Human Physiological Development
and Economic Growth*

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Abstract. This chapter describes a recent attempt at introducing into economic growth theory an explicit role for human physiology in the sense of average body size. This research is motivated by the fact that overwhelming evidence exist, outside economics, in favor of a fundamental trade-off between the average size of offspring and the number of offspring, implying that a model of growth in the long run should involve both endogenous fertility and endogenous body size. We argue that the resulting framework, beyond its intellectual appeal, importantly enriches our understanding of the long-run growth process before, during, and after the take-off to "sustained growth". For instance, it provides an explanation for the puzzling fact that population density in pre-industrial times was lower in areas further away from the equator rather than higher as could be expected on the basis of the standard Malthusian model; and why latitude and economic development are positively correlated today. Moreover, we believe this framework provides new opportunities to test the Malthusian interpretation of the historical record in more credible ways than hitherto possible.

Keywords: unified growth theory, body size, fertility, nutrition.
JEL: O11, I12, J13.

1. Introduction

During the last 15 years a new strand of growth research has emerged, arguing that for fuller understanding of comparative development a much longer historical perspective is needed than what is elucidated by traditional neoclassical growth theory and its offshoots.[1] A key insight from this body of research is that demographic change is key in order to understand the pre-industrial growth record as well as the (relative) timing of the take-off to sustained growth. Malthusian demographic responses are viewed as paramount in the context of understanding why sustained growth did not emerge during most of human history, and the demographic transition is correspondingly viewed as first order in the context of the emergence of sustained growth. Evidence is accumulating that both predictions are empirically valid.[2] The research described in the present Chapter belongs to this recent strand of growth research. The main novelty lies in incorporating human physiology, in the sense of body size, into the existing research platform.

The major motivation for this effort is existing evidence, which largely is found outside economics in the fields of biology and physical anthropology, that humans (and other mammals) face a fundamental trade-off between *size of offspring* and *number of offspring*; a trade-off which arguably has been navigated throughout history. Hitherto this trade-off has not found its way into the literature on long-run growth. As a result, our understanding of the historical growth record, in as much as demography played a central role, is necessarily incomplete. The omission raises the tantalizing questions of whether differences in the nature of how this trade-off was operated in different countries or regions around the world translated into differences in comparative development early on, and into differences in terms of when the process of sustained growth emerged. The research described below argues that it did; introducing human physiology into growth theory importantly enriches our understanding of comparative development in the past and in the present.

We proceed as follows. In the next section we lay out existing evidence on the size-number trade-off. In Section 3 we present a set of puzzles and issues pertaining to the long-run growth agenda, that are either resolved or addressed in important ways by the introduction of human physiology. In Section 4 and 5 we then survey a recent set of attempts at doing just that. In

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[1]The pioneering contribution is Galor and Weil (2000). See also Galor and Moav (2002); Lucas (2002); Hansen and Prescott (2002); Cervellati and Sunde (2005); Strulik and Weisdorf (2008) and de la Croix and Licandro (2013). The literature is surveyed in Galor (2011).

[2]On the historical growth record, see Ashraf and Galor (2011). On the significance of the fertility transition in generating sustained growth see e.g. Cervelatti and Sunde (2013) and Dalgaard and Strulik (2013).

Section 6 we revisit the puzzles issues from Section 3 in light of the developed theory, before we conclude in Section 7.

2. The Size–Number Trade-off

Convincing evidence in favor of a quantity-quality trade-off is found in biology.[3] At the level of the individual mammalian species, the inverse association between body size and rate of reproduction is by now well documented (Charnov and Ernest, 2006; Walker et al., 2008). Indeed, experimental studies manipulating offspring number or environment exist, which document the trade-off (Ruff, 2002). In the context of human populations micro evidence of the size-number trade-off is also available. In subsistence societies the inverse association between family size and size of the offspring has received support by Hagen et al. (2006) who examine the trade-off in the "Shuar" society, which resides in the tropical rainforests of Ecuador. Similarly, Walker et al. (2008) demonstrate a negative link between body size and family size across a sample of 16 subsistence-based societies.

From the perspective of the present study the evidence amassed by biologists and anthropologists is of substantive importance, since it makes plausible that the size-number trade-off is a fundamental one. The systematic link between reproduction and body size in economically primitive societies suggests that the trade-off must have been active for a very long time; certainly before the take-off to sustained growth occurred in Western Europe. As a consequence, temporary income gains should be expected to translate into greater nutritional expenditure on children, implying "quality" investments. The fact that the trade-off transcends the human species implies that the mechanism responsible for it must be generic.

In modern societies evidence of the trade-off is found as well. In an early contribution Douglas and Simpson (1964) examined the results from a national survey of health and development in the UK. Specifically, the survey focused on 1,557 boys and 1,456 girls born in 1946. The physical development of these children was tracked and central health indicators were collected, including height, date of entry into puberty and age of menarche. In addition socio-economic indicators for the households were obtained, including occupation and educational background of the parents. This enabled Douglas and Simpson to categorize the families into social classes, ranging from

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[3]This section largely follows the discussion in Dalgaard and Strulik (2012, Section 2).

Figure 1. Body Size of UK Girls at Age 7 and the Number of Siblings
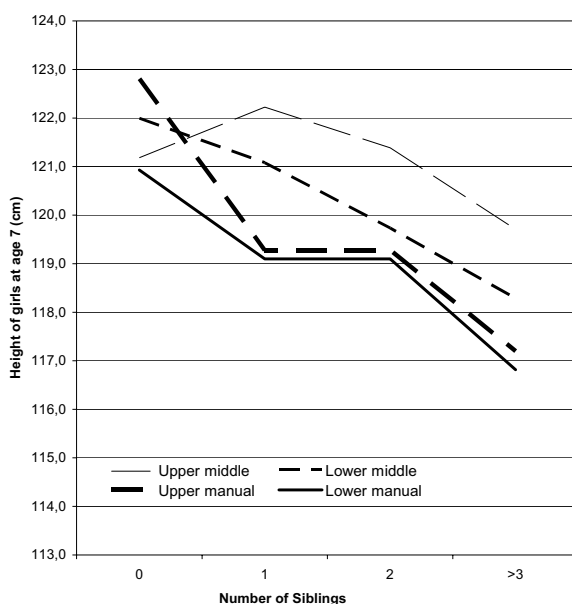
Notes. The individual lines refer to individual social classes, as defined in the text. Source: Dalgaard and Strulik (2012).

