, we would have preferred to use agricultural patents instead of the overall number of patents filed by residents as technology indicators; however, we resorted to the overall number of patents because hardly any data on agricultural patents are available. Although the total number of patent applications filed by residents is not a perfect proxy for technological progress of farming, they allow for knowledge spillovers from the manufacturing sector and, furthermore, are unlikely to be much affected by feedback effects from the dependent variable. The use of labor productivity in agriculture as an alternative measure of technology has the advantage of referring directly to agriculture and, as such, to impact directly on land rent.

According to our model, technology-driven inequality in the pre-industrial era gradually disappears along with increasing returns to education and the associated fertility transition. The withering of the Malthusian trap derails the positive relationship between the R-W ratio and technological progress, leading to a counterbalancing effect from increasing real wages on the increasing real rent. Thus, in (30) and (31) we expect $(f_1, g_1) > 0$, capturing the influence of technology before the onset of the fertility transition. After the onset of the fertility transition, we expect technological progress to reduce population growth and to increase human capital accumulation. The sign of the coefficients (f_2, g_2) are, however, a priori indeterminate and depend on the elasticity of substitution between labor and land, the speed of the fertility transition, and human capital accumulation.

The coefficients of technology may be potentially upward biased, because an increase of the R-W ratio and, therefore, in the profitability of land, may promote agricultural investment that eventually results in higher labor productivity. To address this issue, we use genetic-distance-weighted foreign patent stock for 21 OECD countries as an instrument for the domestic patent stock. There is strong evidence of international technology transmission and that genetic proximity is one of the most important channels of transmission, as shown by Madsen and Farhadi (2018). This identification strategy assumes that the foreign patent stock contains technology and knowledge that is useful for agriculture. Although not all innovations had direct use in agriculture, they had indirect effects through new processes in manufacturing, such as new machinery that is associated with the mechanization of agriculture starting in the early 20th century, the worldwide expansion of synthetic fertilizer, and international breeding programs. The advantage of this identification strategy is that there is unlikely to be any feedback effects from domestic productivity advances in agriculture to the foreign patent stock. The downside of our identification strategy is that the instrument does not specifically target technologies and methods that are useful for agriculture and, as such, potentially violate the exclusion restriction. We limit the IV regressions to the regressions in which patent stock is used as the regressor because genetic proximity weighted foreign agricultural labor productivity turned out to be a weak instrument for domestic productivity. Furthermore, we lag the instrument 5 years to allow for time-lags in technology diffusion.

Estimated from the following weighting scheme, genetic-distance-weighted foreign patent stocks are used as instruments for domestic patent stock:

$$S_{it}^{IV,Pat} = \sum_{j=1,j\neq i}^{21} \sqrt{\frac{1}{D_{ij}^{gen}}} S_{jt}^{Pat}, \tag{32}$$

where D_{ij}^{gen} is the genetic distance between countries i and j, measured as the distance between ethnic groups with the largest shares of the population in each country in a pair (denoted F_{ST} by Spolaore and Wacziarg, 2009), and normalized by the average distance in the sample so that the weights sum to one. The weighting scheme is assumed to be inversely related to the square root of distance to ensure that long distances get higher weights than in the case in which $1/D^{gen}$

is used as weights. Patent stocks for the 21 OECD countries, listed in the online Appendix, are used to create country i's instrumented patent stock.

3.11. **Estimates for the period 1800-1920.** The results of estimating (30)–(31) over the period 1800-1920 are shown in Table 6. The F-test for exclusion restrictions, presented in the lower panel of the table, is high; thus rendering the bias introduced by the instruments in the second-stage regressions low. The coefficients of technological knowledge, S^{pat} and $(Y/L)^{Agr}$, and population are significantly positive in all seven cases. The coefficient of technology is lower in the IV-regression (column (2)) than the baseline OLS regression in column (1). Although the IV results should be interpreted with caution because foreign patents are not ideal instruments, the results indicate that the coefficient of technology in the OLS regressions are likely to be biased upward. The coefficients of the interaction between knowledge stock and the post-fertility-transition dummies, D^{Fet}, are significantly negative in all cases, suggesting that the fertility transition gradually diluted the positive effects of technological progress on the R-W ratio. The coefficients of productivity and population are in the plausible ranges and comparable to the regressions in the previous subsections. The coefficients of labor productivity are on average 0.54, which are lower than the average of 0.63 in the long-run regressions in Table 5, but the gap is not large. These estimates indicate that the approximately 100% increase in labor productivity in Britain during the 19th century, resulted in a 50 to 63% increase in the R-W ratio and, therefore, was a major force behind increasing inequality in Britain during the same period – an increase that was exacerbated by the population expansion. Finally, the coefficients of population are significantly below one, reinforcing the findings from above of an elasticity of substitution between land and labor that is larger than one.

