Physiological Constraints and Comparative Economic Development*

Carl-Johan Dalgaard† Jakob B. Madsen‡ and Holger Strulik**

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Abstract. It is a well known fact that economic development and distance to the equator are positively correlated variables in the world today. It is perhaps less well known that as recently as 1500 C.E. it was the other way around. The present paper provides a theory of why the 'latitude gradient' changed sign in the course of the last half millennium. In particular, we develop a dynamic model of economic and physiological development in which households decide upon the number and nutrition of their offspring. In this setting we demonstrate that relatively high metabolic costs of fertility, which may have emerged due to positive selection towards greater cold tolerance in locations away from the equator, would work to stifle economic development during pre-industrial times, yet allow for an early onset of sustained growth. As a result, the theory suggests a reversal of fortune whereby economic activity gradually shifts away from the equator in the process of long-term economic development. Our empirical results give supporting evidence for our hypothesis.

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†Department of Economics, University of Copenhagen, CAGE and CEPR. Øster Farimagsgade 5, Building 26, DK-1353 Copenhagen, Denmark; email: carl.johan.dalgaard@econ.ku.dk.
‡ Department of Economics, University of Western Australia. 35 Sterling Hwy., Crawley, WA 6009, Australia; email: jakob.madsen@uwa.edu.au
** Department of Economics, University of Goettingen. Platz der Goettinger Sieben 3, 37073 Goettingen, Germany; email: holger.strulik@wiwi.uni-goettingen.de

1. Introduction

It is a well-known regularity that economic development tends to increase as one moves away from the equator. However, this state of affairs is of relatively recent origin. As shown below, in circa 1500, per capita income, proxied by population density, was negatively correlated with latitude across the world as well as within Europe; a result that was first noticed by Ashraf and Galor (2011). The objective of the present paper is to provide a theory that accounts for this remarkable 'reversal of fortune'.

This paper proposes that the intertemporally shifting latitude gradient is a consequence of differences in the physiological constraints faced by individuals at different geographical locations. The argument is anchored in an important fact from the fields of biology and physical anthropology: Individuals are inherently physically bigger (i.e. taller and heavier in terms of lean body mass) in locations farther away from the equator. This phenomenon is labeled "Bergmann's rule" in the relevant literature, after Bergmann (1847). Bergmann's rule is possibly a consequence of positive selection towards greater cold tolerance in the aftermath of the exodus from Africa some 50,000 years ago, but it could potentially have other roots as well (see discussion below). The substantive implication of this "latitude gradient in body size" is that individuals living in colder climates would end up facing higher metabolic costs of fertility, on purely physiological grounds, since these costs are increasing in the body mass of the individual. As a consequence, during pre-industrial times we would expect progressively lower levels of population density the farther we move away from the equator (see Dalgaard and Strulik, 2015). Moreover, if, in the pre-industrial era, technological change was positively influenced by population size, societies where citizens were bigger but less numerous would tend to be technologically less sophisticated, reinforcing the physiologically based reason for low economic development (see Aiyar et al., 2008, and Ashraf and Galor, 2011, for a formal discussion of the link between population density and technological change in a pre-industrial environment).

However, as technological change makes formal education more attractive, it is likely to be adopted sooner in societies where the relative costs of child quantity are greater; that is, places inhabited by bigger individuals, farther away from the equator. This is where the latitude-productivity nexus gradually begins its turnaround: As educational investments are undertaken, fertility declines and economic growth takes off. Consequently, the currently observed positive correlation between absolute latitude and development outcomes may be the product of a differentiated timing of the take-off, which provided places farther away from the equator with a developmental head start in the modern growth regime.

In support of this hypothesis, we develop a unified growth model and test its implications. The model features overlapping generations of children and adults. Adults are the economically active agents and decide on family size, the level of nutrition and schooling of the offspring as well as their own (luxury) consumption. Following Dalgaard and Strulik (2015, 2016) parents are subject to the physiological constraint that they have to cover their metabolic needs, which depend on their own body mass as well as the level of fertility. Moreover, body mass is transmitted via an intergenerational law of motion. Finally, a unique output good is produced using body size augmented labor, human capital, land, and technology.

The theory builds on three key elements. First, utility of parents is increasing in the quality and quantity of offspring as well as own consumption. There are two dimensions to child quality, which are assumed to be imperfect substitutes: nutrition and skill formation. Moreover, preferences are assumed to fulfill a 'hierarchy of needs' principle: In a time of crisis, parents will tend to adjust own (luxury) consumption more strongly than child quantity and quality. Second, the return to skill formation is increasing in the level of technological sophistication and human capital production features a non-convexity. The latter element involves the assumption that parents costlessly transmit a minimum amount of skill to the next generation, which permits a corner solution in terms of skill investments when the level of technology is sufficiently low. Third, technology evolves endogenously and depends on human capital-augmented population size.

These elements interact in the following way. At early stages of development the economy finds itself in a "subsistence regime" featuring low income and a relatively poor state of technology. Consequently, parents only invest in child quantity and the nutrition-based quality component. As technology slowly advances, however, income rises gradually despite the resource diluting influence from population. Eventually, the economy transits into a 'pre-modern regime'. The higher level of income entices the parents to start spending resources on themselves; i.e., above and beyond subsistence requirements. In addition, parents choose to increase the size of the family further. Nutritional investments also rise, but not on a per child basis. Consequently, average body mass is not increasing despite a higher level of income. Yet as technology continues to advance, now at a higher pace, the economy ultimately moves into the 'modern growth regime', where human capital investments are deemed optimal. As quality investments are intensified, individuals respond by lowering fertility, which also allows nutritional spending per child to increase and growth takes off: economically, and physiologically in the sense of increasing body mass. In the long-run the economy converges to a steady state where fertility is at replacement level, average body mass and human capital investments are constant, and economic growth occurs at a constant rate.

We use our model to conduct experiments in order to examine the causes of the shifting latitude gradient described above. Specifically, we compare societies where individuals are inherently of different body size, which potentially could have been due to selection. Before the onset of the fertility transition, societies farther away from the equator spent more on child nutrition and less on child quantity. Due to smaller family size and lower population density they developed fewer new technologies through learning by doing. The transition to modern growth arises when a critical level of technological sophistication is attained enticing individuals to commence human capital investments. This critical level of technology is declining in the average body size of individuals, since families with higher metabolic costs of fertility (child quantity) require less of an inducement to reduce fertility and to invest in child quality in the sense of human capital. Thus, societies farther away from the equator experienced the take-off to modern growth earlier and are richer today.

We test the implications of the model using pre-industrial and post-1800 data as follows. First, we show a reversal of fortune across the world as well as between the European countries anchored in the latitude gradient (Section 2). Second, using cross-country data, we examine the extent to which contemporary economic development is associated with height in 1900 while controlling for several factors that various authors have found to explain economic development, such as culture, institutions, and geographical characteristics (Section 6.1). Third, we use decennial data for Italian regions over the period 1821-2001 to test the implications of our model (Section 6.2). Fourth, we use annual panel data for the OECD countries over the period 1840-1980 to show that the fertility transition was triggered by foreign technological progress transmitted internationally through the trade channel and mediated through height (Section 6.3).

This paper is related to several strands of literature. On the theoretical side, the paper belongs to the literature on growth in the very long run (e.g., Galor and Weil, 2000; Galor and Moav, 2002; Lucas, 2002; Cervellati and Sunde, 2005; Strulik and Weisdorf, 2008; de la Croix and Licandro, 2013). In particular, the model developed below uses elements from Dalgaard and Strulik (2015, 2016) who integrated nutrition, ontogenetic growth, and physiological constraints into theories of long-run economic development. While Dalgaard and Strulik (2015) focus on the impact of physiological constraints on the cross-country distribution of income and body size in Malthusian times, and Dalgaard and Strulik (2016) focus on the take-off of average body size after the fertility transition, we show here how physiological constraints can explain the differentiated take-off to growth and a reversal of fortune. For that purpose, we extend the theory of Dalgaard and Strulik (2015, 2016) by considering education as a second channel of child quality investments and by integrating it with the canonical model of unified growth theory (UGT). The key mechanism of UGT that explains the onset of the fertility transition, mass education, and the take-off from stagnation to modern growth is based on an interaction of advancing technological progress with a child quantity-quality trade-off: Parents start investing in child education and reduce fertility when technological progress increases the return to education sufficiently strongly (Galor and Weil, 2000). By integrating UGT with the physiological model of Dalgaard and Strulik (2015, 2016) we refine the predictions of UGT with respect to regional differences in the timing of the take-off. Specifically, the integrated model predicts that countries or regions populated by bigger people, ceteris paribus, initiate the fertility transition and the take-off to growth earlier. The reason is that child costs are higher for bigger children such that the quantity-quality trade-off with respect to education kicks in already at a (somewhat) lower level of the return to education. Thus, we argue that small differences in initial conditions with respect to underlying physiological constraints are powerful enough to generate the historically observed interregional reversals.

The paper is also related to existing contributions that have aimed to explain observed reversals of fortune in history (Acemoglu et al., 2002; Olsson and Paik, 2016, 2020; Litina, 2016; Dalgaard et al., 2016). The present study differs from previous contributions on two fronts: First, we focus on the role played by absolute latitude, rather than other structural characteristics. Second, whereas previous work has focused on either institutional or cultural drivers, the present study proposes a physiological mechanism. We elaborate on the value added of the present work in the next section.

The paper proceeds as follows. In the next section we document a series of stylized facts, regarding the interrelationship between geography, body mass and economic activity that we require the model to be able to account for. Section 3 develops the model, and Sections 4 and 5 describe the development trajectory implied by the model. The empirics are presented in Section 6, and Section 7 concludes.

2. Motivating Evidence

2.1. **The Reversal Re-examined.** In this section we present evidence for the reversal of fortune: Countries close to equator reverted from being among the most developed in the world around 1500 to being among the least well-off in 2000. The regressions in the first five columns in Table 1 show the link between absolute latitude and population density, approximating the state of development around 1500. We observe a significant negative correlation between absolute latitude and population density regardless of whether continental dummies are included in the models. Population density declines by 8 percent when distance to the equator increases by one degree of latitude, implying that a move from Denmark to Greece increases population density by about 200 percent.

The relationship between latitude and population density remains negative when the sample is limited to Europe (column 4). In column 5 we include pre-1500 potential caloric yield per hectare in low-tech agriculture, Cal (1500) to control for the possibility that height may be affected by accessibility to food and, at the same time, that higher yield leads to higher population density; thus giving rise to an endogeneity bias. Consistent with our prior, the coefficient of calorie yield is significantly positive, while the parameter estimates of latitude remain comparable to the regression in column 1. Finally, results from the modern era, which are reported in the last three columns in Table 1, show the well-known positive relationship between latitude and per capita income. A move from Denmark to Greece is now associated with a 50 to 100 percent decline in per capita income, depending on which regression result from Table 1 is adopted.

In light of the results from Table 1 the question is what kind of mechanism may have driven this reversal. A classic account involves institutions. Acemoglu et al. (2002) observe a reversal of fortune across former colonies, arguing in favor of an institutional explanation. The argument is that places that were initially successful (measured by population density or urbanization rates) were more likely to be characterized by extractive institutions imposed by the colonial powers,

Table 1. Latitude and Development

	1 Pop/Area (1500) World	2 Pop(1500) World	3 Pop(1500) Europe	4 Pop/Area (1500) Europe	5 Pop/Area (1500) World	6 Y/Pop. (2000) World	7 Y/Pop. (2000) Europe	8 Y/Pop. (2000)
Abs. Lat.	-0.08***	-0.05***	-0.20***	-0.23***	-0.07***	0.03***	0.04***	0.02*
	(3.64)	(5.45)	(2.68)	(3.35)	(3.61)	(4.48)	(10.3)	(1.94)
Area		0.51***	0.71***					
		(5.45)	(2.98)					
Cal (1500)					0.47***			
					(3.18)			
R^2	0.37	0.44	0.26	0.32	0.41	0.45	0.31	0.06
Obs	131	131	37	37	129	183	183	38
Cont. FE	Y	Y	N	NA	Y	Y	N	NA

Notes: The numbers in parentheses are absolute t-statistics that are based on heteroscedasticity consistent standard errors. All the dependent variables are measured in logs. Pop/Area(1500) is the population per square km in circa 1500. Pop(1500) is the population in circa 1500. Y/Pop(2000) is per capita income in 2000 in purchasing power parity. Cal (1500) is pre-1500 potential caloric yield per hectare constructed by Galor and Özak (2016). Lat. Abs. = absolute latitude. Cont. FE is continental fixed effects. *, **, ***: significant at 10, 5 and 1% levels.

leading to a reversal in relative prosperity among former colonies. A natural question is whether institutions are implicitly responsible for the reversal of the latitude gradient.