"lower manual" to "upper middle".[4] Figure 1 shows the association between the mean body size of girls at age of 7 and the number of siblings in the family, as reported by Douglas and Simpson.

The general pattern that emerges is one where a large family size is associated with smaller mean body size of the offspring. In addition, for the size of the family given, the average body size of the offspring, measured by height, generally increases as the socio-economic circumstances improve. Douglas and Simpson document that similar patterns persist to the ages of 11 and 15 for both boys and girls. The 1946 cohort has more recently been analyzed by Kuh and Wadsworth (1989). Their regression-based analysis confirms the general impression conveyed by Figure 1; conditional on a host of environmental factors, each additional sibling implies a reduction in mean height of about 6 mm.

At a higher level of aggregation Weir (1993) demonstrates a strong negative association between height and fertility rates across regions in France during the period 1840-1911. Following

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[4]In the "upper middle class" we find parents with a secondary education, families where the father has a non-manual occupation, and where at least one of the parents was brought up in a middle class family with similar characteristics. In contrast, the "lower manual" group is characterized by the father being a manual laborer, by both parents only having primary education, and by upbringing; both parents were raised in a working-class family. Between these two extremes we find the "lower middle class" and "upper manual class"; these groups are differentiated from "upper middle class" and "lower manual class" mainly by their educational attainment.

up on Weir's findings, Schneider (1996) documents similar patterns across nine European countries, covering the period 1750-1920. Controls for health and income do not overturn these findings. In Dalgaard and Strulik (2014a) we perform a rigorous out-of-sample check of Schneider's study by examining the viability of his results in sample of 13 European countries from 1856-1980. We find that the key result, involving a negative link between average stature and fertility around the birth year of the cohort, holds up. In sum, the evidence discussed above pertaining to human societies as well as non-human samples documents an operative quantity-quality trade-off between size and number of offspring, which hitherto has been ignored in the literature on long-run growth.

3. Puzzles and Issues

3.1. **Testing the Malthusian Model.** The standard Malthusian model offers a simple and compelling explanation why episodes of technological change did not translate into sustained increases of income per capita during most of human history. Technological change, by temporarily increasing income, leads to population growth which eventually serves to push income per capita back to its initial level, due to (natural) capital dilution. Hence, the key proposition of the Malthusian model is that technological progress (i) leads to greater population density and (ii) leaves income per capita unchanged.

The first part of the proposition, involving a positive influence of technological change on population density, has been successfully tested empirically; whether one examines the determinants of population density in year 1 C.E., 1000 C.E. or 1500 C.E., a strong positive link between the level of technological sophistication and population density is obtained across a large cross section of countries. Moreover, a compelling case can be made, that technology was (in part) the *cause* of greater population density (Ashraf and Galor, 2011). Naturally, the quality of the data on population density (which is due to the efforts of McEvedy and Jones, 1978), and on the measures of technology, can be questioned. But from an econometric point of view these problems should make it much harder to obtain a significant correlation between the two variables; the issue of data quality therefore works against the hypothesis being tested (at least, as long as the measurement error is classical, see Stefanski, 1985).

Turning to the test of the second Malthusian proposition, the absence of a long-run impact of technological change on per capita income, matters are less clear. While Ashraf and Galor

find support for this proposition, some doubts may linger. A concern is that data on income per capita during the pre-Colombian era is (unsurprising) very scarce. In the data base assembled by Angus Maddison (2001), which currently is the standard source in the literature, only 31 country-observations are found for 1500 C.E., 28 for 1000 C.E. and 30 for 1. C.E.. Moreover, more than half of the observations are for European countries (16 in 1500 C.E.) while Africa and the Americas are only represented by two and three observations in 1500 C.E. This state of affairs very likely implies that the sample variation in the extent of technological sophistication is artificially small in the income sample, compared to what one would expect to find in a sample covering the world to a fuller extent. As a result, it becomes less likely, on *a priori* grounds, that one would be able to obtain a statistically significant correlation between technological sophistication and income, even if the Malthusian proposition was wrong.[5] Moreover, measurement error on the dependent variable (income) and the independent variable (technology) will make it less likely that the Malthusian theory is rejected, and the measurement error issue will be aggravated if indeed the aforementioned problem of limited sample variation is present.[6]

Unfortunately, there is little reason to expect that high quality GDP per capita data with worldwide coverage for the pre-Colombian era will be available any time soon. As a result, a key proposition of the Malthusian model remains difficult to test in a fully convincing manner. As argued below, allowing human physiology to be endogenously determined within the model opens the door to new tests of the Malthusian theory, with no need for new data on income per capita.

3.2. **Physiological Development in Pre-Industrial Times.** As discussed in Section 2, there seems to be a strong case to be made that households have been navigating a quantity-quality trade-off for a very long time. They had to decide between how many offspring to rear and how well to rear them in terms of nutrition. Now, if both "goods" are viewed as normal goods, the implication would be that in times of plenty, perhaps brought on by new technologies in farming, households would respond by expanding the size of their family and by providing

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[5]To illustrate, suppose the Malthusian proposition is wrong; imagine that per capita income is affected positively by technology, and perhaps random factors. Next suppose that the data set only contains information on countries that happened to be identical with respect to technology. Then a formal test would suggest that technology is uncorrelated with income (which in the thought experiment then exhibits variation only because of random shocks), despite the fact that this is not actually the case, which would be evident if more data was available covering countries that were decidedly different in terms of technology.

[6]More formally, the OLS estimate for the parameter b in the regression model $y = a + bx + u$, where u is a noise term, can be written $\hat{b} = b + cov(u,x)/var(x)$. If the covariance $cov(u,x)$ is negative (because of measurement error on x, say) the obtained estimate is biased towards zero, and more so when $var(x)$ is "small".

more nutrition per child. As a consequence, one would expect the next generation of adults to be physiologically bigger compared with their parents. Moreover, if bigger people are more productive people these bigger bodies might be sustainable, until the next innovation arrives.[7] This would seem to suggest that body size should have increased gradually, as the level of technological sophistication rose.