Allowing for the influence of institutions, we extend the regressions by the interaction between time-dummies and the coastline-to-land area ratio, following the analysis of Acemoglu et al. (2005). The regression results, which are presented in columns (5) (patents) and (6) (agricultural labor productivity), show that the principal results are, to a large extent, unaltered by the inclusion of coastline-area interaction effects. Excluding the Napoleonic war years, the interaction effects are trending downwards throughout the estimation period (the results are not shown), indicating that Atlantic trade resulted in reduced inequality; potentially by promoting lower tariffs on imports of grain from the New World that resulted in reduced grain prices and, therefore, reduced land rent. As an additional test for the influence of institutions, we extend the baseline regression with the share of agriculture in total income in columns (3) and (5) as the landed class is more likely to influence the income distribution in their favor the larger is its share of the political and economic elite. The introduction of the Corn Laws in 1815 in the UK was only possible because the landed class had the upper hand in the parliament. However, the Corn Laws were repealed as the position of the landed class weakened. As expected, the coefficients of the agricultural share are significantly positive.

TABLE 6. R-W Ratio and Innovations: 1800-1920

	1	2	3	4	5	6
Dep. Var.	$\ln(R/W)$	$\ln(R/W)$	$\ln(R/W)$	$\ln(R/W)$	$\ln(R/W)$	$\ln(R/W)$
	OLS	IV	OLS	OLS	OLS	OLS
					Atl. Traders	Atl. Traders
$\ln S^{Pat}$	0.63***	0.33***	0.67****			0.35***
	(13.4)	(3.66)	(14.1)			(3.30)
$D^{Fet} \ln S^{Pat}$	-0.30***	-0.05 ***	-0.32***			-0.27***
	(4.16)	(8.48)	(4.51)			(3.72)
$\ln(Y^{Agr}/Y^{Tot})$			0.33***		0.33***	
			(4.06)		(4.61)	
$\ln(Y/L)^{Agr}$				0.06***	0.05***	
				(3.07)	(2.66)	
$D^{Fet} \ln(Y/L)^{Agr}$				-0.04***	-0.05***	
				(6.99)	(7.35)	
$\ln(Pop)$	0.29***	0.84***	0.56***	0.71***	0.93***	0.72***
	(2.91)	(9.17)	(4.93)	(10.9)	(11.2)	(11.2)
Oster	1.64		1.67	6.96	8.67	6.02
R^2	0.96		0.98	0.98	0.98	0.99
Period	1800-1920	1800-1920	1800-1920	1800-1920	1800-1920	1800-1920
Obs.	668	668	668	668	668	668
			First Stage			
$\ln S^{Pat}$		0.95***				
		(11.2)				
F		124.8				
R^2		0.96				

Genetic distance weighted patent stock lagged five years is used as an instrument for S^{Pat}, see Eq. (32). The following countries are included in the regressions: Belgium, Denmark, France, Ireland, Spain, Britain, and the US. S^{Pat} = stock of patent applications of residents based on the perpetual inventory method with 15% depreciation rate; and $(Y/L)^{Agr}$ = labor productivity in agriculture. $Oster$ = Oster (2019) test for an omitted variable bias, where the reported number is the coefficient of proportionality, σ. The observed control variables are the time-dummies and the interaction between the time-dummies and Atlantic traders. Significance at *10%, **5%, ***1% levels.

Finally, we undertake Oster (2019) tests for omitted variables bias of the coefficient of the interaction between the fertility transition dummy variable and agricultural labor productivity (or patent intensity). In addition to the agricultural income share, the time-dummies and, in the relevant regressions, the interaction between the time-dummies and Atlantic traders are the observed controls. The coefficients of proportionality, δ, are generally sufficiently high not to raise concern. Unobserved, omitted control variables would, under the proportionality assumption, have to be 1.15 to 8.67 times more important in explaining the variation the fertility transition dummy variable and the agricultural labor productivity (patent stock) than the included control variables. Thus, the treatment focus variable is unlikely to have been subject to a serious omitted variables bias. Overall, the results in Table 6 give further empirical support for our hypothesis that technological progress is a main driver of inequality before the onset of the fertility transition and that its impact on inequality reverses after the fertility transition.