The results in Table 1 show that the reversal of fortune also occurs within Europe, which suggests that extraction of rent from colonies with high settler mortality cannot be the only explanation for the reversal. More recent work by Olsson and Paik (2016, 2020) draws attention to a reversal involving the timing of the Neolithic revolution, whereas Litina (2016) and Dalgaard et al. (2016) observe a similar phenomenon related to soil suitability for agricultural production. Olsson and Paik (2016, 2020) argue that countries that underwent the Neolithic revolution relatively early developed extractive institutions and norms emphasizing obedience to the detriment of long-run growth. While an early Neolithic revolution allowed for a developmental head start, the cultural and institutional side effects eventually stifled development, allowing latecomers to sedentary agriculture to overtake. Litina (2016) argues that the reversal in soil quality can be explained by cultural change in favor of cooperative behavior in geographically "challenged" nations, eventually allowing them to industrialize comparatively early. Finally, Dalgaard et al. (2016) argue that rich inland soil productivity, relative to the productivity of the nearby ocean, led to less coastal orientation of economic activity early on, and thereby, to the accumulation of capabilities that were less favorable to industrialization. Accordingly, the common feature of this group of studies is a reliance on mechanisms that involve cultural change or an institutional mechanism.

A natural question is whether it is plausible that within country variations in body size (implicitly captured by absolute latitude) could influence within country long-run developments. In a recent study, Kelly et al. (2015) provide a fresh look at the determinants of the Industrial Revolution within two prominent European countries: England and France. In the case of England, the Industrial Revolution first took hold in the North, leading to a reversal of fortune since the South historically had access to richer agricultural lands. Empirically, the authors document that individuals in the North were physiologically relatively bigger than in the South. Kelly et al. (2015) explain the latter fact by persistent differences in the organization of production and a more nutritious diet. In the case of France, the authors also detect a significant link between body size and the timing of the Industrial Revolution. Moreover, people are indeed bigger, on average, in the Northern part of France. Hence, in the case of these forerunner countries of the Industrial Revolution, one observes differences in physiological development prior to the take-off, which have predictive power vis-a-vis subsequent comparative regional development. In Section 6.2 we scrutinize the physiological explanation of the reversal of fortune across the regions of Italy.

2.2. **Geography and Physiology.** In biology, Bergmann's rule (Bergmann, 1847) is a well established regularity with bearing on body size for (most) mammalian species. The rule states that average body mass (kg) of individuals is increasing in the distance to the equator. In the context of the human species, support is found in Gustavson and Lindenfors (2009) among others. However, to have bearing on the reversal documented above, the latitude gradient needs to be apparent across countries and not just across indigenous societies, which has been the favored unit of analysis in the relevant empirical literature within physical anthropology.

Table 2. Cross-Country Evidence of Bergman's Rule, 1500 and 1900

	1	2	3	4	5	6	7	8	9	10	11	12
	H(1500)	H(1500)	BM(1500)	BM(1500)	H(1900)	H(1900)	H(1900)	H(1900)	H(1900)	H(1500)	BM(1500)	H(1900)
	World	World	World	World	World	World	Europe	Adj. World	Adj. Europe	World	World	World
Abs. Lat.	0.09***	0.06**	0.004***	0.002	0.001***	0.001***	0.002***	0.001***	0.001***	0.010***	0.032***	0.009***
	(5.65)	(2.76)	(5.24)	(1.42)	(7.60)	(5.12)	(6.65)	(5.48)	(4.41)	(5.32)	(5.34)	(7.73)
Cal(1500)										0.000	0.007	
										(0.07)	(0.94)	
Cal(1900)												0.001
												(1.55)
Cont. FE	N	Y	N	Y	N	Y	NA	Y	NA	N	N	Y
R^2	0.34	0.46	0.39	0.55	0.24	0.61	0.57	0.61	0.34	0.33	0.36	0.60
Obs.	49	49	33	33	197	197	41	159	37	44	30	197

Notes: The numbers in parentheses are absolute t-statistics that are based on heteroscedasticity consistent standard errors. Height and body mass are measured in logs. $H(1500)$ is the height of the pre-1500 birth cohort. $H(1900)$ is the height of the 1900 birth cohort. $BM(1500)$ is the body mass of the pre-1500 birth cohort. Adj. World and Adj. Europe indicate that the absolute latitude is ancestry-adjusted. Cal (1500) and Cal (1900) are the pre-1500 and post -1500 potential caloric yield per hectare constructed by Galor and Özak (2016). Cont. FE is continental fixed effects. *, **, ***: significant at 10, 5 and 1% levels.

The first four columns of Table 2 report the results, with and without continental fixed effects, from regressing height and body mass in the pre-1500 period absolute latitude. The coefficients of latitude are significant in three cases, but insignificant in the regression where body mass is the dependent variable and continental fixed effects are included in the model, where the insignificance presumably reflects a small-sample problem. Accordingly, to further examine the cross-country viability of Bergmann's rule we employ height data for the population born in 1900, which cover a much larger cross-section of countries. Admittedly, data on body weight would be a more ideal measure but it does not appear to be available for this period. Hence, we use height as a proxy for body weight. In Columns (5)-(7) we present the worldwide link between latitude and height in 1900, with and without continental fixed effects. In all cases, body size is significantly positively correlated with absolute latitude across the world and within Europe.

However, if the link between body size and latitude is generated by way of natural selection, these tests may not be ideal, since the post-Colombian period witnessed considerable international migration (Putterman and Weil, 2010). As a result, the geographical location of people today does not necessarily reflect the geographical location of their ancestors. Hence, in order to control for the potential influence of post 1500 people flows, we examine the link between ancestor-adjusted absolute latitude and contemporary body mass. Evidently, places that today are inhabited by individuals with ancestors who lived far from the equator are characterized by greater average body mass than places inhabited by individuals with ancestors from locations closer to the equator.[1] The results in which latitude is ancestor-adjusted, are displayed in columns (8) (world) and (9) (Europe) in Table 2. The coefficients of ancestor-adjusted absolute latitude remain statistically highly significant and of similar size to the coefficients for unadjusted absolute latitude.

Finally, to control for the possibility that the size of the population is affected by land fertility, we include potential caloric yield per hectare in low-tech agriculture in the pre-1500/post-1500 period as regressors in columns (10)-(12) in Table 2. The coefficients of the absolute latitude in the regressions with height in 1500, body mass in 1500 and, height in 1900 as dependent variables, remain highly significantly positive; thus, giving further support to the Bergmann

[1]Ancestor-adjusted latitude for country j is constructed as a weighted average of the absolute latitude of the country of origin of ancestors, $Lat.Anc._j = \sum_{i=1} \lambda_i X_i$, where λ is the contemporaneous population share with country i ancestry, including that of country j, and X_i is the absolute latitude of country i. The source of the international post 1500 migration matrix is Putterman and Weil (2010).

hypothesis. The coefficients of caloric yield are insignificant, suggesting that the influence of height for economic development is not driven by potential calorie yield. In agreement with the theory developed in Dalgaard and Strulik (2015, 2016), higher agricultural productivity leads, in the long run, to greater population density (cf. Table 1) but not to bigger bodies.

Overall, the results reported in Table 2 complement the findings of Ruff (1994) and Gustavson and Lindenfors (2009) of a positive latitude gradient in body size, in keeping with Bergmann's rule. The most common interpretation of this latitude gradient is that it emerged due to selective pressure whereby individuals with body characteristics that ensure greater cold tolerance have been positively selected in colder locations, in the aftermath of the exodus from Africa (e.g., Ruff, 1994; Katzmarzyk and Leonard, 1998). The logic is, as a matter of geometric fact, that the surface area to volume ratio declines as body mass increases, which serves to reduce the heat loss (see Ruff, 1994). Evidence of recent (i.e., over the last 50,000 years) genetic selection towards greater cold tolerance in human populations is found in Hancock et al. (2010).

It is important to emphasize that our proposed theory does not hinge critically on any particular origin of a latitude gradient in body size. The theory remains relevant as long as absolute latitude predicts body size variation across countries *regardless* of the exact underlying reason. For example, if Bergmann's rule turns out to be caused by variation in disease load rather than evolutionary forces, this would not undermine the proposed physiological theory for the reversal of the latitude gradient.

3. The Model

In this section we develop a unified growth model that can account for this set of facts, thereby providing a potential explanation for the reversal of the latitude-development gradient.

3.1. **Preferences.** Consider an economy populated by a measure L_t of adult individuals, called households or parents. We abstract from gender differences such that any per capita variable can be thought of as being measured in per parent terms. Households derive utility from children, spending on child quality, and from consuming non-food (luxury) goods.

As Strulik and Weisdorf (2008) and Dalgaard and Strulik (2016), we assume that utility is quasi-linear. Non-food goods enter linearly, which makes them less essential and easier to postpone. This creates a simple device according to which consumption is restricted to subsistence needs when income is sufficiently low. The qualitative results would not change under a more general utility function as long as the elasticity of intertemporal substitution for child nutrition is smaller than for non-food (luxury) consumption.

Spending on child quality comes in two dimensions: nutrition and education. Following the anthropological literature (Kaplan, 1996) we assume that, from the preference, side there is no big difference between both of these quality components. Thus, both enter parental utility with the same weight. The most natural way to model this idea is to assume that both components are imperfect substitutes such that child quality (Becker, 1960) is given by the compound $c_t h_{t+1}$, in which c_t is expenditure on child nutrition (approximating physiological quality) and h_{t+1} is the human capital of the grown up child (approximating educational quality).

Summarizing, the simplest functional representation of utility is

$$u = \log n_t + \gamma \left[\log c_t h_{t+1}\right] + \beta x_t, \tag{1}$$

in which n_t is the number of offspring, x_t is non-food consumption, and $\beta > 0$ and $\gamma > 0$ are the relative weight of non-food consumption and child quality in utility. We assume that $\gamma < 1/2$ such that parents always want to have children and the constraint $n_t \geq 0$ never becomes binding with equality.

Parental child expenditure is driven by (impure) altruism, or the "warm glow", i.e., it is not instrumental; parents do not calculate how expenditure improves child productivity and future wages. Parents take into account how education improves the human capital of their children but not how nutrition affects body size. Given that humans invested in nutrition of their offspring long before they understood human physiology, this seems to be a plausible assumption. Moreover, at the steady state, the stock variable (body mass) is proportional to nutritional investments. Accordingly, in the long-run the two formulations will lead to similar steady-state results.[2]

Notice that, for simplicity, we did not include child mortality in the model. In the simplest case where dead children incur no costs, net fertility (as well as all other choice variables) are independent of child mortality (Galor, 2012). An impact of mortality on net fertility can be generated by assuming that all children consume nutrition but only surviving children receive education. If then, additionally, child mortality depends on latitude, there will be an independent

[2]Dalgaard and Strulik (2015) demonstrate that a "utility from body mass" model and a "utility from nutrition" model yield very similar results at the steady state. Yet the utility from body mass formulation is analytically considerably more cumbersome.

influence of latitude on fertility as well as on all other choice variables. Thus, in the regressions below, we always check the robustness of the results when latitude is added as a control variable.[3]

3.2. **Technology.** Following Galor and Weil (2000) and Galor and Moav (2002), we assume that production takes place according to constant returns to scale technology using the factors land X and human capital $\tilde{H}_t$, such that aggregate output is

$$Y_t = A_t \tilde{H}_t^{\alpha} X^{1-\alpha}, \tag{2}$$

in which A_t is the endogenously determined level of technological knowledge at time t. Aggregate human capital is determined by the number of workers L_t times their human capital h_t times their physical capacity (muscle force) which scales with body mass m_t, such that $\tilde{H}_t \equiv m_t^{\tilde{\phi}} h_t L_t$. We denote human capital in the narrow sense, i.e., the aggregate productive knowledge incorporated in people, by H_t, where $H_t = h_t L_t$. Following conventional unified growth theory, we assume no property rights on land such that workers earn their average product, and income per capita is given by $y_t \equiv Y_t/L_t$. Normalizing land to unity we obtain

$$y_t = A_t m_t^{\phi} h_t^{\alpha} L_t^{\alpha-1}, \tag{3}$$

in which $\phi \equiv \alpha\tilde{\phi}$. For simplicity, we focus on a one-sector economy such that output can be converted without cost into food and non-food.

The main motivation for adding body mass to the production function is that body mass matters for the amount of force the individual can muster; "brawn", in other words. Because muscle force is proportional to muscle cross-section area, measured in square meters, it rises with weight as $m^{2/3}$ (e.g., Astrand and Rodahl, 1970; Markovic and Jaric, 2004). Of course not all tasks in the production processes rely on 'brute force' to the same extent. Theoretical reasoning and empirical estimates in sport physiology suggest that individual performance in different tasks scales with body size as m^{ϕ}, in which $\phi = 2/3$ for exerting force (as for example plowing and digging), $\phi = 0$ for moving and $\phi = -1/3$ for supporting body weight (Markovic and Jaric, 2004). In practice, one would then probably expect a positive exponent, which is bounded from above at 2/3.