Empirically, this does not seem to have been the case. Koepke and Baten (2005) study the evolution of European average body size, measured by height, over the last two millennia. Average height is calibrated using skeleton remains. Their key finding is that average height, while occasionally undergoing (significant) cyclical variation, has been constant between the first century C.E. and until the 18th century. Similarly, Steckel (2004) also finds no evidence of secular increases in average height in Europe, until recently. If anything, average height seems to have declined albeit the statistical significance of the decline is hard to gauge. The analysis in Kunitz (1987), which pertains to England, also fails to detect an upward trend in average body size, until recently.

This evidence begs an explanation. Why did we not see step wise improvements in physiological development, in tandem with technological improvements? Why did average body size stagnate (at best) until recently? What does it tell us about the evolution of average income?

3.3. **Physiological Development during Industrialization.** A remarkable facet of the English and American Industrialization concerns the evolution of average body size. Rather than following a monotonically rising tendency, as would perhaps be expected in view of observed improvements in average living standards, average body size first *declined* before it began its ultimate rise, cf Figure 1, panel A. Since these data speak to army recruits, a skeptic might voice concerns about the representativeness of the sample, and thus the pervasiveness of the observed U shaped path. In this regard it is worth noting that a similar non-monotonic path is found in adult mortality (cf Figure 1, panel B). As average body size in practise is a good predictor of adult mortality (Fogel, 1994), this provides some assurance that the "dip" in body size is "real".
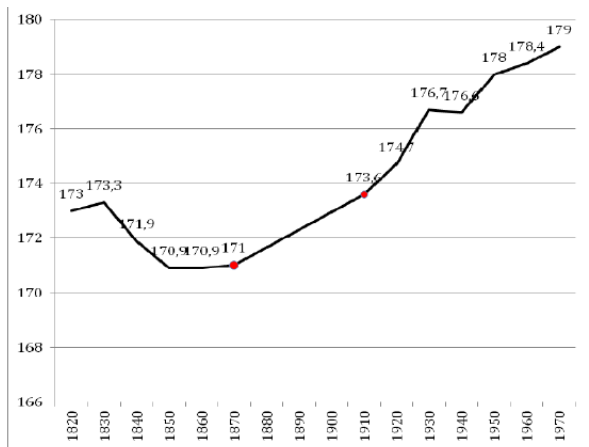
Over the years a number of possible explanations for this puzzling trajectory have been proposed in the anthropometric economic history literature, but no attempts have been made to provide a formal argument, which at the same time accounts for other salient features of the data for the period in question: the fertility decline, the growth acceleration, and structural
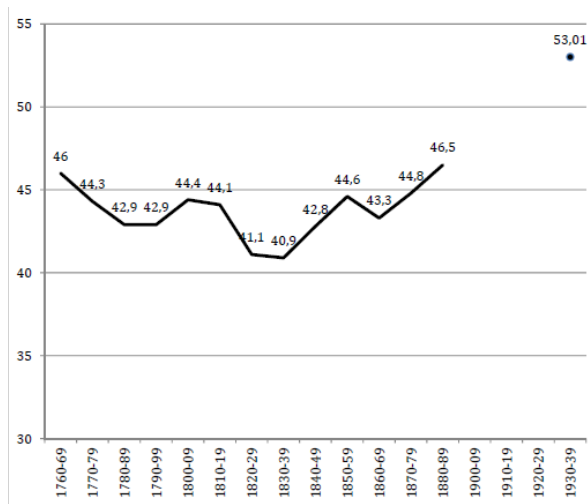
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[7]See e.g., Fogel (1994) and Weil (2007) for evidence on the positive link between body size and labor productivity.

FIGURE 1: AVERAGE BODY SIZE AND ADULT MORTALITY DURING INDUSTRIALIZATION

A: Average height, by birth cohort   B: Life expectancy at age 20, by birth cohort

Notes: Panel A shows average height (cm) by birth cohort in the US. Sources: Komlos (1987; 2007). Before 1870 the data refers to army recruits, after 1910 it is based on population surveys. Panel B depicts life expectancy at age 20 by birth cohort, also for the US. Data source: Pope (1991)

change (see Steckel, 2009, for a review). Below we discuss our own attempt at bridging this gap in the literature.

3.4. **The Reversal of the Latitude Gradient during Development.** Figure 2 depicts the correlation between absolute latitude and population density in 1500 C.E. As can be seen, when we rely on the within continent variation (continent dummies are implicitly controlled for in the figure): places further away from the equator were more sparsely populated at the dawn of the Age of Discovery. The standard Malthusian model would seem incapable of explaining this regularity. In a standard Malthusian framework, if mortality is endogenous, regions with greater disease incidence (and thus greater extrinsic mortality rates) should be characterized by lower population density, and higher per capita income, for the level of technology given. Since it is well established that pathogen diversity and thus historical disease incidence is declining in the distance to the equator (or rising in average ambient temperature), the standard Malthusian model would suggest that in pre-industrial times, population density should have been greater (and income per capita lower) as one moved away from the equator, ceteris paribus. Yet this is not what the available data suggests.[8]

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[8]On the link between climate and pathogen diversity and prevalence, see Guernier et al. (2004) and Dunn et al. (2010).