3.12. **Estimates for the period 1920-1980.** The results of estimating (30)-(31) over the period 1920-1980 are shown in Table 7. The F-test for excluded restrictions, which is presented in the lower panel of the table, is 7.8, suggesting that the relevance criterion is not satisfied and, consequently, that the results in the second-stage regression need to be interpreted with caution. The coefficients of technology, S^{pat} and $(Y/L)^{Agr}$, are insignificant in both the baseline OLS and IV regressions, which, consistent with our theory, suggests that the positive impact of agricultural technological advances on the R-W ratio is broken. The coefficients of the interaction between technology and the fertility-transition dummies, D^{Fet}, are also insignificant at any conventional significance levels. These results are again consistent with our theory. Technological progress induces education and human capital accumulation. For an elasticity of substitution close to one, increasing human capital would not affect the R-W ratio significantly. Finally, the principal results remain unaltered when the share of agriculture in total income is included in the model.

3.13. **Allowing for Political Economy Variables in the 1920-1980 Estimates.** The period 1920-1980 was a turbulent period in terms of wars, depressions, and labor unrest, suggesting that forces other than technological advances in agriculture must have played a role for the evolution of the R-W ratio; particularly political economy variables that affect the strength of the labor movement vis-a-vis the landed and capitalist classes in the struggle over income distribution. Domestic and foreign union strength are potential threats to the autocratic elites (i.e., industrialists and landowners) through internal and external forces. Foreign union strength is likely to constitute a threat to the landowners and the industrialists. They may fear that a strong international labor movement would alert the domestic labor movement to the potential pecuniary and political gains from organized labor. The research of Aidt and Jensen (2014), Aidt and Franck (2015) and Madsen et al. (2015), for example, has shown that democratic reforms transmit internationally by motivating the elite, as preemptive measures in the face of organized

Table 7. R-W Ratio and Innovations: 1920-1980

	1	2	3	4	5	6
	OLS	IV	OLS	OLS	OLS	OLS
Dep. Var.	$\ln(R/W)$	$\ln(R/W)$	$\ln(R/W)$	$\ln(R/W)$	$\ln(R/W)$	$\ln(R/W)$
$\ln S^{Pat}$	-0.09 (1.10)	-1.94 (1.14)	-0.13 (1.77)*			
$D^{Fet} \ln S^{Pat}$	0.00 (0.26)	-0.01 (1.01)	0.00 (0.07)			
$\ln(Y/L)^{Agr}$				0.01 (0.10)	0.01 (1.53)	0.16 (1.78)*
$D^{Fet} \ln(Y/L)^{Agr}$				-0.01 (0.32)	-0.01 (1.45)	0.02 (0.57)
$\ln(Y^{Agr}/Y^{Tot})$			-0.30 (3.34)***		-0.03 (3.48)***	-0.38 (4.33)***
$\ln Union$			-0.04 (0.74)			-0.02 (0.35)
$\ln Comm^F$			-0.57 (1.26)			-0.45 (0.98)
$\ln(L^{Man}/L^T) \ln Comm^F$			-0.18 (4.27)***			-0.20 (4.40)***
$Oster$	0.13		0.02	0.01	0.06	0.03
Period	1920-1980	1920-1980	1920-1980			1920-1980
R^2	0.93	0.93	0.93	0.93	0.93	0.86
Obs.	427	427	427	427	427	427
			First Stage			
$\ln S^{Pat}$		0.62 (2.79)***				
R^2		0.99				
F		7.79				

See notes to Table 6. Union = unionization. Comm = communist influence

opposition, to undertake democratic reforms. In the same spirit, Madsen et al. (2018) use external communist threat as an instrument for inequality because of the preemptive measures taken by the elite against the threat of revolt or a fully fledged revolution. [11] Domestic unions, which may well have gained their strength and inspiration from international union movements, impact directly on wages by extracting greater shares of the rent by direct action (strikes), through negotiations and being a threat to the landed class and industrialists through their potential to organize a labor revolt such as the Russian Revolution.