[3]In reality, child mortality and morbidity are likely to interact with nutrition and body size. Diseases increase the metabolic needs of sick children and parents may be induced to adjust nutrition to the survival prospects of their children (Strulik and Weisdorf, 2014).

3.3. **Human Capital.** Human capital production is a positive function of parental education expenditure per child e_t and the level of knowledge that could potentially be learned at school A_t. Specifically we assume that

$$h_{t+1} = \nu A_t e_t + \bar{h}, \qquad 0 < \nu \leq 1. \tag{4}$$

The parameter $\nu > 0$ controls for the productivity of the education sector (or the share of productive knowledge that can be conveyed at school): The constant $\bar{h}$ denotes human capital picked up for free, for example, by observing parents and peers at work. The production function for human capital could be made more general at the cost of analytical inconvenience. The only crucial part is, as in Galor and Moav (2002), that the return on education is not infinite for the first unit of educational expenditure. This feature, generated by the assumption of some costless acquisition of human capital, produces a corner solution, i.e., the possibility that not investing in human capital is optimal in some environments. It allows us to capture the long epoch of stagnation where investment in formal education arguably did not take place (to a first approximation).

3.4. **Physiological Constraints.** Parents are assumed to experience utility from consumption above subsistence needs x_t but not from subsistence food consumption. Yet they have to eat to fuel their metabolism. The metabolic rate is endogenous and depends – as in Dalgaard and Strulik (2015, 2016) – on body size and fertility. As elaborated by Kleiber (1932) and many studies since, energy requirements of non-pregnant humans scales with body size according to $\theta \cdot m^b$, with $b = 3/4$; this parameter value has withstood empirical falsification for decades, and is consistent with theoretical priors, see Dalgaard and Strulik (2015) for more details. Moreover, rearing a child from conception to weaning increases the mother's metabolic needs by a factor ρ (Prentice and Whitehead, 1987; Sadurkis et al., 1988). This means that metabolic needs of an adult with n_t children is given by $(1 + \rho \cdot n_t)\theta m_t^b$. In order to convert energy into goods we employ the energy exchange rate ϵ, which is measured in kilocalories per unit of a unique consumption good.[4] Summarizing, the parental budget constraint reads

$$y_t = x_t + (c_t + e_t)n_t + (1 + \rho n_t)\frac{\theta}{\epsilon} m_t^b. \tag{5}$$

[4]See Dalgaard and Strulik (2015) for a more detailed elaboration of these physiological foundations.

In order to construct the intergenerational law of motion for body size, we begin with the following energy conservation equation:[5]

$$E_t^c = b_c N_t + e_c(N'_{t+1} - N_t) \tag{6}$$

in which E_t^c is energy consumption during childhood after weaning (prior consumption is covered by adult metabolic needs), N_t denotes the number of human cells after weaning, N'_{t+1} is the number of cells of the child as a grown up, b_c is the metabolic energy a cell requires during childhood for maintenance and replacement, and e_c is the energy required to create a new cell. Hence the left hand side is energy "input" and the right hand side captures energy use.

Observe that the conservation equation does not allow for heat loss. The extent of heat loss is thus implicit in the parameters; a human who manages greater heat loss can thus be seen as one featuring greater energy costs of cell maintenance and repair, i.e., a greater parameter value for b_c. As discussed in Section 2, there is good reason to believe that humans operating under different climatic circumstances are different in terms of cold tolerance, i.e., are different in terms of how effective the body is at releasing heat. Accordingly, a simple representation of acclimatization or genetic selection toward cold resistance would be that of a *smaller* value for b_c, implying less "wasted" energy expenditure due to heat loss. Less disease, which works to sap the individual of energy, would work in a similar way. Hence, in our simulations below we will allow b_c to differ across countries and study how this affects the relative timing of the take-off and, thereby, comparative development, economically and physiologically.

The next step involves solving (6) for N'_{t+1} so as to obtain the number of cells of an adult as a function of the number of cells of a child after weaning and energy intake during childhood, i.e., by isolating N'_{t+1} in the equation above. We can further exploit the fact that the mass of a body is simply the mass of a cell $\bar{m}$ times the number of cells. This implies for the size of an adult that $m_{t+1} = \bar{m}N'_{t+1}$. Moreover, using the fact that after weaning, the size of a child equals μ times the size of the mother (Charnov, 1991, 1993), we have $\bar{m}N_t = \mu m_t$, $0 < \mu < 1$.[6]

[5]Implicitly, we draw on West et al.'s (2001) model of ontogenetic growth; see also Dalgaard and Strulik (2015).
[6]A physiological justification for this assumption is that child development until weaning depends on energy consumption in utero and during the breastfeeding phase. Since bigger mothers consume absolutely more energy the offspring should be larger at this point as it receives a fraction thereof. With this interpretation, the linearity should be seen as a simplification. It has no substantive implications for our main results if the linearity is relaxed, except for reduced tractability.

This leaves us with:

$$m_{t+1} = \frac{\bar{m}}{e_c} E_t^c + \left(1 - \frac{b_c}{e_c}\right) \mu m_t. \tag{7}$$

The intergenerational law of motion for body size has a simple interpretation: The size of the adult, m_{t+1} is determined by energy consumption during childhood, E_t^c, plus initial size, μm_t, adjusted for energy needs during childhood, $-(b_c/e_c)\mu m_t$.

Given that c_t denotes consumption of a child in terms of goods, total energy intake during childhood is $c_t \cdot \epsilon = E_t^c$, where ϵ converts units of goods into calories. Inserting this into (7) we obtain a law of motion for body size across generations:

$$m_{t+1} = a \cdot \epsilon \cdot c_t + (1 - d) \cdot \mu \cdot m_t, \tag{8}$$

in which $a > 0$ and $0 < d < 0$ such that the size of a grown up child correlates positively with the size of the mother. The "deep" physiological parameters a and d are given at the population level but may differ across populations, as observed above. In particular, we will allow d (implicitly, b_c) to differ: b_c will be assumed to be larger in locations closer to the equator, and smaller in places farther away from the equator where greater cold tolerance is assumed to prevail.

3.5. **Individual Optimization.** Parents maximize (1) subject to (4) and (5) and non-negativity constraints on all variables. Let λ denote the shadow price of income and let $B_t \equiv \theta m_t^b/\epsilon$ denote the metabolic needs of a non-fertile adult in terms of goods. The first order conditions for a utility maximum are:

$$0 = (\beta - \lambda) \cdot x_t \tag{9a}$$

$$0 = 1/n_t - \lambda(c_t + e_t + \rho B_t) \tag{9b}$$

$$0 = \gamma/c_t - \lambda n_t \tag{9c}$$

$$0 = \left[\frac{\gamma \nu A_t}{\nu A_t e_t + \bar{h}} - \lambda n_t\right] \cdot e_t. \tag{9d}$$

Depending on the environment, the solution is assumed at the interior or at the corner where non-negativity constraints on education or on non-food consumption are binding with equality. These solutions identify a "modern equilibrium", a "pre-modern equilibrium", and a "subsistence equilibrium", respectively.

3.6. **Interior Solution: The Modern Equilibrium.** The interior solution of (9) is obtained as:

$$n_t = \frac{(1-2\gamma)\nu A_t}{\beta(\nu A_t \rho B_t - \bar{h})} \tag{10a}$$

$$c_t = \frac{\gamma\left(\nu A_t \rho B_t - \bar{h}\right)}{\nu A_t (1-2\gamma)} \tag{10b}$$

$$e_t = \frac{\gamma\rho\nu A_t B_t - (1-\gamma)\bar{h}}{(1-2\gamma)\nu A_t} \tag{10c}$$

$$x_t = y_t - B_t - 1/\beta. \tag{10d}$$

A key result here is that education and nutrition are positively correlated. The result is intuitive. When the return on education increases because of increasing knowledge (increasing A_t), parents prefer to spend more on education and substitute child quantity for quality. The lower number of children reduces the total cost of child nutrition, to which parents respond by spending more on nutrition for each child.

Another important result is the trade-off between fertility and body size; since bigger mothers (with greater B_t) face greater metabolic costs of child rearing compared to smaller mothers, the result is intuitive. As seen below, this trade-off is obtained in all regimes, though the level of fertility and body size may vary. Empirically, there is strong support to be found in favor of a "size-number trade-off". Within biology the association is documented in e.g., Charnov and Ernest (2006) and Walker et al. (2008), and in the context of human societies the inverse link between size and number of offspring is documented in e.g. Hagen et al. (2006) and Silventoinen (2003); see Dalgaard and Strulik (2015) for a fuller discussion.

3.7. **Corner Solution for Education: The Pre-Modern Equilibrium.** The pre-modern era is defined by the feature that there is no education but income is high enough for parents to finance consumption above subsistence level.

Proposition 1. *Parents do not invest in education when the level of knowledge A_t is sufficiently low and thus the return on education is relatively low such that*

$$A_t \leq \bar{A} \equiv \frac{(1-\gamma)\bar{h}}{\nu\gamma\rho B_t}.$$

The threshold $\bar{A}$ is declining in the weight of child quality in utility (γ), the metabolic needs of adults ($B_t = \theta m_t^b/\epsilon$), and the productivity of education ν.

The proof solves (10c) for $e_t = 0$. Notice that the threshold is more easily crossed when parents put more weight on child quality or when parents are bigger. The latter result occurs because children of bigger parents are more energy intensive, which causes parents to have fewer children and makes them more inclined to invest in their education.

The solution at the pre-modern equilibrium (i.e. for $x_t > 0$ and $e_t = 0$) are

$$n_t = \frac{1-\gamma}{\beta\rho B_t} \equiv n_t^x \tag{11a}$$

$$c_t = \frac{\gamma\rho B_t}{1-\gamma} \equiv c_t^x \tag{11b}$$

$$x_t = y_t - B_t - 1/\beta. \tag{11c}$$

Notice that, in contrast to the modern equilibrium, the child quality-quantity decision is independent from knowledge.

3.8. **Corner Solution for Education and Parental Consumption: Subsistence Equilibrium.** It seems reasonable to assume that the broad population lived at subsistence level in most of their history.

Proposition 2. *Parents do not spend on non-food (luxury) consumption when*

$$A_t \leq \underline{A} \equiv \frac{B_t + 1/\beta}{m_t^\phi \bar{h} L_t^{\alpha-1}}.$$

The proof solves (11c) for $y_t \leq 0$ and inserts (2). The result becomes immediately intuitive after noting from (11a) and (11b) that total child expenditure $c_t n_t$ is simply $1/\beta$ at the pre-modern equilibrium.

The solution at the subsistence equilibrium ($e_t = x_t = 0$) is obtained as

$$n_t = \frac{(1-\gamma)(y_t - B_t)}{\rho B_t} \equiv n_t^s, \tag{12}$$

and nutrition per child c_t is the same as in (11b).

Proposition 3. *Fertility at the subsistence equilibrium is increasing in income and declining in body size.*

The proof follows from inspection of (12). This result was already obtained and extensively discussed by Dalgaard and Strulik (2015).

In principle, there exists a fourth equilibrium at which the education constraint is already relaxed ($e_t > 0$) while the subsistence constraint still binds with equality ($x_t = 0$). As shown in the Appendix, at this equilibrium nutrition and education are as in (10a) and (10b) while fertility is still increasing in income for until the subsistence constraint is relaxed and the fertility transition sets in. Since the optimal condition for education is the same as for the interior solution, the education threshold remains the same as in Proposition 1. This means that the main mechanism of the reversal of fortune, namely the feature that societies of bigger people cross the education threshold earlier, is preserved and qualitatively we obtain the same results, as discussed below. Empirically, the 'Malthus-cum-Education' regime is less appealing and in order to be brief, we neglect it here by assuming that parameters and initial values are such that the subsistence constraint is first relaxed when the level of technology advances, i.e., we assume that $\underline{\mathrm{A}} < \bar{A}$.

4. Macroeconomic Dynamics and Stages of Development

We next place the households into a macro economy. The size of the adult population evolves according to

$$L_{t+1} = n_t L_t. \tag{13}$$

Following conventional unified growth theory (Galor and Weil, 2000, and many other studies), we assume that knowledge creation is a positive function of education and population size. Denoting growth of knowledge by $g_{t+1} = (A_{t+1} - A_t)/A_t$, we thus assume

$$g_{t+1} = g(e_t, L_t) \tag{14}$$

with $\partial g/\partial e_t > 0$, $\partial g/\partial L \geq 0$, and $\lim_{L\to\infty} g(e_t, L_t)$ bounded from above. The assumption that the effect of population size on g is bounded means that there cannot be permanent long-run growth driven by population growth alone. It excludes the empirical unobserved case that technological progress generated by population growth overpowers the depressing effect of limited land such that the pre-modern economy explodes with forever rising population and rising rates of technological progress without the initiation of education.