Figure 2: Population density 1500 C.E. and distance to the equator
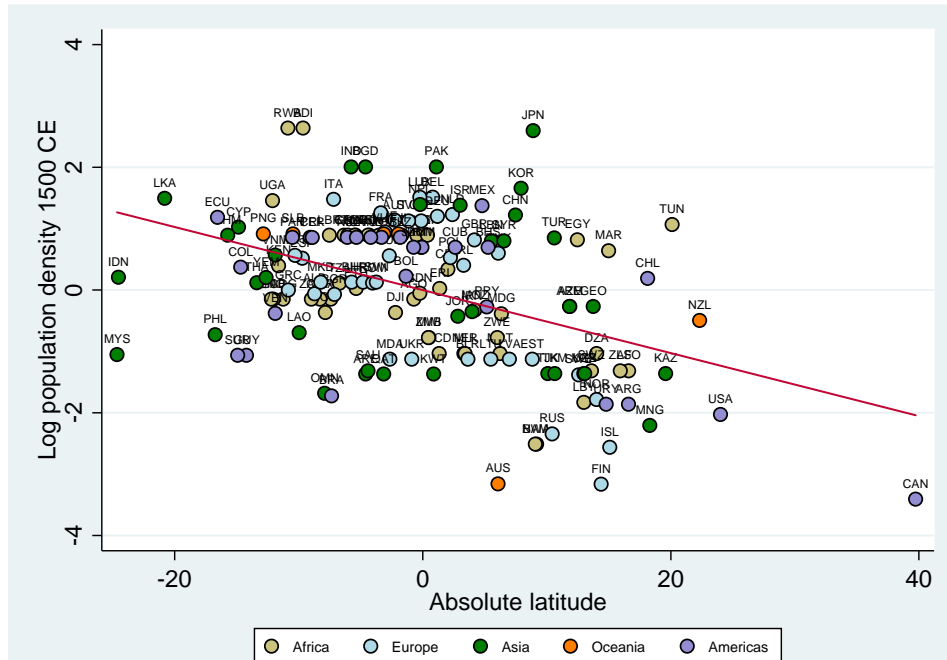
The figure show the correlation between absolute latitude and population density in 1500 C.E. across the world. Continental fixed effects have been partialled out, and the depicted line is estimated by OLS. Source: Dalgaard and Strulik (2014b).

Another way to look at the link between latitude and population density is by assuming latitude is picking other information up, beyond that which pertains to survival. In particular, the observed pattern could be taken to mean that countries further away from the equator were less technologically sophisticated in 1500 C.E. To be sure, this is a viable interpretation. But in this event we must recognize that during the last half millennium the world has experienced a reversal of fortune; today prosperity rises rapidly as one moves away from the equator. What forces might have helped bring about this remarkable change in the "latitude gradient"? Below, we argue that by introducing endogenous physiology into otherwise standard unified growth theory we may obtain an explanation.

4. A Simple Model of Pre-industrial Stagnation

In this section we sketch a simple model of long-run growth for the pre-industrial era (a simplified version of Dalgaard and Strulik, 2012). Consider an OLG economy in the process of development. Time is discrete and extends into the infinite future. People live for two periods:

childhood and adulthood. The economy is closed and produces a unique output good employing technology, land, and body mass augmented labor.

4.1. **Production.** Output per worker, $y_t \equiv Y_t/L_t$, is produced using the production function $y_t = A m_t^\phi L_t^{-\alpha}$, in which A is technology, m_t is average body mass (kg) and L_t is the size of the labor force. Implicitly, land has been normalized to one. In each period we assume the representative member of the labor force is remunerated by her average product, y_t, in keeping with e.g. Galor and Weil (2000). The presence of body mass in the production function is motivated by the idea that more muscle force allows more output to be produced. This interpretation allows us to gauge the likely size of ϕ, which we return to below.

4.2. **Physiological Elements I: Subsistence Requirements.** During adulthood individuals make economic decisions. However, we shall require from the adults that they by default abide by a fundamental physiological constraint. Namely, that they consume food so as to cover their basal metabolic rate; the amount of energy required to keep the body functioning when at rest. Since Kleiber (1932) it has been known that metabolic needs rise with body mass in keep with the law $B_t = B_0 m_t^b$, where $b = 3/4$. This association, known as Kleiber's law, holds across an amazing range of mammalian species; from the shrew to the whale (e.g., West and Brown, 2005). Moreover, the equation (right down to the parameter value for b) can be given microfoundations as a manifestation of how energy is diffused within organisms subject to natural selection (West et al, 1997; Banavar et al., 1999).

As alluded to above, Kleiber's law speaks to humans (mammals) at rest. During pregnancy, however, basal metabolism is elevated. Specifically, metabolic needs rises with a factor $\rho < 1$ per child (e.g., Prentice and Whitehead, 1987). As a result, we shall require from the representative individual, with n_t offspring, that she consumes for herself energy to the amount of $(1 + \rho n_t) B_t$.

4.3. **Individual Optimization.** All individuals live for two periods. In the first period individuals are children and live of the nutrition offered by their parents. This is the period of body growth. In the second period individuals are adults and their body size is pre-determined by past investments. Hence, individuals value family size, n_t, as well as the amount of nutrition they can offer each of their offspring, c_t.. Formally they maximize utility $u_t = \gamma \ln(c_t) + \ln(n_t)$. In each period they divide their income, once their basal metabolic needs have been covered, $(1 + \rho n_t) B_0 m_t^b$, between quality and quantity of kids.

Notice that this problem involves the size-number trade-off documented in Section 2; conditional on income above subsistence requirements, parents have to divide their income between nutrition of their offspring (quality) and family size (quantity). The model can be extended to allow for parental non-food consumption, time costs of children, and to allow body size to enter the utility function rather than child nutrition (see Dalgaard and Strulik, 2012).

In the present setting we obtain the following solution for fertility and nutritional spending

$$n_t = \frac{(1-\gamma)\left(y_t - B_0 m_t^b\right)}{B_0 m_t^b \rho}, \qquad c_t = \frac{\gamma}{1-\gamma} B_0 m_t^b \rho.$$

Two observations are worthwhile. First, the model preserves the standard Malthusian feature: when income goes up, fertility expands. Second, bigger parents have a relative preference for child quality investments. The reason is that metabolic costs of child quantity (on the margin: $B_0 m_t^b \rho$) are greater for bigger parents, for which reason they will tend to lower fertility and increase investments in child quality. In the present setting quality investments per child are independent of income. However, this result is modified if parents face a time cost of children (Dalgaard and Strulik, 2012). Yet, note that total nutritional spending on offspring $c_t n_t$ is in fact increasing in income.