Following Aidt and Jensen (2014), Aidt and Franck (2015) and Madsen et al. (2018), we include communist threat, unionization and the interaction between communist threat and the manufacturing employment share as control variables in the regressions of Table 7. Unionization is measured by the share of the employed that are members of unions. We include the interaction between communist threat and manufacturing employment shares because the communist threat is more likely to influence the income distribution when the urban working class is large. We use the external communist threat index constructed by Madsen et al. (2018). The index is based on 111 countries for which a dummy takes the value of one for countries with communist

[11]The Bolshevik-led Russian Revolution, for example, gave the impetus for the worldwide syndicalist successes in the wave of labor unrest following WWI and resulted in syndicalist-lead strikes and labor uprising across Europe and Latin America (Collier, 1999). The heightened working-class pressure in Germany, Belgium, Sweden and Finland "was surely activated as much by the Russian Revolution as by World War I. From the side of the working class, what perhaps changed most was not the greater force of its pro-democratic agitation, but the revolutionary rather than the democratic example of the Russian Revolution" (Collier, 1999, p. 78-79).

governance and zero otherwise. The composite index is a weighted average, where the weights are the population size, multiplied by linguistic proximity as a proxy for culture. Thus, communist influence is an increasing function of 1) the number of countries that are formally ruled by communist governments; 2) the more populous the communist country is; and 3) the linguistically closer country i is to a country j under communist rule.

The results of including the political economy variables in the baseline regressions are displayed in columns (3) and (6). The coefficients of the interaction between the manufacturing income share and communist threat are significantly negative in both regressions, indicating that a communist threat increases the relative bargaining power of workers when the manufacturing working class is a sufficiently large relative to the total labor force. The coefficient of the agricultural share is also statistically significant but, in contrast to the pre-1920 regressions, it is negative - a negativity that is not easy to explain and it cannot be ruled out that the negativity is due to omitted variables bias. In fact, all the Oster tests in Table 7 point toward omitted variables. However, the extent to which the coefficients are biased has no bearing on the validity of our hypothesis as the coefficients of technology can take any value and still be consistent with our model. The low coefficients of proportionality do suggest that the R-W-model is not well specified for the post-1920 period.

4. Conclusion

In this paper we proposed a new theory on the evolution of inequality in the very long run. We implemented the common wisdom that, in a pre-industrial world, workers do not benefit from technological progress because Malthusian "checks" cause income to return to subsistence level in the long run, and we extended the basic model by adding a landed elite who earns land rents above subsistence level. Inequality, measured by the rent-wage ratio, is then increasing with economic development, directly through land-biased technological change and indirectly through population growth. Using data on new titles of farming books in Britain 1515-1895, as a direct measure of available technology, we showed that about 45 percent of the increase of inequality can be explained by land-biased technological change and about 20 percent by population growth, which in turn is, to a large degree, explained by technological change.

Eventually, however, technological progress initiates a fertility transition and the associated take-off of education. If the elasticity of substitution between labor and land is greater than one, inequality reaches a peak shortly after the onset of the fertility transition and declines with the subsequent human capital accumulation and increasing wages. Using a panel of OECD countries and patents over the period 1800-1980 (and, alternatively agricultural productivity) as a measure of technology we find support for a technology-driven inequality reversal around the time of the onset of the fertility transition.

By devising a theory of inequality in the very long run that comprises stages of development from Malthusian stagnation to modern growth, this paper has contributed to a better understanding of why technological progress in agriculture in pre-industrial societies has favored the landed class and, in particular, resulted in the reversal of inequality during the fertility transition. Other, complementary suggestions have attributed the historical inequality reversal of the now-developed countries to globalization and declining land rents (O'Rourke and Williamson, 2005), income taxes and income tax progressions (Roine et al., 2009), and communist threats (Madsen et al., 2018b). It can be argued, however, that these mechanisms are largely country- and situation-specific and perhaps provide less external validity for the understanding of inequality in contemporaneous developing countries. Furthermore, these mechanisms provide little guidance on why inequality started declining at beginning of the fertility transition in the late 19th century. Our technology-driven mechanism proposes a unified framework in which to consider inequality trends in the very long run.