4.1. **Body Size and Fertility in the Three Regimes.** In the subsistence regime and the pre-modern regime, optimal nutrition expenditure is given by (11b), which is independent of the state of technology A_t. Inserting (11b) into (8) we obtain the law of motion for body size

$$m_{t+1} = \frac{a\gamma\rho\theta m_t^b}{1-\gamma} + (1-d)\mu m_t. \tag{15}$$

The fact that body size is determined simply by a differential equation for m_t, independent of the state of technology (and other dynamics variables), allows us to state the following result.

PROPOSITION 4. *In the the subsistence regime and the pre-modern regime, body size converges towards the steady state*

$$m^x = m^s = \left(\frac{a\gamma\rho\theta}{(1-\gamma)[1-(1-d)\mu]}\right)^{1/(1-b)}. \tag{16}$$

The proof solves (15) for $m_{t+1} = m_t$ and shows that $0 < \partial m_{t+1}/\partial m < 1$ at m^s. Strictly speaking, we should call (16) a quasi-steady state, since technology is evolving. Thus, akin to the evolution of the economy in the standard unified growth model (Galor and Weil, 2000), there exists a subsystem (here for body size) with steady-state convergence dynamics, while globally, the system continues to evolve due to technological progress. As long as the economy is in the subsistence regime or pre-modern regime, i.e., for $A_t < \bar{A}$, body size converges to (16). Once the threshold is crossed, body size evolves to the steady state body size that applies in the modern regime.

PROPOSITION 5. *At the modern equilibrium, child nutrition, education, and fertility are independent of income. Education and nutrition are increasing functions of knowledge and fertility is a declining function of knowledge. With rising knowledge, education, nutrition, and fertility converge to the constants*

$$e^* = c^* = \frac{\gamma\rho\theta(m^*)^b}{\epsilon(1-2\gamma)}, \quad n^* = \frac{\epsilon(1-2\gamma)}{\beta\rho\theta(m^*)^b},$$

and body size converges towards the constant

$$m^* = \left(\frac{a\gamma\rho\theta}{(1-2\gamma)[1-(1-d)\mu]}\right)^{1/(1-b)}.$$

The proof begins with assuming that m_t converges towards a constant m^* and concludes that consumption (10b) converges to c^* for $A_t \to \infty$. Inserting c^* into (8) and solving for the steady state at which $m_{t+1} = m_t$ provides the solution for m^* and verifies the initial assumption that body size is constant. Inspection of (10) provides the results of comparative statics. Comparison of body sizes in Propositions 4 and 5 verifies the following result.

Proposition 6. *Ceteris paribus (i.e. for given parameters), individuals are bigger in the modern regime than at the (quasi-) steady state of the subsistence regime and the pre-modern regime, i.e.* $m^* > m^s = m^x$.

At any (quasi-) steady state we observe the following comparative statics.

Proposition 7. *Ceteris paribus (i.e., for given other parameters), a smaller value for* d *implies a greater body size at every (quasi-) steady state* m^s, m^x, *and* m^*.

The proof follows from taking the derivative of m^j with respect to d, $j \in \{s, x, *\}$. Hence, if, via selection or plasticity and acclimatization, the body shape of people changes to allow for less heat loss, and thereby greater cold tolerance, then the model predicts that such societies will also feature bigger people. We next compare fertility in the three regimes.

Proposition 8. *Fertility is highest at the pre-modern (quasi-) steady state.*

For the proof we first utilize the fact that body size is the same at the pre-modern steady state and subsistence steady state such that B_t is the same in (11a) and (12). Then, $n^s < n^x$ implies $1 < \beta(y_t - B_t)$, which is true whenever the subsistence constraint binds. To see that $n^* < n^x$, insert m^s into (11a), i.e., $n^x = \epsilon(1-\gamma)/[\beta\rho\theta(m^s)^b$, and notice that $(1-2\gamma) < (1-\gamma)$ and $m^* > m^s$.

4.2. **The Transition towards Modern Growth.** Suppose that human history begins at a sufficiently low level of A such that both the education constraint and the subsistence constraint are binding initially. Human economic and physiological development then runs through three distinct phases: a subsistence regime, a pre-modern era and a modern era.

When A_t is below the subsistence threshold $\underline{A}$ and the education threshold $\bar{A}$, no income is spent on non-food (luxury) consumption or on education, and all income gains are channeled to higher fertility. Body size in the subsistence regime converges towards m^s. With output per capita gradually growing, the economy eventually surpasses the threshold $\underline{A}$ and people start enjoying utility from non-food (luxury) consumption. Fertility rises to a higher level (see Proposition 8) but food provision per child remains at subsistence level. This means that body size remains unchanged, $m^x = m^s$. With body size and thus metabolic needs B_t fixed at (quasi-) steady state level, the threshold $\bar{A}$ is a constant. The threshold is lower in countries inhabited by bigger people and thus crossed at a lower level of knowledge A_t.

Once the threshold has been crossed, parents start investing in the education of their children. This has a double effect on economic growth. Education increases the productivity of the current worker generation as well as, through knowledge improvements, the productivity of the next generation, which then invests even more in education such that the economy eventually converges to the steady state e^*. Along the transition to the steady state, fertility declines, which reduces the Malthusian pressure and leads to further increasing income. As a result, the economy takes off, enjoying accelerating growth rates. Eventually, economic growth stabilizes at a high plateau at the end of the fertility transition when education expenditure has reached its steady state.

With respect to education and fertility, the transition to the modern era is similar to the transition established in conventional unified growth theory (e.g. Galor and Weil, 2000). The present model additionally explains the physiological transformation of humans: with the take-off to growth, humans start getting bigger (Proposition 6). As explained above, the uptake of education and the entailed reduced fertility make spending on nutrition of children more desirable and, subsequently, the next generation of adults is bigger. The grandchildren are even bigger because there is a double effect: Grandchildren are born bigger because they are conceived by bigger mothers, and their parents spend more on nutrition because increasing knowledge increases their preference for child quality in both the education and nutrition dimension. Eventually, however, nutrition and thus body size converges to a constant (see Proposition 5).

5. Physiological Constraints and Comparative Economic Development

Consider two regions (or countries) named A and B that share all parameter values aside from the one for heat loss, d, due to natural selection or plasticity and acclimatization. We assume that d is lower in region A than in region B. Consequently, humans are bigger in region A.

5.1. **Analytical Results.** In order to discuss the reversal of fortune analytically, we need two further assumptions on technology that will be relaxed in Sections 5.2 and 5.3. First, we assume (akin to the analysis in Kremer, 1993), a knowledge production function (14) that creates new knowledge only occasionally such that fertility, according to (12), adjusts to the Malthusian steady state ($n = 1$) that prevails at the current level of technology. Second, we assume that the two regions share the same knowledge base. That is, technology is locally determined by population size (and when relevant: education) but the produced ideas spread instantaneously. Concretely, let $\tilde{A}_t^j$ denote the knowledge that has been *created* in region j, $j = A, B$. Knowledge *available* in region j, denoted by A_t^j, is given by

$$A_t^j = \tilde{A}_t^A + \tilde{A}_t^B. \tag{17}$$

PROPOSITION 9. *Consider two regions that differ in the metabolic needs of adults determined by d (heat loss) and are otherwise identical. Then the region with the smaller d*

(1) *is inhabited by bigger individuals*

(2) *is less densely populated*

(3) *creates less knowledge in the Malthusian era*

(4) *and enters the modern era earlier.*

Result 1 follows from Proposition 7. In order to derive result 2 we compute the Malthusian steady state for a given level of technology $A_t = A$. To obtain steady state population density, we set $n_t = 1$ in (12) and (13). Inserting (3) and (16) into (12) solving $n_t = 1$ for $L_t = L^s$ provides population density

$$L^s = \left(\frac{\epsilon(1-\gamma)A\bar{h}}{\theta\left[\rho/(2-\gamma)\right]} \right)^{1-\alpha} \left(\frac{(1-\gamma)(1-d)\mu}{a\gamma\rho} \right)^{\frac{b-\phi}{1-\alpha}}. \tag{18}$$

The comparative static with respect to d shows that the region inhabited by bigger individuals is less densely populated at any given level of technology. Result 3 follows from applying the knowledge creation function (14) for each region. Result 4 follows from applying Result 1 and Proposition 1.

Proposition 9 rationalizes the reversal of fortune that we aimed to explain since we expect d (i.e. cell maintenance costs b_c) to be inversely correlated with absolute latitude. These results reproduce the stylized facts listed in Section 2 when it is further recalled that an earlier take-off will yield an income gap between the two regions if observed at an appropriate point in time after the region inhabited by bigger people has taken off. Moreover, these results are quite intuitive. Relatively higher metabolic costs of fertility will, in the Malthusian era, work to lower fertility in places inhabited by physiologically bigger people. Lower fertility implies a lower population density and thus less creation of new knowledge since technological change is generated through learning-by-doing.[7] However, the high metabolic costs of fertility and subsequent nutrition requirements of bigger children makes the region populated by bigger individuals more inclined to invest in education, and thus to substitute child quantity with quality. As a result, a lower critical level of technology is required for the fertility transition to take place. Consequently, an income gap emerges in favor of the region inhabited by physiologically bigger people.[8]

Notice that the theory does not predict that the response to changes in the environment for fertility or education is greater for bigger individuals. In fact, $\partial^2 e_t/(\partial A_t \partial B) = 0$, which can be verified from equation (10c), indicating that the partial strength of the response to technological change is independent of body size. Instead, the theory predicts that bigger individuals respond earlier with investment in education and reduced fertility to increasing technological sophistication of production (i.e., at a lower level of technology). These results are independent of the specification of the utility function $u(c, h, n)$ since they do not need any further assumptions on preferences beyond decreasing marginal returns. Intuitively, the threshold is crossed when, for the first time, the marginal utility derived from a unit of education equals the marginal utility of nutrition. Since parents of bigger children (who become bigger adults) spend more on nutrition, the marginal utility derived from nutrition is lower such that it is already equal to the marginal utility from education at a lower level of the return to education, i.e., at a lower level of technological sophistication.

5.2. **Comparative Dynamics.** In order to illustrate the comparative dynamics, we use the parameterizations suggested in Dalgaard and Strulik (2015). Specifically, we set $b = 3/4$, $\theta = 70$, $\mu = 0.15; \rho = 0.2$, $\epsilon = 0.28$ and, for the benchmark run, $d = 0.5$. We set β and γ such that population growth peaks at 1.5 percent annually and fertility converges to replacement level at the modern steady state. This provides the estimates $\gamma = 0.1$ and $\beta = 0.0053$. We set a such that the average body weight in Malthusian times is 60 kg. This provides the estimate $a = 1.65$. Region B (the region closer to the equator) is populated by individuals who share the same

[7]As in most of the related literature where technological progress is driven my learning-by-doing (e.g. Kremer, 1993; Galor and Weil, 2000), we do not explicitly consider the distribution of the population within countries. Learning-doing may take place at greater intensity in cities and the notion would then be that more densely populated areas are also characterized by the presence of more and/or larger cities, which, in turn, generate more new knowledge. See Lucas (2009) for an approach to taking differences of rural and urban learning explicitly into account.

[8]Sustainability of long-run growth of income at a positive rate requires that $g(e^*, L_t) - (1 - \alpha)n^* > 0$. The reversal of fortune, however, is obtained irrespective of whether long-run growth is sustainable since it is based on the conditions that apply at entry into the modern era.

parameters except d, which is 0.8. In region B, average body weight is, therefore, 49.6 kg in the subsistence regime. We set $\alpha = 0.8$ and $\phi = 0.25$.