4.4. **Physiological Elements II: Dynamics.** The size of the labor force evolves in the standard fashion, $L_{t+1} = n_t L_t$. People are reproducing in proportion to their number. But what about body size? In Dalgaard and Strulik (2012) we adapt the model of ontogenetic growth due to West et al. (2001) to the present generational setting. We start from an equation of energy conservation, stating that the amount of energy intake during ontogenetic growth is spent on maintaining and repairing initial body cells after weaning (until then the mothers' metabolism is doing the work) and in order to increase the number of body cells. Exploiting the fact that body size equals the weight of a cell multiplied by the number of cells and assuming that initial body size after weaning is proportional to the size of the mother, as documented by the literature on life history (Charnov, 1993), we derive an intergenerational equation of motion for body mass, formally given by $m_{t+1} = ac_t + (1-d)\mu m_t$.

It is worth observing that the extent of heat loss is implicit in the parameters. As discussed below, there is good reason to believe that humans have adapted to colder climate zones via adjustments in their body proportions to allow for less heat loss. In particular, Allen's rule states that for (most) mammalian species the surface to volume area declines as one moves away

from the equator (Allen, 1877); in the human species this can occur via a relative shortening of body extremities (arm and leg length) relative to trunk size. The most natural interpretation is that this move serves to lower heat loss (as heat is transmitted via the surface area), which is an obvious advantage in colder climates. Allen's rule is supported, using data for traditional societies, in e.g. Ruff (1994), Holliday (1997), Katzmarkzyk and Leonard (1998), and in a cross country setting by Dalgaard and Strulik (2014b). As shown in Dalgaard and Strulik (2012) it is captured in the equation of motion for body size by the parameter d, which is lower in colder environments.

The dynamics of the model are characterized by a system equations of motions for population size and body size, determined by the households' fertility and nutrition decisions. It can be shown that there exists a unique (non-trivial) steady state (m^*, L^*) at

$$m^* = \left(\frac{a\rho B_0 \gamma}{d(1-\gamma)} \right)^{\frac{1}{1-b}}, \qquad L^* = \left[\frac{(1-\gamma)A}{B_0(1-\gamma+\rho)} \right]^{\frac{1}{\alpha}} (m^*)^{\frac{\phi-b}{\alpha}}.$$

Interestingly, we observe that the implied labor productivity (income) at the steady state, $y^* = B_0(m^*)^b(1-\gamma+\rho)/(1-\gamma)$, is a simple mark-up on basal metabolic needs, $B_0(m^*)^b$. It is a mark-up since income also needs to be able to fund consumption of the offspring. Accordingly, absent adequate measures of y^* the model's predictions regarding long-run living standards can be examined via average body mass. This is a useful result in that data on y are extremely scarce for most of the period during which the Malthusian model could be considered a good proxy for the actual state of affairs.

In the present case the stability of the steady state is ensured as long as $b < 1$ and $\alpha < 1$. This state of affairs is modified in the more general setting, where the dynamics of average body mass depend on population size as well as body mass, which occurs because nutrition per child becomes income dependent once time cost of children are introduced (Dalgaard and Strulik, 2012). In this case, stability of the steady state requires that $\alpha < 1$ and $\phi < b$. This means, perhaps surprisingly, that the standard Malthusian assumption that $\alpha < 1$ (the 'positive check'), is not sufficient to guarantee stability of the Malthusian steady state. Additionally, $\phi < b$ has to hold, which we call the 'physiological check'. This restriction says that when body mass expands the metabolic requirements increases more than output. The assumption guarantees that body mass, despite being positively influenced by income at the household level, does not increase in the long-run.

In practise the physiological check is quite reasonable, from an empirical standpoint. As alluded to above, body mass enters the production function to capture the impact from 'muscle force on output. With this in mind it becomes possible to gauge the size of ϕ. The argument is as follows. Muscle force is proportional to muscle cross-section area, measured in meters^2. As a result, it rises with weight as $m^{2/3}$ (e.g., Astrand and Rodahl, 1970; Markovic and Jaric, 2004). Naturally, muscle force is not equally important for all tasks in production. 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 practise, one would then probably expect a positive exponent, which is bounded from above at 2/3. Observing from Kleiber's law that b is 3/4, the physiological check follows.

Inspection of the steady state reveals that in the long run, technology (A, α, ϕ) only affects population density but leaves body mass and labor productivity unaffected. The model thus generalizes the standard Malthusian result that changes in technology only serve to increase population density, yet leave labor productivity unaffected; in the present framework we can additionally show that average body mass also remains unaffected. This result might have been anticipated from the solution to the household problem, where evidently changes in income do not influence child consumption. Accordingly, in the short run, innovations only serve to temporarily increase fertility. Eventually, due to diminishing returns to labor income, income falls back to its initial level, leaving only population density larger.

In the richer model developed in Dalgaard and Strulik (2012) these results also apply despite the fact that temporarily higher income increases investments in nutrition per child. In the more general setting the requirement that parents cover their basal metabolic needs gets important. While the "first generation" after a technological improvement grows larger and more productive, it also grows more energy requiring. This means that nutritional investments per child inevitably decline (along with fertility) even though the level of income has not declined across generations due to the elevated metabolic needs of the parent. The fact that these elevated metabolic costs carry a "bite" is assured by the existence of the physiological check. In the long run, therefore, innovations still only serve to elevate population density but leave average body mass and labor productivity unaffected.

Changes in the physiological parameters (a, d, B_0, ρ), in contrast, influence body mass, population density and labor productivity in the long-run. More precisely average body size is positively affected if a or d declines, or if B_0 and ρ increases. Further, such changes will induce higher steady state labor productivity, y^*, and - provided the physiological check holds - lower population density. These results generalize to the model developed in Dalgaad and Strulik (2012). As mentioned above, there is good reason to believe that humans have adapted to colder climatic conditions in the aftermath of the exodus from Africa. This may have occurred through genetic selection (e.g. Ruff, 1994). Another possibility, however, is that plasticity in the growth process has allowed for changes in body proportions to occur (James, 2010). Either way, such changes would imply that the (average) surface-to-volume ratio would end up exhibiting systematic variation across the world: greater surface-to-volume ratios would be found near the equator.