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Appendix A: Coercive Institutions

Suppose that wages and land rents with coercion are given by

$$W_t^C = (1-\omega_t)W_t \tag{33}$$

$$R_t^C = R_t + \omega_t W_t, \tag{34}$$

in which W_t and R_t are the marginal product of labor and land as in (2) and (3) in the paper. With coercion, a fraction ω_t of the return on labor is paid as (extra) rent to the landowner. For $\omega_t = 0$, we have no coercion and thus the model of the paper. Proceeding as in the paper and solving the full model, we arrive at an implicit equation for population density at the Malthusian steady state:

$$\tilde{G} = (1-\omega)(1-\alpha)A_t^L A_t \left[\alpha \left(\frac{A_t^X}{A_t^L}\right)^{\psi} \left(\frac{L_t}{X}\right)^{-\psi} + (1-\alpha)\right]^{\frac{1-\psi}{\psi}} - \frac{\bar{c}}{1-\tau} = (1-\omega)G = 0, \tag{35}$$

in which G is defined as in equation (18) in the paper. Applying the implicit function theorem we obtain

$$\frac{\mathrm{d}(L_t/X)}{\mathrm{d}A_t} = -\frac{\partial\tilde{G}/\partial A_t}{\partial\tilde{G}/\partial(L_t/X)} = -\frac{\partial G/\partial A_t}{\partial G/\partial(L_t/X)} > 0, \qquad \frac{\mathrm{d}(L_t/X)}{\mathrm{d}A_t^X} = -\frac{\partial\tilde{G}/\partial A_t^X}{\partial\tilde{G}/\partial(L_t/X)} = \frac{\partial G/\partial A_t^X}{\partial G/\partial(L_t/X)} > 0,$$

These expressions are independent of ω_t and exactly the same as those of Proposition 1 in the main text. Similarly, we can prove Lemma 1 and Proposition 2. Formally, the reason for independence is that $(1-\omega_t)$ cancels out in partial derivatives in the numerator and the denominator. Intuitively, higher ω_t reduces population density at the steady state since, due to the coerced lower wages, there is lower off-steady-state fertility than in the simple model (and thus the steady state population level is lower):

$$\frac{\mathrm{d}(L_t/X)}{\mathrm{d}\omega} = -\frac{\partial\tilde{G}/\partial\omega}{\partial\tilde{G}/\partial(L_t/X)} < 0.$$

But since labor productivity is higher with fewer workers, there is also a lower level of technology needed to ensure that fertility is at replacement level at the steady state:

$$\frac{\mathrm{d}A_t}{\mathrm{d}\omega} = -\frac{\partial\tilde{G}/\partial\omega}{\partial\tilde{G}/\partial A} < 0.$$

These two effects balance each other such that the association between population density and technology, and thus the association between the rent–wage ratio and technology at the Malthusian steady state, is independent of ω_t. Of course, coercion influences other variables of the model, in particular, it increases the rent-wage ratio. The association between the rent-wage ratio and the level of technology, however, remains unaffected.

Appendix B: Physical Capital

Physical capital, K_t, can be integrated meaningfully by writing aggregate output as a nested CES production function:

$$Y_t = A_t \left\{\alpha(A_t^X X)^{\psi} + (1-\alpha)\left[\lambda(A_t^L L_t h_t)^{\epsilon} + (1-\lambda)(A_t^K K_t)^{\epsilon}\right]^{\frac{\psi}{\epsilon}}\right\}^{\frac{1}{\psi}} \tag{36}$$

The previous simple version is contained as a special case for $\lambda = 1$. A plausible assumption for a modern economy is $\sigma \geq 1$ and $\sigma_K \equiv 1/(1-\epsilon) \leq 1$. Then, human capital and physical capital are complements in production but both together are a substitute for land. Industrialization is then conceptualized as increasing physical and human capital, which gradually substitute for land as an important production factor (the land share goes to zero).

Nevertheless, for the wage-rent ratio, all results from the simple model remain valid. To see this take the derivatives of (36) with respect to X and L_t and arrive at (4). The concrete slope of the adjustment path, is formed by the assumptions about the size of ψ, ϵ, α, and λ. Notice that the wage-rent ratio is not affected by assumptions about who the owners of physical capital are. A minimal-invasive introduction of capital accumulation is thus that capital formation is a linear function of aggregate output. Assuming that capital depreciates fully in one generation, this implies $K_{t+1} = sY_t$.

Blue (solid) lines in Figure A.1 show the evolution of an example economy with $\psi = 0.5$ (as in Figure 1), $\lambda = 0.6$, and $\epsilon = 0.01$, i.e. the capital-labor production function is approximately Cobb-Douglas, as in most applications of the neoclassical growth model. The initial A is adjusted such that the demographic transition starts in 1880. All other parameters are retained from the benchmark model. The main feature to note is that the extension towards physical capital preserves the key results. Technological progress is positively associated with the rent-wage ratio before the fertility transition and negatively afterwards.