In this section we maintain the assumption of perfect knowledge sharing and relax the assumption of only occasional knowledge creation. Following Lagerlöf's (2006) parametrization of the Galor and Weil (2000) model, we assume knowledge created in region j grows at rate

$$g^j_{t+1} = \delta(e^j_t + \lambda) \cdot \min\left\{(L^j_t)^\eta, \;\; \Lambda\right\}. \tag{19}$$

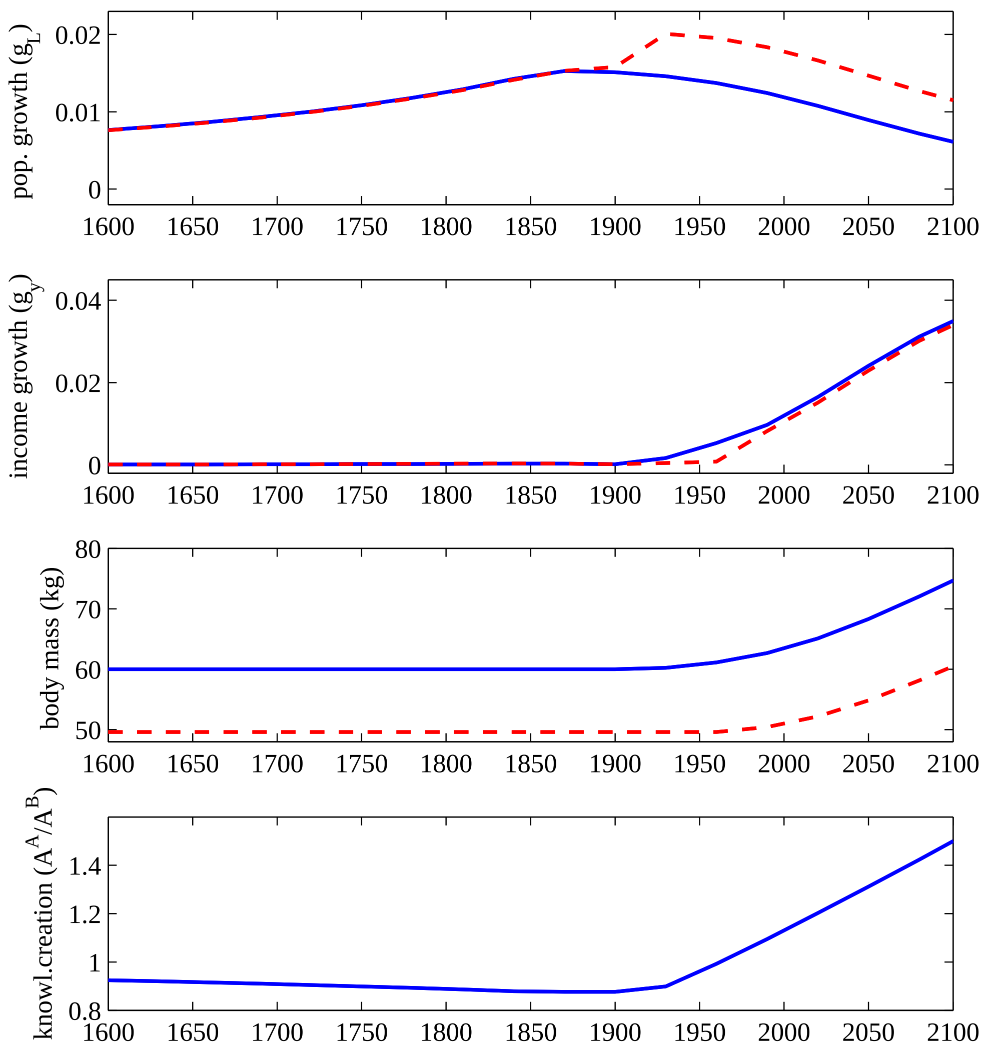
We set the productivity parameters such that the model generates plausible growth rates during the subsistence era, pre-modern era, and modern era. This leads to the estimates $\delta = 0.05$, $\lambda = 0.8$ and $\eta = 0.3$. We set $\Lambda = 2.5$.

Finally, we normalize $\nu = 1$ and $\bar{h} = 1700$ such that region A experiences a century of almost constant high fertility rates before fertility begins to decline. After running the experiment we convert all variables in units per year using a period length of 30 years. We start the economies in the year 1000 and determine the initial population size and technology level such that region A leaves the Malthusian phase in the year 1830. The implied initial fertility rate is 1.106 and the implied population growth rate is 0.34 percent. Region B shares the same initial technology and the same initial fertility rate, which means that it is more densely populated since people are smaller. The implied initial population ratio is $L^B_0/L^A_0 = 1.42$.

Figure 1 shows the implied trajectories for population growth, income growth, and body mass. Solid lines reflect the trajectories of region A and the dashed lines show region B. The bottom panel shows the relative stock of technologies invented in region A. The figure starts in the year 1600 because the years before 1600 look very much like 1600 (aside from population growth which is gradually increasing). Both regions share virtually the same population growth rate during the subsistence phase, implying that region B remains more populous and poorer than region A. Because of its larger size, region B produces more innovations; the innovation ratio $A^A/A^B = (L^A/L^B)^\eta$ is around 0.9 during the Malthusian phase and mildly falling.

In the year 1870, region A starts investing in education and initiates the fertility transition. Consequently, income growth takes off one period later, when the educated children enter the workforce and contribute to knowledge creation. In region B the take-off occurs two generations later. The technological leadership switches after the take-off of region A and the innovation ratio improves very quickly. In the year 1950 we observe, for the first time since the year 1000,

Figure 1: Long-Run Comparative Dynamics



Solid lines: region A ($d = 0.5$); dashed lines: region B ($d = 0.8$).

that both regions contributed the same to the worldwide stock of knowledge. From then on region A's relative contribution is increasing rapidly due to its better-educated workforce. After the take-off, average body weight is gradually increasing and reaches 65 kg in the year 2000.

Region B benefits from the take-off of region A since the newly created knowledge diffuses freely. In region B, however, the resulting increasing productivity is initially used predominantly to further expand fertility because the region is still in its subsistence phase and then briefly enters the pre-modern phase. Consequently, population growth increases further and approaches a high plateau in the first half of the 20th century, while income growth is improving only very little. Then, in 1930, with a delay of two generations, region B invests in education and in 1960, income takes off, population growth starts to decline, body size increases, and income growth converges to that of region A.

5.3. **Robustness: Gradual Diffusion and Imperfect Knowledge Sharing.** The assumption of instantaneous diffusion of ideas is admittedly extreme and biases the results in the direction of an early take-off in societies that are inhabited by bigger but fewer people. In this section we explore how robust the reversal of fortune is when we allow for slow and incomplete diffusion of ideas. In assessing the results below it is important to recall the nature of the stylized fact in focus. We are exploring a mechanism that can potentially account for a reversal of fortune *within continents,* or even countries. As demonstrated in Section 2, the positive latitude-economic activity gradient holds when the data is pruned for country fixed effects. Whereas ideas surely traveled more slowly in pre-industrial times than today, the frictions in technology transfer that we have in mind do *not* refer to those between, say, China and Northern Europe but rather to frictions in the diffusion of knowledge between Southern Europe and Northern Europe, or within China.

In order to allow for only partial and gradual diffusion of ideas, we replace (17) with

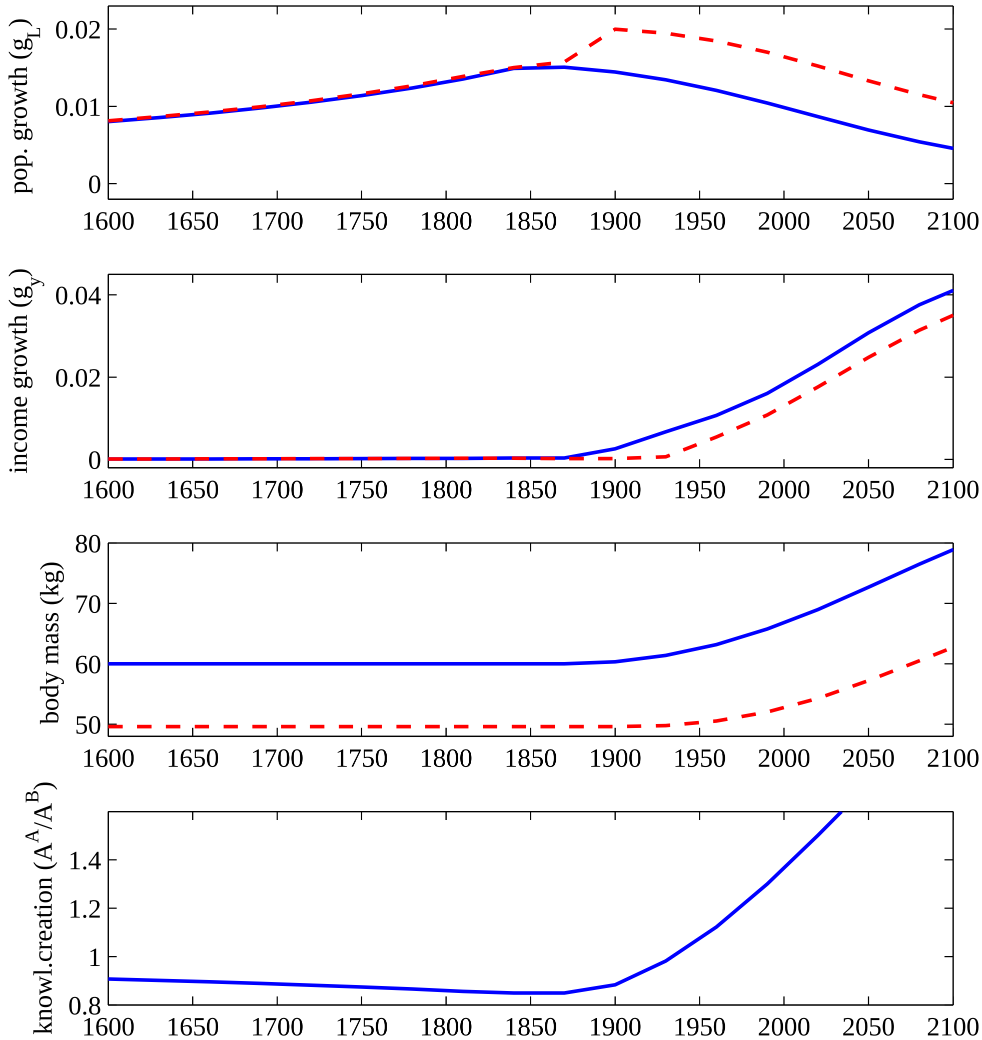
$$A_t^A = \tilde{A}_t^A + \xi \tilde{A}_{t-k}^B, \qquad A_t^B = \tilde{A}_t^B + \xi \tilde{A}_{t-k}^A. \tag{20}$$

In the equation above, ξ captures the fraction of ideas that (asymptotically) can be diffused. Hence, $\xi < 1$ means that some ideas are never diffused. Furthermore, the equation above captures that new ideas arrive in the non-innovating countries with a delay of k generations. Aside from these novel elements, we keep the structure of the model unchanged, along with the parameter values discussed above.

The initial value of technologies available in each region is adjusted such that both countries initially share the same fertility rate (as in the benchmark run). This implies that the initial technologies created in each region are given by $\tilde{A}_0^A = (A_0^A - \xi A_0^B)/(1-\xi^2)$ and $\tilde{A}_0^B = (A_0^B - \xi A_0^A)/(1-\xi^2)$. We adjust the initial value of population size such that region A experiences the take-off in 1870 and the outcome is comparable with Figure 1.

Figure 2 shows results for $\xi = 1$ and $k = 2$, i.e., for a 60 year delay in international knowledge diffusion. Interestingly, and perhaps surprisingly, the delayed knowledge flow does not delay the take-off of region B. The reason is that imperfect knowledge flows also operate during Malthusian times, during which region B is the technological leader. Imperfect knowledge flows thus reduce the speed at which region A reaches the threshold $\bar{A}$. The difference compared to the development in Figure 1 is mainly that delayed knowledge flows reduce the catch up speed of region B after its take-off.

Figure 2: Long-Run Comparative Dynamics: Gradual diffusion of ideas



Parameters as for Figure 1 but knowledge diffuses with a lag: knowledge created in one region at time t reaches the other region at time $t-2$.

More generally, we can use the model and ask the question: For which delay in international knowledge diffusion does the result of the earlier take-off of region A break down? The results are summarized in Table 3.

If all knowledge is usable in all countries ($\xi = 1$), then region A takes off first up to a diffusion lag of 12 generations (360 years). The maximum diffusion lag decreases as we reduce the degree of international knowledge sharing. If only 60 percent of knowledge are transferable

TABLE 3. ECONOMIC DEVELOPMENT, HEIGHT IN 1500 AND LATITUDE

ξ	1	0.8	0.6	0.4	0.2
k	12	9	5	2	–

The table shows, for alternative degrees of international knowledge sharing ξ, up to which diffusion lag (in terms of generations) the result that the initially backward region A takes off first continues to hold.

internationally, region A takes off earlier for up to a diffusion lag of 5 generations (150 years). If 20 percent or less of the knowledge is shared internationally, region A fails to take off earlier.

We experimented with different numerical specifications of the model and found generally that region A takes off one to two generations earlier and that this result is robust to substantial impediments to knowledge diffusion. Usually we can allow for delays if ten or more generations when all knowledge is shared across regions (i.e., within continents or countries) and up to just 50 percent interregional knowledge sharing when the diffusion delay is 3 generations or less. The theoretical result of the reversal of fortune, which we could prove only for perfect knowledge sharing, appears to be robust to substantial imperfections in interregional knowledge sharing.

The testable implications of the theory are that countries or regions inhabited by bigger individuals were less densely populated before the onset of the fertility transition, experienced the fertility transition earlier, and are richer and better educated today. Another testable implication of the theory is a refinement of standard unified growth theory (UGT) in which technological advances increase the return to education and, if sufficiently strong, induces an increase in education and a reduced fertility (Galor and Weil, 2000). Our theory proposes that the UGT mechanism is mediated by height, i.e., that countries populated by bigger individuals respond to technological progress earlier (and thus, at any given time after the onset of the fertility transition, more strongly) with reduced fertility.