As explained above we can capture the consequence of such changes in human populations by the parameter d; thus being lower in high latitude areas. The prediction offered by the model is that individuals in colder climatic zones should grow bigger, measured by lean body mass, m^*. The intuition is simple. In areas where d is smaller less energy is "wasted" on heat loss implying that more of the nutrition goes into body growth. Notice that this result implies a positive climate gradient in average body mass in the pre-industrial context. In fact, this is also a regularity known in the field of macro ecology, which is named Bergmann's rule (Bergman, 1847). Like Allen's rule it has received support across traditional human societies (Roberts (1978), Ruff (1994), Katzmarzyk and Leonard (1998) and Gustavson & Lindenfors (2009)) and across countries (Dalgaard and Strulik, 2014b). The model thus predicts that "Allen's rule implies Bergmann's rule". Moreover, this reasoning suggests that societies further away from the equator, historically, were characterized by greater labor productivity. Hence, genetic change or plasticity in the growth process, prompting variations in human physiology in the pre-industrial era should produce differences in income per worker in pre-industrial times.

In addition, provided the physiological check is operative, greater average body mass should come at the cost of lower population density. As a result, the prediction would be that, although average body mass and labor productivity would rises as one moves away from the equator, population density should decline with absolute latitude. This prediction is indeed borne out in the data, as discussed in Section 3.

5. Beyond Stagnation

Whereas the theory discussed above pertains to the mechanics of development for most of human history it is clearly incapable of describing the more recent development trajectory whereby income per capita has started rising secularly, fertility has declined and average body size has grown systematically. In this section we describe two recent attempts (Dalgaard and Strulik, 2014a,b) at explaining how the economy was released from stagnation.
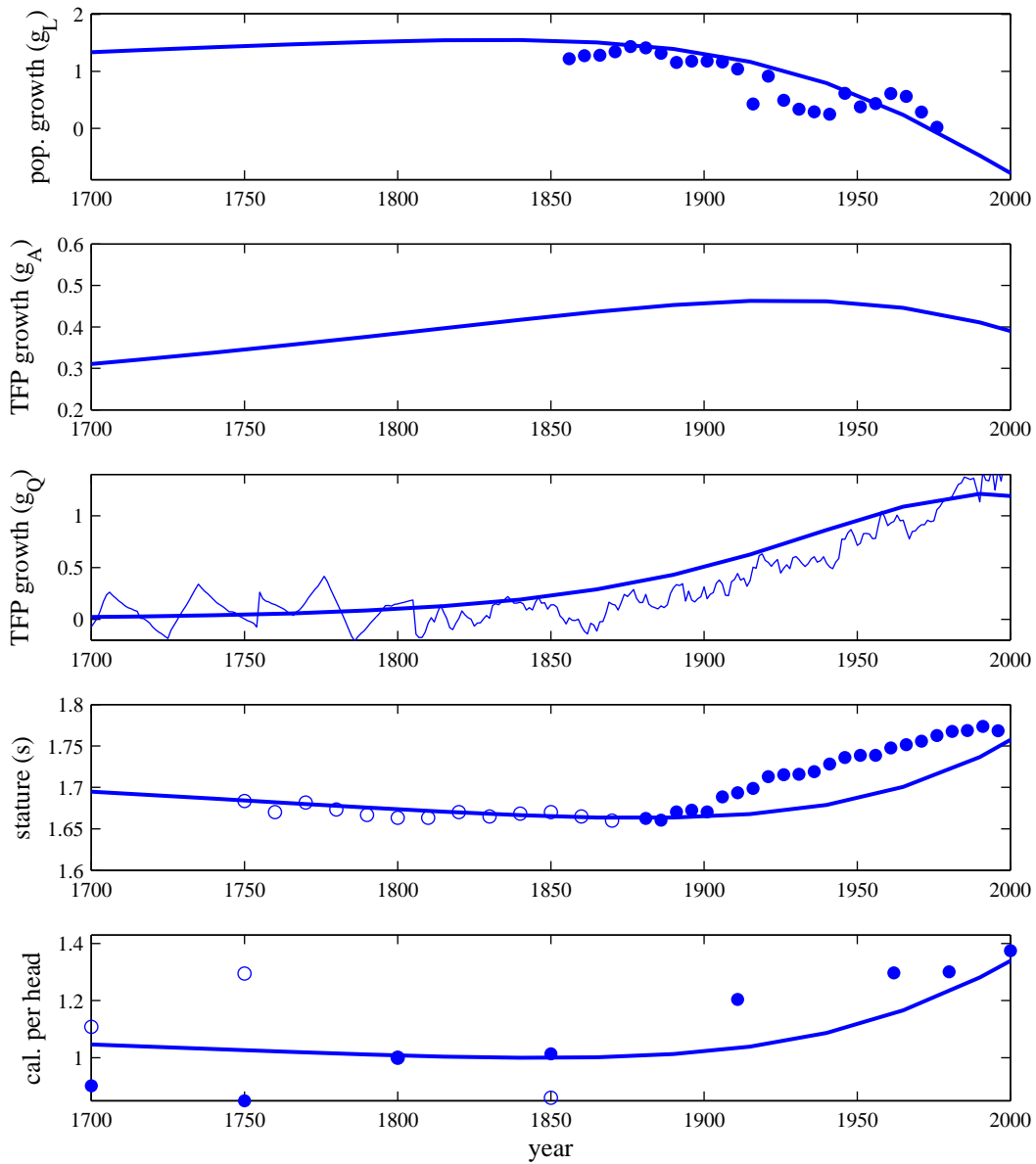
5.1. **The Price of Child Rearing.** In Dalgaard and Strulik (2014a) we explore a two-sector version of the basic Malthusian model featuring endogenous body size. This model specifically involves two key extensions, which together generate new results on the quantity-quality interaction along the demographic transition and the take-off to growth.

First, the model involves an agricultural sector, where diminishing returns to labor input prevail due to the presence of a fixed factor (land), and an industrial sector featuring constant returns to labor input. In both sectors technological change advances endogenously due to learning by doing. Hence, as the economy undergoes structural change, whereby labor shifts out of agriculture and into industry, the relative speed of technological change shifts in favor of industry.