The bottom panel in Figure A.1 shows the evolution of the land share and the capital share. The land share is continuously declining (from about 40 percent) and the capital share is rising towards 40 percent. These developments can be made more non-linear by re-introducing the technology-driven elasticity of substitution. We take $\psi(A)$ as specified for Figure 2 (20) and set $\epsilon = 0.05$, i.e. we allow for an elasticity of substitution between labor and capital that is slightly greater than one. Again, the initial A is adjusted such that the demographic transition starts in 1880. Figure A.2 shows the development of the economy.

The model now produces a more drastic decline of the land share and the rent-wage ratio in the 20 century as well as a mildly increasing capital share (mildly declining labor share) in the 20th century. The main qualitative features of the basic model are preserved.

Figure A.1: Long-Run Productivity and Inequality: Physical Capital Accumulation

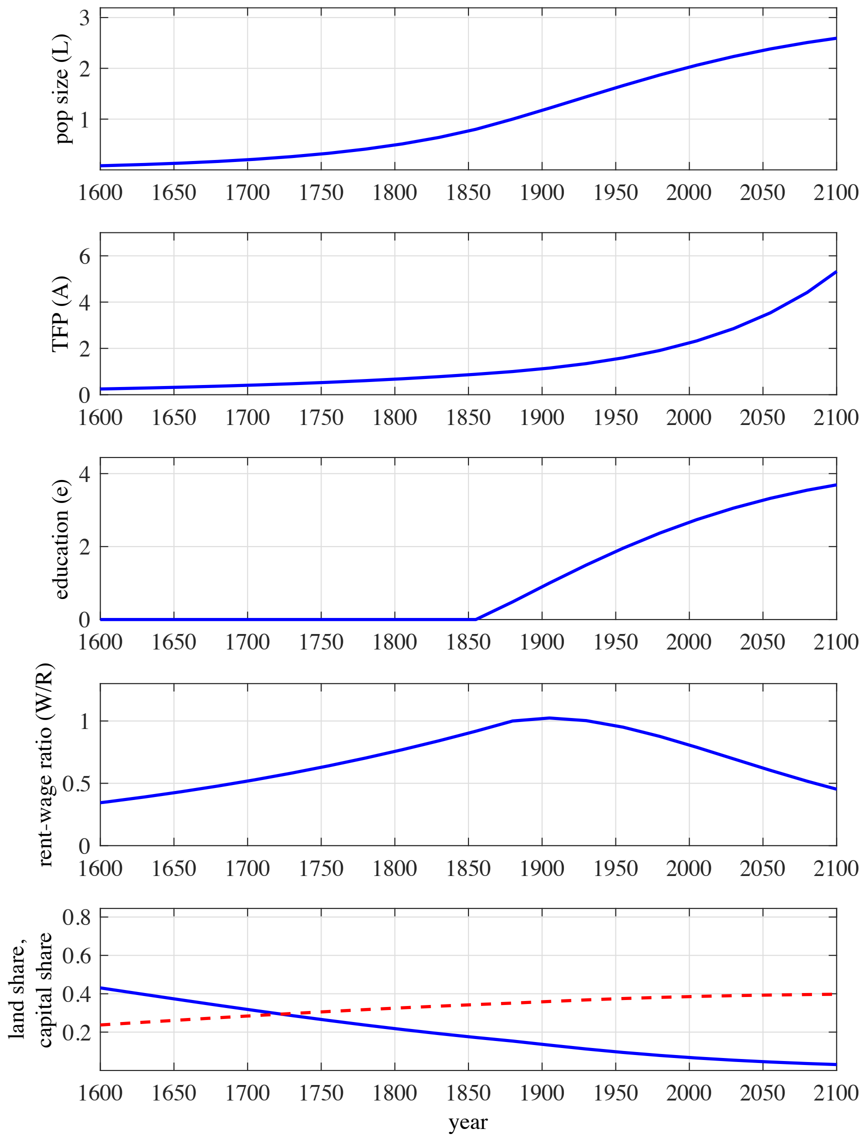
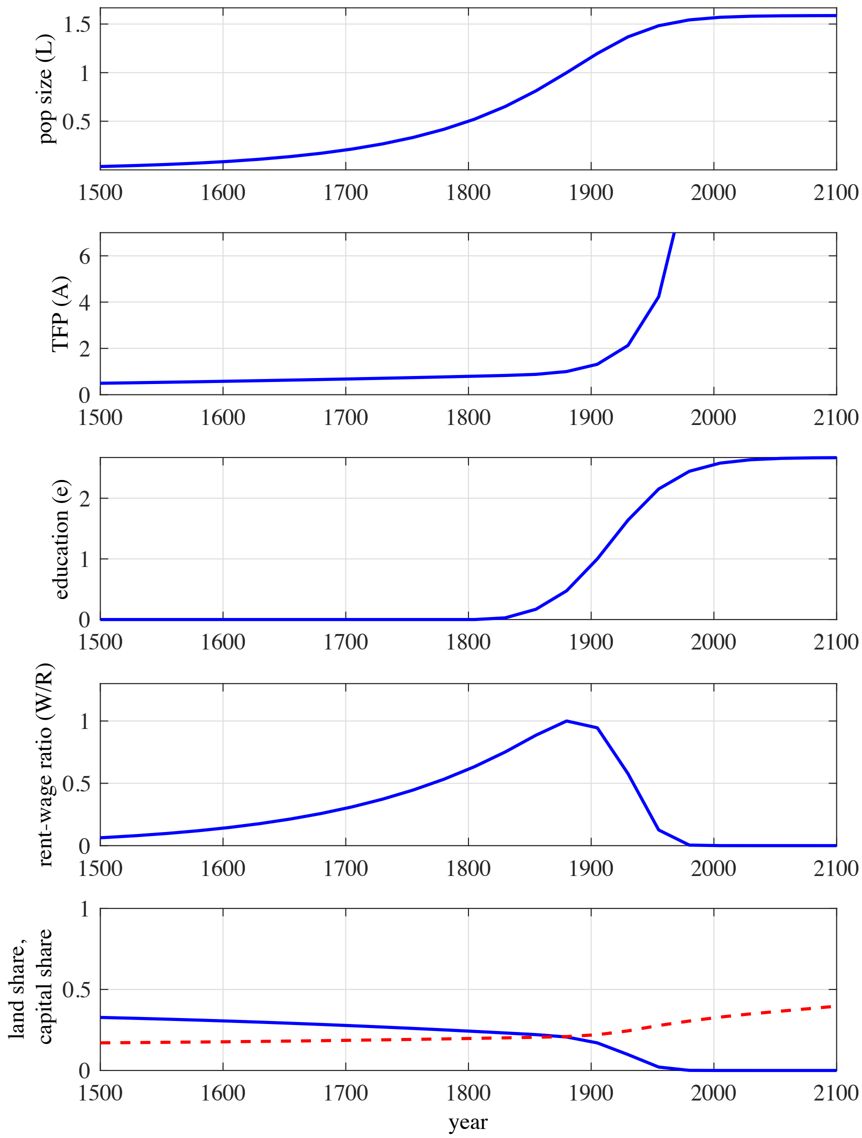


Figure A.2: Long-Run Productivity and Inequality: Capital Accumulation and Varying ψ



Appendix B

Table B.1: Summary Statistics

	N	Mean	St. Dev.	Min.	Max.
Britain 1525-1895					
$\ln(R/W^{Agr})$	371	-2.59	0.85	-4.47	-1.46
$\ln(R/W)$	371	-0.78	0.61	-2.11	0.07
$\ln(Book^{P})$	371	3.63	1.38	0.69	5.86
$\ln(Book^{S})$	371	6.92	2.4	0	9.97
$\ln(Pop)$	371	9.38	0.55	8.42	10.58
European Countries 1265-1850					
$\ln(R/W)$	2103	0.41	1.67	-3.14	4.24
$\ln(Y/L)^{Agr}$	2103	-0.63	1.46	-3.74	0.91
$\ln(Pop)$	2103	8.71	0.92	6.86	10.5
OECD Countries 1800-1980					
$\ln(R/W)$	1267	3.18	1.83	-.036	5.84
$\ln(S^{Pat})$	1267	7.10	4.48	-6.21	13.1
$\ln(Y/L)^{Agr}$	1267	0.94	1.16	0.65	5.47
$\ln(Pop)$	1267	9.60	1.23	6.98	12.3