6. EMPIRICAL ESTIMATES

In this section we show that height has been a significant determinant of economic development across time and space, where we focus on the three proxies for economic development: the fertility transition, per capita income, and education. To show this, we present three modules of estimates in this section: 1) cross-country regressions using pre-1500 height and body mass as regressors; 2) cross-country regressions using height in 1900 as regressor; and 3) panel regressions for the Italian regions over the period 1821-2001 in which long lags of height are employed as regressors. Finally, we carry out panel regressions for 18 OECD countries over the period 1840-1980 to examine whether the effect of technological change on fertility reductions is mediated by height.

6.1. **Reduced Form Predictions: Cross-Country Estimates.** The following regressions are carried out using the sample pertaining to height in 1500 and in 1900:

$$\log FTran_i = \alpha_0 + \alpha_1 \log H(X)_i + Z_i \zeta' + \epsilon_{1,i}, \tag{21}$$

$$\log Y(2000)_i = \beta_0 + \beta_1 \log H(X)_i + Z_i \xi' + \epsilon_{2,i}, \tag{22}$$

$$\log Edu(2000)_i = \gamma_0 + \gamma_1 \log H(X)_i + Z_i \tau' + \epsilon_{3,i}, \tag{23}$$

where $FTran$ is the year of the onset of the fertility transition (where we use the years computed by Reher, 2004; extended with missing countries as documented in the online Appendix); $Y(2000)$ is per capita income in purchasing power parity in 2000; $Edu(2000)$ is educational attainment (years of education) of the adult population in 2000; $H(X)$ is the average male height (or, in one case, body mass) in year X = 1500, 1900; Z is a vector of control variables; ϵ is a disturbance term; and subscript i refers to country i. All variables, including the control variables, are in logs to dampen the leverage of extreme observations. The coefficients of height are expected to be positive in the models for per capita income and educational attainment, but negative in the model for fertility transition as height triggers an earlier fertility transition.

In the $H(1500)$ regressions we only control for latitude, caloric yield, and continental fixed effects because the limited number of maximum 42 observations constrains the room for maneuver. In the post-1500 regressions we additionally control for variables that are potentially correlated with height such as cultural factors, institutional factors, health insults and geographic characteristics. It is possible that geographic characteristics influence the outcome variables through channels other than height. To adjust for this possibility, absolute latitude (Abs. Lat.) is included as an additional regressor.

6.1.1. *Evidence Using pre-1500 Height.* In this sub-section we use height and body mass data, mostly referring to height within the period 1300-1500, which we have collected from a large number of sources as detailed in the online Appendix. The results of estimating (21)-(23) are shown in Table 4. Consider first the estimates in the three first columns from the left in Table 4 (columns 1-3 for height and columns 10-12 for body mass). The coefficients of height and body mass are significant at the 1 percent level and have the expected signs in all cases.[9]

To check the robustness of these results, we include latitude, as it is widely acknowledged that economies farther away from the equator are more successful in terms of economic development, while countries close to the equator have a higher prevalence of disease, a highly variable rainfall and inferior soil quality (Gallup et al., 1999). Furthermore, we include the pre-1500 potential caloric yield per hectare that is constructed by Galor and Özak (2016). This variable provides the potential calories that one could get from low-tech agriculture and, therefore, controls for the possibility that height is partly a result of the accessibility to food. When latitude is included in the regressions, the coefficients of height and body mass are rendered insignificant at the 5% levels in the models in which income or educational attainment in the year 2000 are the outcome variables, while they are significantly negative in the fertility regressions (columns 4-6 and 13-15). Since per capita income and education in 2000 are outcomes of a myriad of factors where height is just one of them, the insignificance of height in these regressions is not so surprising. Furthermore, as argued below in Section 6.1.2, measured education is likely an imperfect proxy for human capital. Of importance is the significance of height in the fertility transition regressions, particularly because it is the key outcome variable explained by our theory. Finally, the significance of the coefficients of height and body mass are hardly affected by the inclusion of potential calories (see columns 7-9 and 16-18).

Another plausible reason for the insignificance of height when latitude is included in the income or education regressions is that absolute latitude is positively correlated with measurement error. Regressing height in 1900 on height in 1500 yields a coefficient of height in 1500 of 0.52 ($t = 4.36$), while the reverse regression yields a coefficient of 0.63 ($t = 5.21$), $N = 47$, which, unsurprisingly, suggests that the measured height in 1900 is a more reliable measure of the population height than measured height in 1500 (all variables are measured in logs and latitude is controlled for, see for reliability tests, Krueger and Lindahl, 2001). More importantly, in these regressions the coefficient of absolute latitude is significantly positive at the 1% level when $H(1500)$ is the

[9]It may be helpful to relate the results from Table 4 to the earlier results discussed in Dalgaard and Strulik (2016). There, a negative association between the year of the fertility transition and contemporaneous body size is established. A quantity-quality trade-off explains why, after the onset of the fertility transition, later born offspring are taller and heavier. Here, we argue that countries that were populated by taller people (long) before the fertility transition, initiated the fertility transition earlier and are thus richer and better educated today. In other words, the 2016 study focused on within country developments and a predictive causality running from the timing of the fertility transition to contemporaneous body size, while this study focuses on the predictive causality of historical body size for cross-country differences in the timing of the fertility transition.

Table 4. Economic Development, Height and Body Mass in 1500

	Height								
	1	2	3	4	5	6	7	8	9
	FTran	*Y*(2000)	*Edu*(2000)	*FTran*	*Y*(2000)	*Edu*(2000)	*FTran*	*Y*(2000)	*Edu*(2000)
H(1500)	-0.37***	16.8***	3.09***	-0.23**	5.34	0.80	-0.18**	1.24	-0.52
	(5.65)	(3.71)	(3.44)	(2.99)	(1.37)	(0.69)	(2.42)	(0.32)	(0.39)
Abs. Lat.				-0.01***	0.70***	0.15*	-0.01***	1.27***	0.35***
				(3.10)	(2.66)	(1.89)	(3.64)	(6.02)	(3.57)
Cal(1500)							0.00	0.04	0.03
							(0.10)	(0.60)	(1.20)
R^2	0.34	0.20	0.11	0.56	0.59	0.46	0.45	0.52	0.46
Obs.	46	47	43	46	47	43	43	44	42
	Body Mass								
	10	11	12	13	14	15	16	17	18
	FTran	*Y*(2000)	*Edu*(2000)	*FTran*	*Y*(2000)	*Edu*(2000)	*FTran*	*Y*(2000)	*Edu*(2000)
BM(1500)	-0.11***	5.36***	1.10***	-0.07**	2.49*	0.52	-0.11***	2.66***	0.00
	(7.04)	(4.42)	(2.86)	(3.41)	(1.82)	(1.26)	(3.39)	(5.80)	(0.02)
Abs. Lat.				-0.01***	0.65***	0.13*	-0.82*	0.01	0.34***
				(3.83)	(2.28)	(1.86)	(1.83)	(0.93)	(3.77)
Cal(1500)							0.00	0.02**	0.05*
							(0.70)	(2.16)	(1.83)
R^2	0.44	0.26	0.12	0.57	0.43	0.23	0.63	0.67	0.51
Obs.	32	32	25	32	32	28	30	30	28

Notes: The numbers in parentheses are absolute t-statistics that are based on heteroscedasticity consistent standard errors. All variables, except for educational attainment, are measured in logs. $Y(2000)$ is per capita income in 2000 in purchasing power parity. *FTran* is the year of onset of the fertility transition. Abs. Lat. is absolute latitude. $BM(1500)$ is body mass in 1500. $H(1500)$ is height in 1500. Cal (1500) is pre-1500 potential caloric yield per hectare constructed by Galor and Özak (2016). *, **, ***: significant at 10, 5 and 1% levels.

regressor, but insignificant in the regression in which $H(1900)$ is the regressor. These results suggest that latitude is likely to be correlated with the measurement error of height in 1500 and, therefore, that the parameter estimates of height in 1500 are downward biased when latitude is included as regressor.

Turning to economic significance based on the results in columns (1)-(3) in Table 4, suppose that the average height of a Filipino of 156 cm in the pre-1500 period was equal to the height of the sample average of 166 cm, where the Philippines had the shortest population in our sample in 1500. Then, the Philippines would have experienced the fertility transition in 1906 instead of 1955. Furthermore, their per capita income and educational attainment would have been 110% and 33% higher in 2000 compared to the actual outcomes (the height elasticity of educational attainment is estimated from the sample average of 8.47 years of education in 2000). In the other extreme, if the average height of a Norwegian was 156 cm as opposed to its actual height of 173.6 cm, Norway would have experienced a fertility transition in 1974 instead of the actual year of 1905.

6.1.2. *Cross-Country Evidence over the Last Two Centuries.* The results of regressing (21)-(23) using height in 1900 as the regressor are presented in Table 5. The coefficients of height are highly significant and have the expected signs in the bivariate regressions (columns (1)-(3)) and in the regressions that include continental fixed effects and latitude as controls (columns (4)-(6)). The principal results remain unaltered if pre-1900 fertility transitions are excluded from the regressions regardless of whether continental fixed effects and latitude are included (see online Appendix Table A6). As predicted by our model, absolute latitude is positively associated with economic development; however, the effect is not nearly as significant as in bivariate regressions because height and continental fixed effects are included in the regressions (the results without continental effects are not shown). Quantitatively, changes in height have approximately the same effects on the timing of the fertility transition and per capita income in 2000 as in the regressions using pre-1500 height, suggesting consistency across estimates and that height is influential for economic development regardless of whether height is measured in 1900 or in circa 1500.

Table 5. Economic Development and Height in 1900

	1	2	3	3	4	5	6	7	8
	FTran	*Y*(2000)	*Edu*(2000)	*FTran*	*Y*(2000)	*Edu*(2000)	*FTran*	*Y*(2000)	*Edu*(2000)
H(1900)	-0.36***	15.54***	50.57***	-0.22***	9.77***	38.8***	-0.242***	10.92***	4.99**
	(8.12)	(5.03)	(7.80)	(5.17)	(2.86)	(3.87)	(5.21)	(2.96)	(2.10)
Abs. Lat.				-0.002*	0.18**	0.33	-0.001	0.11	-0.07
				(2.02)	(2.29)	(1.38)	(0.71)	(1.01)	(1.34)
Dist. Sea							0.003***	-0.32***	-0.14*
							(2.64)	(2.78)	(1.78)
Y(1900)							-0.007***	0.52***	0.05
							(4.24)	(4.04)	(0.71)
Elev							-0.002	0.17	0.10
							(1.24)	(1.48)	(1.33)
Temp*(1-*DAfr*)							0.002	-0.11	-0.17**
							(1.07)	(0.97)	(2.34)
Temp**DAfr*							0.005***	-0.36***	-0.31***
							(2.96)	(3.66)	(4.53)
Agr. Sui.							-0.003	-0.46**	0.14
							(1.12)	(2.26)	(1.20)
Cont. FE	N	N	N	Y	Y	Y	N	N	N
R^2	0.32	0.10	0.25	0.61	0.45	0.58	0.70	0.68	0.52
Obs.	176	182	135	176	182	135	141	127	111

Notes: The numbers in parentheses are absolute t-statistics that are based on heteroscedasticity consistent standard errors. All variables, except educational attainment, are measured in logs. *FTran* is fertility transition year. $Y(2000)$ is per capita income in 2000 in purchasing power parity. $Edu(2000)$ is educational attainment of the adult population in 2000. $H(1900)$ is height of the 1900 birth cohort. Abs. Lat. is the absolute latitude. Dist. Sea. is distance to an ocean or a navigable river. $Y(1900)$ is per capita income in 1900. Elev is average elevation above sea level. Temp is average temperature. *DAfr* is a dummy variable taking the value of 1 for an African country and zero elsewhere. Agr. Sui. is agricultural suitability. *, **, ***: significant at 10, 5 and 1% levels.

For education, however, the economic significance of height is substantially higher in the estimates with height in 1900 than with pre-1500 height, suggesting that the estimates are sensitive to country selection. The sensitivity to sample selection may be because education is an imperfect measure of human capital and, therefore, does not adequately capture parents' investment in their offspring's education (see, e.g., Hanushek and Woessmann, 2011). Furthermore, variables that are generally considered important for economic development, such as latitude and per capita income in 1900, are both insignificant in the regression in the last column in Table 5, reinforcing the impression that education may not adequately capture human capital. Finally, Caselli and Ciccone (2019) show that returns to education tend to be significantly higher in advanced than in developing countries because the skill premium is partly driven by technology, institutions and other factors.