Second, households derive utility from child quality and quantity along with parental non-food consumption. Moreover, preferences are specified such that they abide by a "hierarchy of needs" principle: In a time of crisis (declining household income) parents will try to smooth nutrition for children harder than family size, but take most of the adjustment in non-food consumption. As discussed in Dalgaard and Strulik (2014a), this behavior is broadly supported by empirical analysis of household behavior during crisis, and conceptually via work in psychology. Note that the "flip side" implication of the hierarchy of needs is that when income *rises* households will eventually spend their income on non-food items. In this manner the theory abides by Engel's law. Another implication of the assumptions made on preferences is that child quantity (fertility) is determined by the relative price of provisions: When the relative price of food increases households respond by lowering family size and instead intensify investments in child quality (nutrition per child).

Figure 3 depicts the resulting development trajectory. During early stages of development most of the population is preoccupied with food procurement; i.e., employment is mainly in agriculture. As a result, productivity growth is faster within agriculture than outside agriculture.

Figure 3: Long-Run Economic and Physiological Development

Bold lines: model prediction for England. Dotted lines: Data. Source: Dalgaard and Strulik (2014a, Figure 4).

The relative price of agricultural goods is thus declining, favoring investments in the quantity of children. Rising fertility raises overall productivity growth, due to the positive influence of population growth on learning-by-doing generated knowledge. While fertility thus is increasing, quality investments are modest, leading to a (weakly) declining body size of the representative individual. However, as a consequence of Engel's law and productivity growth in both sectors, employment is gradually being shifted towards non-food activities. Eventually, productivity

growth in the non-agricultural sector exceeds that of agriculture. As a result, the relative price of agricultural goods begins to rise. This shifts the balance between quantity and quality investments at the level of the household; parents respond to the changing relative price by investing more heavily in quality and less in the quantity of children. Correspondingly, average body size rises, whereas fertility declines. In the long-run the economy ventures onto a growth path featuring constant growth in income per capita. Overall, the model therefore accounts for the escape from Malthusian stagnation along with three salient features of the long-run development trajectory: structural change, the fertility transition and what one might label the "physiological transition" that eventually allows average body size to rise secularly.[9]

5.2. **The Rise of Human Capital.** In Dalgaard and Strulik (2014b) we examine the consequences of adding another dimension of child quality – education - to the Malthusian framework discussed above. Compared to the baseline Malthusian model we add three new elements.

First, we modify preferences. In Dalgaard and Strulik (2014b) parents value family size, own (non-food) consumption and child quality in two dimensions: nutrition and education. As in Dalgaard and Strulik (2014a), non-food consumption is assumed to be a second order priority, ensuring that when households become sufficiently poor they go to a corner where the focus is solely on child quality and quantity. Meanwhile the two dimensions of quality are assumed to be imperfect substitutes. Second, we add endogenous skill formation. The process of human capital accumulation involves a non-convexity: even absent deliberate investments in schooling *some* human capital will be passed on from generation to generation. Moreover, following Galor and Weil (2000) we assume that as technology advances the perceived return on formal skill accumulation is elevated. Third, technology evolves endogenously and is stimulated by human capital augmented labor.

These three elements, and the physiological components of the model, interact in the following way. At early stages of development both income per capita and the level of technology is very low. As a result, households do not spend resources on non-food items, and they do not provide formal education for their offspring due to the presence of the non-convexity in skill formation. The model thus "collapses" to the Malthusian baseline discussed above. However, as technology advances (due to a scale effect from population) income per capita rises gradually

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[9]It is worth noting that despite the extensions of the basic structure beyond Dalgaard and Strulik (2012) we can nevertheless confirm the principal findings for the Malthusian era, as discussed above, as long as technology is assumed to be parametrically fixed.

since population growth is unable to completely offset the influence from rising productivity. Eventually, therefore, households start spending on non-food items. Moreover, fertility rises along with total spending on child nutrition; on a per child basis, however, nutrition does not expand. Finally, once a sufficiently high level of technology has been reached, households start spending on child quality in the sense of both nutrition and schooling. At this point the fertility transition sets in, and quality investments intensify. The economy takes off to sustained growth. In the long-run the economy converges towards a balanced growth trajectory featuring constant investments in education, constant average body size, constant fertility and growth in income per capita. During transition the economy ventures through the fertility transition and the take-off in average body size.

While the theory thus provides an auxiliary mechanism by which a country may emerge from stagnation in physiological terms (as well as economically), the main objective of Dalgaard and Strulik (2014b) is to examine the implications of physiology for the relative timing of the take-off. Specifically, the theory suggests that countries that *initially* were facing different physiological constraints, attributable to differences in body size and shape, will take off at different points in time. In particular, in places where individuals were physiologically bigger, due to selective pressure or plasticity in the human growth process, the theory predicts that the onset of growth will occur earlier. The intuition is simple. In places where individuals are physically bigger the costs of child quantity will be greater, on physiological grounds, as shown in the model above. Consequently, such parents will need less "encouragement" to lower fertility and start investing in education. As a result, the fertility transition can occur at lower levels of technological sophistication, ceteris paribus.

A countervailing force, however, is that societies where people are bigger tend to be less densely populated, which discourages technological change in so far as we view the economy as a closed system. Hence, in societies that initially were inhabited by smaller but more people, technology advanced more rapidly and the take-off could occur earlier since they manage the "threshold" level of technology sooner than the "big-but-few" societies. To explore the issue of who takes off sooner in detail, Dalgaard and Strulik (2014b) provide a multi-regional version of the model described above, where we allow for gradual and possibly incomplete diffusion of ideas across borders. Our numerical experiments suggest that for a large range of parameter values the society inhabited by larger individuals takes off sooner. We show, for instance,

that if societies asymptotically share all knowledge, then places featuring physiologically bigger people will transit to the modern growth regime relatively earlier unless the diffusion lag in the transmission of ideas is more than 12 generations, which in our experiments translates into 720 years. Accordingly, initial conditions with regards to human physiology, shaped thousands of years ago, might have contributed in a significant way to the formation of the global income distribution that we observe today.

6. Revisiting Puzzles and Issues

6.1. **Testing the Malthusian Model.** As shown in Section 4, in the long run, income per worker should reflect basal metabolism and therefore average body size. Accordingly, one may test a key prediction of the Malthusian model (the absence of income improvements in face of technological change) by using average body mass as independent variable.