As checks on the robustness of the results and endogeneity induced by the omission of variables that are simultaneously correlated with the outcome variables and height, we sequentially include control variables that are often considered essential for economic development (see, e.g. Gallup et al., 1999; Hall and Jones, 1999; Nunn and Puga, 2012; Dell et al., 2012; Michalopoulos, 2012; Michalopoulos and Papaioannou, 2018). As control variables, we include institutions (constraints on executive in 1900, social infrastructure in 1990, pre-industrial village democracy), geographic characteristics (precipitation, temperature, distance to an ocean or a navigable river, altitude, ruggedness, soil quality, agricultural suitability, post-1500 potential caloric yield per hectare, parasitic and infectious disease in 1900), economic development (per capita income in 1900, the same year at which height is measured), and culture (individualism/collectivism). The results are presented and discussed in the online Appendix. In all cases, the coefficients of height remain statistically significant at the 1% level and with the expected signs, suggesting that the significance of height in the regressions is not caused by endogeneity induced by key omitted variables that are simultaneously correlated with height and the outcome variables. Overall, the results in this subsection give strong support for the hypothesis that height is a robust determinant of economic development.

To see how far we can push our hypothesis, we include the control variables that we find statistically the most significant determinants of the outcome variables in the regressions in the online Appendix. We, additionally, include per capita income in 1900 as probably the variable that controls for the level of economic development the best at the time at which the 1900 height cohort was born. The results are presented in the last three columns in Table 5. The coefficient of height is statistically significant in all three models; thus, giving strong supporting evidence that our baseline results are not driven by endogeneity due to omission of essential variables.

6.1.3. *Placebo Tests.* Thus far, we have checked for endogeneity by including several variables that are potentially correlated with the error terms and used historical height data to ensure that there are no feedback effects from the outcome variables to height. As a final causality check, we undertake a placebo test by including the bilateral geographic distance to the UK for each individual country as an additional regressor in the cross-country baseline regressions in which the outcome variables consist of the fertility transition, and per capita income and education in 2000. The geographical distance to the UK is a natural contender to latitude because the UK is the cradle of the First and Second Industrial Revolutions, which rapidly spread to neighboring countries through trade, migration, travel, and publications. The regression results are presented in Table A5 in the online Appendix with three sets of base-line regressors: pre-1500 height, pre-1500 body mass, and height in 1900. We additionally include continental fixed effects in the regressions with height in 1900. The coefficients of distance to the UK are all insignificant except in one case in which educational attainment is a significant positive function of distance – the opposite result of what we would expect. The coefficients of height remains significant at the 1% level and with the expected sign in all cases.

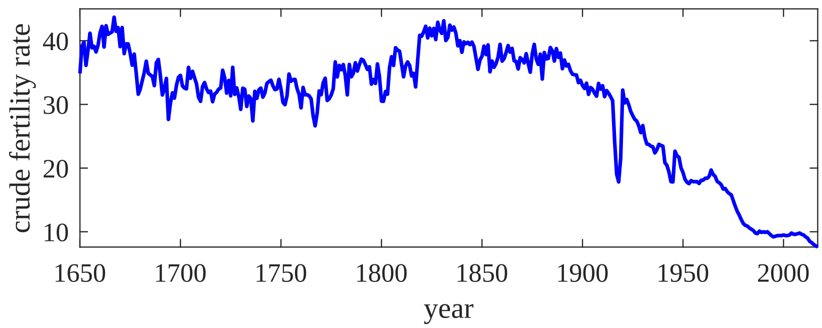
6.2. **Reduced Form Predictions: Panel Data Evidence for Italy.** To give more substance to our theory we use Italy as a case study to examine the influence of historical levels of height on contemporary regional inequalities. Italy makes a good case because it is an example of a country in which the gravity of economic activity, according to recent research, has moved from the South towards the North in the later second half of the last millennium. Furthermore, using panel data over the period 1821-2001 for the Italian regions, we show that height is influential for education, the fertility transition and per capita income and, consequently, that height has been influential for the advantages that the North has enjoyed over the South over the past one and half centuries.

6.2.1. *Reversal of Fortune.* A well-known fact is that the northern part of Italy is today economically more developed than its southern counterpart. What is less well known, is that the South of Italy was probably more developed than the North in the 16th century. The leading paradigm has long been that an advanced northern Italian manufacturing sector has dominated a stagnant, backward southern agricultural sector that has prevailed at least since the medieval period (Epstein, 2003). Since the South did not engage in foreign trade and lacked the entrepreneurial spirit of the North, it became dependent on the North for its manufacturing products in exchange for staple agricultural products (see, e.g. Luzzatto, 1948, pp. 103-115). However, new studies have rejected the old paradigm. Based on detailed analysis of archival documents and data, Epstein (2003), an economic historian, shows that Italy's contemporaneous North-South divide finds its origins and causes in the southern Italian economy's dependence on manufacturing imports from the North during the Middle Ages. Furthermore, Malanima (1998) finds that the biggest Italian cities were located for the most part in the South of the Italian peninsular and in Sicily during the period 1000-1300, while only some maritime cities and very few in the interior had attained a prominent position in the center and in the North of Italy.

The South also showed resilience to economic shocks. In response to the fourteenth-century crisis, Sicily restructured its regional markets, resulting in a significant expansion of income and population size (Epstein, 2003). In the second half of the 15th century, for example, Sicily experienced a two-fold increase in its population size (the increase was 20 percent for Italy over the same period, Madsen et al., 2019). Even if some of the population expansion was driven by a comparatively strong convergence towards the steady state following the Black Death, the population expansion could not have taken place without marked technological or efficiency advances. Moreover, at no time during the 15th and 16th centuries did less than 30 percent of the population in Southern Italy live in the urban centers (Malanima, 1998), suggesting that the South of Italy was already quite developed in this period, but eventually fell behind the North.

6.2.2. *Econometric Evidence for the Italian Regions.* To show that height has been a factor in the reversal of fortune between the North and South of Italy, we use decennial data for the existing 19 Italian regions, spanning the maximum period 1821-2001, again, using fertility, education and income as outcome variables. Furthermore, we check whether height during the Roman Empire period predicts contemporaneous outcome variables. To get a long perspective on the timing of the fertility transition in Italy, Figure 3 displays the crude fertility rate (births per 1000 population) for Italy over the period 1650-2016. The fertility rate fluctuated around a relatively constant level over the period 1650-1890 and since then transited to the current level over the approximate period 1890-1980. In the estimates we focus on the period 1891-1981, or periods in-between, while allowing for long lags in height.

Figure 3: Fertility in Italy 1600-2000



6.2.3. *Fertility as the Outcome Variable.* The regression results with the level or the change in fertility as the outcome variable are presented in Table 6. The crude fertility rate, *CFR*, is the outcome variable and height is lagged 6 or 13 periods (60 or 130 years) to cater for potential endogeneity. The length of the lags is dictated by the first year at which the data are available. We use the level as well as the change in fertility as outcome variables, a consideration that is not too important since fertility rates were not that different before the fertility transition, but the fertility discrepancy increased during the course of the fertility transition: The cross-region standard deviation of the log of the *CFR* was 0.073 in 1871, shortly before the fertility transition, and increased gradually to 0.276 in 1931.

In the bivariate regressions covering the period 1891-1981 in the first two columns in Table 6, the coefficients of height are highly significantly negative and have approximately the same magnitude regardless of whether time-dummies are included in the estimates. In column 3 latitude and a three-period lag of population density are added to the model, noting that population density is used for income because per capita income data are not available before 1891. Population density is lagged for only three periods because it is first available from 1861. The coefficients of latitude and population density are significantly negative and, being highly significant, height still has a significant independent effect on fertility even when economic development and latitude are accounted for. Measuring the dependent variable in six-period differences (column 4), the coefficients of all the regressors are again significantly negative and the magnitudes of the

Table 6. Effects of Height on Crude Fertility Rates (*CFR*): Italian Regions

	1	2	3	4	5	6	7	8
	CFR(t)	*CFR*(t)	*CFR*(t)	*CFR*(t)-*CFR*(t-6)	*CFR*(t)	*CFR*(t)	*CFR*(t)	*CFR*(t)
$H(t\text{-}6)$	-38.74***	-37.39***	-26.56***	-20.48***				
	(21.4)	(18.2)	(10.61)	(8.8)				
$H(t\text{-}13)$					-17.17***	-10.25**	-16.79**	
					(6.58)	(2.76)	(5.71)	
Latitude			-22.78***	-20.77***		-1.73**		
			(9.88)	(9.90)		(2.31)		
Pop. Density(t-3)			-0.83***	-0.86***				
			(7.19)	(7.86)				
$Y(t\text{-}9)$							-0.11	
							(0.44)	
Height Rom. Emp.								-8.58*
								(2.04)
Period	1891-1981	1891-1981	1891-1981	1891-1981	1981	1981	1981	1931
Estimator	FE-OLS	OLS	FE-OLS	FE-OLS	OLS	OLS	OLS	OLS
R^2	0.79	0.86	0.87	0.83	0.65	0.70	0.65	0.15
Obs.	190	190	190	190	19	19	19	12
Time-Dummies	N	Y	N	N	N	N	N	N

Notes: All variables are in decennial frequencies and are measured in logs. The numbers in parentheses are absolute t-statistics based on heteroscedasticity and serial correlation consistent standard errors. Regional dummies are included in the FE-OLS estimates. *CFR* is crude fertility rate. H is height. Y is per capita income. *, **, ***: Significant at 10, 5 and 1% levels.

coefficients are not that dissimilar to those in the level regression in column 3. This result underscores that fertility rates across regions were not that different before the fertility transition and, therefore, reconfirms that level regressions are as informative as first-difference regressions.

Thus far, we have tested our model in a panel setting. Cross section regressions are presented in the last four columns in Table 6. Consider first the estimates in columns 5-7, in which fertility in 1981 is regressed on height in 1850. Here, the year 1850 represents a year at which the fertility transition had not started and the broad population in all regions lived close to subsistence level, noting that per capita income in Italy was flat over the period 1700-1870 before it started to increase. Furthermore, the cross-state variation in income was probably very low in 1850 since the 16% standard deviation of per capita income across regions in 1891 increased to 33% in 1936. The coefficients of height are all significant, even when per capita income in 1891 and latitude are controlled for. An important aspect of these estimates is that the coefficient of height is unaffected by the inclusion of per capita income in 1891 (column 7). Thus, suggesting that income was not the root cause of the fertility transition, mediated through height, but that height had an independent effect on fertility.

Finally, fertility in 1931 is regressed on height during the Roman Empire for the 12 regions for which data are available, where the cross-region variation in the timing of the fertility transition is best captured in 1931 (using fertility in 1911, 1931 and 1936 give the same principal results).

Fertility measured close to 1981, for example, is too late because the fertility transition was completed in all regions at this time and the years around 1891 are too early because the fertility transition had not started in any of the regions at that time. The coefficient of height is significantly negative at the 10% level (column 8), but becomes insignificant when latitude is included in the model (the results are not shown). However, the insignificance of height when latitude is controlled for does not undermine height as a principal driver of fertility because measurement error for height during the Roman Empire period is likely to be large and correlated with latitude.

6.2.4. *Education as Outcome Variable.* According to the QQ-tradeoff in our theoretical framework, the fertility decline is associated with a simultaneous increase in education as parents can devote more resources per child to education as they lower their fertility. To check for the influence of height on education during the fertility transition, we treat, as outcome variables, the levels and changes in literacy and gross enrollment rates, measured as the fraction of population of school age that is enrolled in primary, secondary and tertiary education. The estimates are presented in Table 7. The coefficient of the six-period lag of height is a highly significant determinant of gross enrollment rates regardless of whether latitude and lagged population density are included in the regression (columns 1-3). The coefficient of height remains significantly positive when a six-period change in gross enrollment rates is the outcome variable and latitude and population density are included as control variables (column 4), noting that the data period starts in 1931 because gross enrollment rates are first available from 1871.

Six-period changes in literacy rates are regressed against a six-period lag in height, latitude, and a three-period lag in population density in columns 5 and 6 in Table 7. Note that 1911 and 1931 are the end years for the literacy estimates because compulsory schooling years increased during the 20th century and, therefore, ensured that literacy rates converged across regions such that the entire population was literate at the end of the century. The coefficients of literacy are highly significant and comparable to the coefficient of gross enrollment rates in column 4. To get a long-term perspective on the effects of height on literacy, we regress the level of literacy in 1931 on a 10-period lag in height and a four-period lag in per capita income (column 7). The coefficient of height remains significantly positive at the 1% level. Finally, we regress gross enrollment rates and literacy rates on height during the Roman Empire. The coefficients of

Table 7. Effects of Height on GERs and Literacy: Italian Regions

	1	2	3	4	5	6	7	8	8
	GER(*t*)	*GER*(*t*)	*GER*(*t*)	*GER*(*t*)-*GER*(*t*-6)	Lit(*t*)-*Lit*(*t*-6)	*Lit*(*t*)-Lit(t-6)	Lit(t)	GER(t)	*Lit*(t)
H(*t*-6)	14.79***	31.55***	27.00***	11.44***	7.25***	8.82***			
	(14.4)	(18.8)	(9.44)	(4.23)	(8.76)	(13.6)			
H(t-10)							2.52***		
							(5.06)		
Latitude			11.44***	4.60***	3.15***	6.01***			
			(7.00)	(4.46)	(3.15)	(6.81)			
Pop. Density(*t*-3)			3.02***	0.48	0.04	15.7***			
			(4.01)	(1.38)	(0.85)	(3.65)			
Y(*t*-4)							0.12		
							(1.31)		
Height Rom. Emp.								9.80***	10.67***
								(4.18)	(3.33)
Period	1891-1981	1891-1981	1891-1981	1931-1981	1891-1911	1891-1931	1931	1931	1931
Estimator	FE-OLS	FE-OLS	FE-OLS	FE-OLS	OLS	OLS	OLS	OLS	OLS
R^2	0.44	0.73	0.81	0.74	0.98	0.95	0.46	0.30	0.29
Obs.	190	190	190	114	57	95	19	12	12
Time-Dummies	N	Y	Y	Y	N	N	N	N	N

Notes: The numbers in parentheses are absolute t-statistics based on heteroscedasticity and serial correlation consistent standard errors. All variables are in decennial frequencies and are measured in logs. Regional dummies are included in the FE-OLS estimates. *GER* is gross enrollment rates at primary, secondary and tertiary levels. *Lit.* is literacy rate in percent. *H* is height. *Y* is per capita income. *, **, ***: Significant at 10, 5 and 1% levels.

height are significant at the 1-percent level; thus giving further support to the hypothesis that height was influential for the rise in education.

6.2.5. *Effects of Height on per Capita Income.* As a final test of the reduced form effects of height on economic development, we regress the level and the change in per capita income on latitude and lags of height and income (Table 8). The coefficients of the six-period and even the 13-period lags in height are highly significant in the regressions in the first five columns, regardless of whether time-dummies, lagged income and latitude are included in the regressions and whether the level or the growth in income is the outcome variable. Furthermore, the coefficient of height in the Roman Empire period is significantly positive.

Based on the coefficients of height in the regressions in the fourth column in Tables 6 to 8 in the six-period difference estimates (three periods for income), a one standard deviation increase in height in 1891 (1.3%) is associated with a 26.6% decrease in the crude fertility rate, a 29.1% increase in the gross enrollment rate, and a 51.4% increase in per capita income (the height elasticity of gross enrollment rates is found by dividing the coefficient by the average gross enrollment rate of 55% in 1891).

Table 8. Effects of Height on Per Capita Income: Italian Regions

	1	2	3	4	5	6
	$Y(t)$	$Y(t)$	$Y(t)$	$Y(t)$-$Y(t$-3)	$Y(t)$	$Y(t)$
$H(t$-6)	58.26***	61.31***		18.34***		
	(20.04)	(24.37)		(5.49)		
$H(t$-13)			15.19***		5.97**	
			(6.51)		(2.46)	
Latitude		15.13***		-2.43**	2.10***	
		(8.69)		(2.52)	(4.56)	
$Y(t$-9)					0.35***	
					(2.95)	
Height Rom. Empire						9.21**
						(1.86)
Period	1891-1981	1891-1981	1981	1921-1981	1981	1931
Estimator	FE-OLS	FE-OLS	OLS	FE-OLS	OLS	OLS
R^2	0.72	0.91	0.70	0.19	0.88	0.11
Obs.	152	190	19	131	19	12
Time-Dummies	N	Y	N	N	N	N

Notes. The numbers in parentheses are absolute t-statistics based on heteroscedasticity and serial correlation consistent standard errors. Regional dummies are included in the FE-OLS estimates. Y = per capita income. H is height. All variables are in decennial frequencies and are measured in logs. *, **, ***: Significant at 10, 5 and 1% levels.

6.3. **Testing the Take-Off Prediction.** The key mechanism established by unified growth theory (UGT) as the driver of the fertility transition and the take-off to modern growth is technological progress in conjunction with a child quantity-quality trade-off. Technological progress increases the return to education such that parents start investing in education and reduce their fertility (see Galor and Weil, 2000; Galor, 2011; see Madsen and Strulik, 2020 for recent empirical support of the UGT mechanism). In this section we examine whether the UGT mechanism is mediated by height, as proposed by our theory. Specifically, to test whether international technological progress acted as a mechanism that facilitated an early fertility transition in the countries with the tallest populations through the channel of imports, we infer whether height acts as a mediator through its interaction with transmission of technology. For this purpose, we estimate the following model for a panel of 18 OECD countries over the period 1840-1980:

$$\log FerG_{it} = \lambda_0 + \lambda_1 \log H_{it} + \lambda_2 \log(Pat/Pop)^F_{it} + \lambda_3 \log H_{it} \log(Pat/Pop)^F_{it} + CD + TD + \epsilon_{4,it}, \tag{24}$$

where $FerG$ is the general fertility rate (number of births by females in the reproductive age, 15-44); H is height; $(Pat/Pop)^F$ is import-weighted foreign patent intensity (foreign patents divided by their population size); CD is country dummies; and TD is time dummies. The estimation period is sufficiently long to cover the entire fertility transition in the countries that are included in our sample. The country sample is listed in the notes to Table 9 and the data sources are described in the online Appendix.

Foreign patent intensity is estimated as the weighted number of patent applications of residents divided by the population using data for 21 OECD countries (including the 18 countries used here). Bilateral imports as the share of GDP of the *exporting* country are used as weights under the assumption that imports of intermediate products gives the importing country an opportunity to produce more efficiently. For details on the weighting schedule, which is not based on simple bilateral weights but on income of the exporting country, see Madsen (2007).

International technology spillovers influence fertility rates directly and indirectly through height. For $\lambda_3 < 0$, international technological progress has a potentially stronger effect on fertility the taller individuals are, on average, in the home country. Conversely, if $\lambda_3 = 0$, then height is not a mediator of foreign technological progress.

TABLE 9. EFFECTS OF INTERNATIONAL TECHNOLOGY ON FERTILITY THROUGH HEIGHT

	$H(t)$	$((Pat/Pop)^F)(t)$	$H(t)$*$((Pat/Pop)^F)(t)$	Obs.	Sobel
FerG	-1.59(2.90)***	3.20(13.22)***	-0.63(13.22)***	2538	
Height as mediator					68.8***

Notes: All variables are measured in logs including each variable in the interaction term. *FerG* is the general fertility rate. H is height. $(Pat/Pop)^F$ is patent-population ratio. Annual data over the period 1840-1980 are used. The country sample comprises Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, the UK and the US. Country and time-dummies are included in the regressions and the t-ratios (in parentheses) are based on serial correlated and heteroscedasticity consistent standard errors. Sobel = Sobel t-test for height as a mediator of the international technology transmission under the null hypothesis that height has not acted as a mediator. *, **, ***: Significant at 10, 5 and 1% levels.

The results of regressing *FerG* on height, foreign technology, and their interaction are presented in Table 9. The coefficient of the interaction term is highly significantly negative, implying that transmission of foreign patent intensity through the channel of imports amplifies the negative fertility effect of height. In other words, for a given height, an increase in the foreign patent intensity reduces the fertility rate because it pays to invest more in education at the expense of lower fertility. Furthermore, for a given level of foreign patent-intensity, an increase in the height of the population shows that a lower level of technology is needed to elicit a fertility response when the population is relatively tall.

The effects of the increase in foreign patent intensity on fertility through height can be estimated from the derivative of (24):

$$\mathrm{d}\log FerG = (\lambda_2 + \lambda_3 \log H)\mathrm{d}\log\left(\frac{Pat}{Pop}\right) = (3.2 - 0.63\log H)\left[\log\left(\frac{Pat}{Pop}\right)_{1840} - \log\left(\frac{Pat}{Pop}\right)_{1980}\right] = -0.31,$$

where the derivative of patent-intensity is estimated as the average change in the import-weighted foreign patent-intensity for the 18 OECD countries in our sample over the period 1840-1980 and height is measured as the average height in 1980. This exercise shows that the expansion of the world technology frontier over the period 1840-1980 resulted in a 31% decline in the general fertility rate mediated by height over the same period. Since the average fertility rates declined by 54% over the same period, our model goes a long way in explaining the fertility transition in the OECD countries.

Finally, to formally test our hypothesis that external triggers affect fertility through height (mediator) we conduct a Sobel test, which essentially tests whether there is a significant reduction in the effect coming from the (Pat/Pop)-term in the fertility regression when height is added to the model and, consequently, whether the mediator effect is statistically significant. The null hypothesis that height is not the mediator is strongly rejected by the Sobel test (t=69), see Table 9. In sum, the evidence presented gives support to the hypothesis that transmission of technological progress effectively triggered the early fertility transition in the OECD and that this process was mediated by height.

7. Conclusion

In this paper we have proposed a theory of the reversal of fortune; the remarkable shift in the latitude gradient with respect to economic development, which appears to have occurred over the last roughly 500 years. We advance the hypothesis that differences in physiological constraints faced by individuals in different geographical locations can account for the observed reversal. In places where humans were bigger historically, the physiological costs of children were greater, leading to low population density early on. However, the relatively high cost of children simultaneously provided a comparative advantage in child quality investments for physiologically bigger parents, which worked to bring forth an earlier take-off. Hence, in the contemporary era historical body size should be positively correlated with economic development. Since average body mass and height exhibit a clear latitude gradient (Bergmann's rule) our theory suggests that this physiological mechanism could have been responsible, in part, for the changing latitude gradient in the course of history: A negative link between absolute latitude and population density in 1500 C.E. but a positive correlation between absolute latitude and economic development today.

In order to corroborate this hypothesis, we have developed a unified growth model which captures the above elements. Importantly, the model allows us to examine the robustness of the highlighted explanation to an important countervailing mechanism. In historical times it is plausible that a higher density of people led to more ideas. This scale effect could work to circumvent the physiological mechanism, thereby allowing the more innovative society inhabited by more but physiologically smaller people to take off earlier. We find, however, that even if knowledge diffusion is gradual, and possibly incomplete, the physiological mechanism is likely to prevail.

To substantiate the empirical implications of the theory we examine the following chain of events. We show that population density, as a proxy for economic development, was negatively related to height in the pre-1500 period. However, as the world technology frontier increased at a sufficiently strong pace, the returns to education increased and taller populations had more to gain from a reduction in their fertility and to invest in their offspring's education instead. Using annual data for 18 OECD countries over the period 1840-1980, we find that the fertility decline in response to the international transmission of technology through the channel of imports was significantly mediated through height. From the parameter estimates we inferred that more than half of the fertility transition in these OECD countries over the period 1880-1980 can be explained by the interaction between height and international technology transmission.

Furthermore, based on cross-country estimates for countries in the world, we show that countries with the tallest population in circa 1500 and in 1900 experienced the earliest fertility transitions and have the highest contemporary level of education and and per capita income. The results based on height of the 1900 birth cohort were robust to per capita income in 1900, different aspects of institutions and culture, and several geographic variables such as weather, distance to navigable water, ruggedness and several other controls. Finally, using data for Italian regions over the period 1821-2001, we showed that fertility, education, and income are significantly associated with height 6 to 13 decades earlier as well as with height in Roman times.

The findings of the paper have implications for the world inequality path over the past five centuries. While the reversal of fortune hypothesis of Acemoglu et al. (2002) has been the leading explanation for the development path across the world, we have shown that geographical factors and not only institutions have shaped development. In fact, we find that the reversal is not only limited to the West exploiting its former colonies since it occurred also within Europe.

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When the education constraint is not binding ($e_t > 0$) while the subsistence constraint is binding ($x_t = 0$), we obtain the following solution from the optimality conditions (9):

$$n_t = \frac{(1-2\gamma)\nu A_t(y_t - B_t)}{\nu A_t \rho B_t - \bar{h}}$$

$$c_t = \frac{\gamma\left(\nu A_t \rho B_t - \bar{h}\right)}{\nu A_t(1-2\gamma)}$$

$$e_t = \frac{\gamma\rho\nu A_t B_t - (1-\gamma)\bar{h}}{(1-2\gamma)\nu A_t}.$$

At this "Subsistence-cum-Education" steady state, fertility depends positively on income while the solution for c_t and e_t coincide with the interior solutions (10b) and (10c). Consequently, the education threshold remains at $\bar{A}$ and is earlier crossed in countries populated by bigger people. This implies, qualitatively, a reversal of fortune as for the "ordinary" sequence of regimes discussed in the main text. Notice that the education threshold does not depend on income or population size and that technology A cannot decline. Once education started, Malthusian dynamics cannot drive the economy back to subsistence. Instead, the economy eventually crosses the subsistence threshold and reaches the modern regime.