In principle data on lean body mass, for most of human history, could be constructed using skeleton remains. In the literature on physiological anthropology methods that can be employed in this regard have been developed, and are well validated (Auerbach and Ruff, 2004). For example, with data on on femoral head anterior-posterior breadth (FH) lean body mass can be calibrated using the formula developed by Ruff et al. (1991):[10]

$$m = (2.741 \cdot FH - 54.9) \cdot 0.90. \tag{1}$$

Large sample data sets that report on FH are not commonly available at present. The key point, however, is that such data *could* be constructed. With proper dating on the underlying skeletons, one could even imagine time series estimates being constructed, with reasonable reliability and relatively broad world wide coverage.

It is worth noting that the use of such methods have already been employed in the anthropometric economic history literature (Steckel, 2009 for an overview). However, the focus has long been on estimating body height, which can be done using measurements of femoral maximum length. In practise, therefore, what would be needed is a shift of attention to another part of the same bone that hitherto has been in focus in the literature.

It is also worth stressing that while height and body mass generally are positively correlated, height can be a misleading proxy for lean body weight if societies with different genetic make-up

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[10]This formula pertains to males. A slightly modified one exists for females.

(or who simply exposed to different ambient environments) are compared, as would be the case if the Malthusian theory is to be exposed to tests across a large number of countries, or regions. For example, in the Dogon tribe (residing in modern day Mali) average male body mass was 58.9 kg and average male height was 170.3 cm when measured by Froment and Hiernaux (1984). In comparison, the male members of the Iglulik Inuits (residing in northern Canada), reported on by Eveleth and Tanner (1976), weighted 69.3 kg on average, yet measured only 165.3 cm. In this case, the use of height data would lead to misleading conclusions, from the point of view of the proposed theory.

It is very hard to conceive of how reliable data on income per capita, for a broad world wide sample of countries, can ever be constructed. This makes it very hard to test the standard Malthusian model in a fully convincing way. But with the physiologically augmented framework in hand, the absence of GDP per capita data is no longer a barrier to the empirical testing of the Malthusian interpretation of the long-run growth record, prior to industrialization.

6.2. **Physiological Development in Pre-Industrial Times.** The theory introduced in Section 4 provides a key mechanism by which episodes of technological change would leave average body size unaffected: The physiological check. During periods of plenty households will tend to increase family size and spend more resources on nutrition per child, and since more nutrition leads to bigger descendants, the question is why body size growth would stagnate in pre-industrial times, as available evidence suggest. In Dalgaard and Strulik (2012) we propose a simple mechanism, which builds on the fact that as body mass increases basal metabolic needs increase as well. Consequently, even though income does not decline between the generation receiving a favorable technology shock, and the next, the amount of resources available to build a family, and provide adequate nutrition for the offspring, shrinks as parents need to keep a bigger share of per family income for themselves in order to stay alive. Consequently, nutrition per child and family size in generation "$t + 1$" shrinks. In the long-run technological change therefore only raises population density, but leaves average body size unaffected. As income per worker is pinned down by basal metabolism, the former is also unaffected in the long-run.[11]

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[11]In Dalgaard and Strulik (2011) we investigate a static economy populated by individuals of idiosyncratic body size. In this context it makes sense to distinguish metabolic rate at rest and when exerting effort since larger bodies are more energy-efficient. The entailed interaction on the labor market yields a physiological foundation of the efficiency wage model. It would be an interesting yet challenging task to integrate idiosyncratic body size into the dynamic context of long-run growth.

6.3. **Physiological Development During Industrialization.** As discussed in Section 5, the theory developed in Dalgaard and Strulik (2014a) is capable of accounting for the puzzling "dip" in average body size during the take-off where income per capita is rising. The essential intuition behind the result, depicted in Figure 3, is that the model features a quantity-quality trade-off in terms of nutrition and fertility. Hence, as fertility in the early phases of industrialization rises, body size declines, a state of affairs that is reversed once the fertility decline emerges.

We recognize that there could be many reasons why average body size declines during the early phases of industrialization in England and the US (Steckel, 2009). The open question is whether these alternative theories simultaneously are consistent with other salient features of the data for the period in question; e.g., sectoral change as well as general fertility patterns. In Dalgaard and Strulik (2014a) we provide a theory that is consistent with these features.

6.4. **The Reversal of the Latitude Gradient During Development.** As demonstrated in Section 4 the baseline Malthusian model, featuring endogenous body size, predicts a negative link between distance to the equator and population density in pre-industrial times. This prediction flows from two mechanisms. First, that evolutionary forces (or plasticity in the human growth process) has led to physiologically bigger people in colder environments, and, second, the size-number trade-off.

In the theory advanced in Dalgaard and Strulik (2014b), and discussed above, it is further explained how regions inhabited by physically bigger people may have been disadvantaged in the past (since a smaller population historically may have instigated less innovation for the usual "more-people-more-ideas reason) may end up experiencing the take-off to growth relatively early, thus becoming relative *more* economically developed today. Consequently, the theory predicts a positive latitude gradient in the degree of technological sophistication (and income) in the contemporary world.

7. Concluding Remarks

The research surveyed in this Chapter suggests that the evolution of body size importantly influenced the long-run growth record and, ultimately, comparative development. It also provides opportunities for the testing of existing interpretations of the long-run growth record. In general we see several opportunities for future work in this area.

First, it would be very useful to collect data on lean body mass for historical societies. As discussed above, this requires a shift in focus away from body height, and implicitly towards other measurements of the sort of skeleton remains that hitherto been in focus. This sort of effort will allow for much more compelling tests of the Malthusian interpretation of the historical growth process than what has been possible so far on cross-country data. As observed in the Introduction, a clear understanding of the forces that historically kept countries stagnating will very likely provide clues as to why some countries remain in a (near) zero growth regime.

Second, the issue of optimal growth in human body size (and together with population growth: human biomass) seems worth pursuing, as this measure of humanity has obvious connections to long-run sustainability of the growth process. This research would also involve an inquiry into whether the secular growth of human body size that has been observed around the planet during the preceding century should be viewed as optimal. Is there an argument to be made that people are growing too big? In this context it will surely be useful to integrate a role for human obesity, which is at present ignored in our theory of physiological and economic development.

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