assessment paper

MALNUTRITION

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COPENHAGEN CONSENSUS on Human Challenges

Malnutrition

Global economic losses attributable to malnutrition 1900-2000 and projections to 2050

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Abstract

Poor nutrition affects economic productivity both directly (since undernourished adults are less able to perform work), and indirectly (through poorer cognition and school achievement). A database of mean heights of adult men is used to document worldwide height trends from 1900 to 2010, and make projections to 2050. Adult height is an indicator of nutritional status during early childhood. In the course of industrialization, mean heights of adult men increase by approximately 15cm, from as low as 163cm (sometimes lower), to about 178cm.

We model the loss function of GDP with height and estimate that the annual loss in GDP associated with inadequate nutrition can be as much as 12% in poor countries (much of the effect occurring via cognition). The main productivity losses due to undernutrition in the twentieth century were in the developing countries, although by 2000 nutrition improvements in Latin America began to benefit productivity. Worldwide annual productivity losses associated with undernutrition fell from around 12% in 1900, to around 6% in 2000. Without nutrition improvements, world GDP would have averaged 8% lower over the century. Using projections to 2050, the loss of world GDP for the period 2000-2050 falls to 6%, as nutrition improvements first in Latin America and then in Asia take effect.

Achieved adult male height can also proxy for increased mortality risks in childhood, although this underestimates the overall effect of nutrition, since it relies only on chronic undernutrition. We model the relationship between adult male height and the proportion of child (postneonatal) mortality attributable to nutrition. On average, 14.6 million children under 5 died each year in the twentieth century. Of the 8.8 million dying after the first month of life, 1 in 3 deaths was attributable to chronic undernutrition as an underlying cause (this increases to one half if acute nutritional status is also included). The improvements in nutrition over the twentieth century (as measured by improved height) are estimated to have saved 40.6 million lives over the century (0.41 million child lives each year on average).

Introduction

The two-way link between improved nutrition and higher income is well known. Higher income allows people to obtain a more varied and nutritious diet. Higher income is associated with improved sanitation and health, such that there is less loss of nutrients associated with infection. More maternal education (associated with higher income) is associated with better infant feeding practices, and mothers who are better able to obtain care for themselves during pregnancy. Of course, higher income also can bring with it an overly sedentary lifestyle, excess consumption of fat and added sugar, and associated risks of non-communicable disease. However in this paper we focus on the beneficial aspects of income for nutrition because a large share of the world's population was stunted during much or most of the 20th century.

Similarly, better nutrition is associated with higher productivity. Better nourished individuals are more productive in physical labour, because of higher stamina, higher maximal work output etc. Better nourished infants and young children have improved cognitive skills, which translate to higher productivity as adults. We use the results from micro-level data to disentangle the effect of nutrition on productivity from that of income on nutrition, making broad estimates over the past century for various world regions.

During the 20th century, nutrition improved considerably in most regions of the world, as evidenced by increases in stature. This increase in stature was not uniform (some countries did not experience an improvement), and the timing and rate of this increase varied greatly. Data suggest that as living standards improve (associated with modern economic growth), mean height of young adults/all adults/conscripts (a sample for whom data are readily available) in national populations can increase from 163cm or even lower, up towards 178 cm. Mean heights lower than 160cm have been observed in subpopulations of particular ethnic groups (pygmies, Bushmen for example in Africa; Maya, Quechua and Yanomano in Latin America), as well as in regions of particularly low per capita income (for example, Japanese conscripts recruited in 1900). However, the assumption is that all populations have similar genetic potential for height, even though this may take more than one generation to achieve. Data on heights of wealthy households in different countries support this assumption (Eveleth and Tanner, 1990; Bogin, 1999).

Height is a good indicator of long-run nutritional status. In this regard it is useful to think of the human body as a biological machine that receives fuel as a mixture of protein, calories, micronutrients, and so forth, which it expends on basal metabolism (maintaining vital functions while at rest), physical activity and fighting infections. Physical growth ceases if net nutrition is poor but children experience catch-up growth if conditions improve. Anthropometric studies around the globe show that individuals who are malnourished as young children are stunted as adults, and the extent of stunting depends upon the duration, timing and severity of malnutrition. Stunting is commonly measured by height-for-age (by sex) relative to international standards. Evidence on children adopted from poor into rich countries shows that the human capacity for catch up or compensatory growth may be substantial (but still incomplete) depending upon the quality of nutrition and the age at which conditions improve.

Height does not capture all the beneficial effects of nutrition. For undernourished adults, improved diet (both in calories and micronutrients) can improve productivity. For children, improved micronutrient status can have effects on cognitive development independent of height. However we do not have worldwide data on calorie availability and distribution over the past century, nor on micronutrient status of children. Hence our estimates underestimate the benefits of improved nutrition.

In the next section we summarize the literature on the effects of height on wages or earnings, to obtain a range of coefficient estimates. This is not easy to do, since household decisions on investments in nutrition, health and education of their children are correlated. Child nutrition impacts cognitive skills and education, and child nutrition and health act synergistically. Adult height, education, cognitive skills and health all are known to affect earnings. We extract coefficients from a number of empirical studies to produce estimates of the effect of height (our proxy for nutrition) and earnings. We also summarize key references on the effect of nutritional status (as represented by height) on child mortality.

The third section of the paper describes the height database and discusses the caveats associated with using height as a measure of nutrition, for our purpose. An international height database was assembled to provide broad trends in men's height over the time period 1900 to 2000. This is compiled for the five major geographic regions identified for this project (Africa, Asia, Europe, Latin America and North America), as well as for developed and developing countries separately. Data on height for Australasia is lacking, and we assume there is a similar pattern to the US; this region is included with Asia. There are very few data for Africa: the broadest coverage is only for women from DHS surveys, and goes back only to about 1950. Given the data limitations for many countries and even whole regions (Australasia, Africa) these are broad estimates only.

We then turn in the fourth section to explain the model used to make the calculations, which combines the coefficients from the literature review with the height database, to estimate both the economic and human losses. This is the most technical section of the chapter, and less technically-minded readers may prefer to gloss over the details in this section. The fifth section presents the detailed results for our estimates of income losses and mortality losses associated with nutritional deficiencies over the twentieth century, as measured by men's height. These are presented both for the five geographic regions, as well as the developed/developing country grouping. We present income losses for 1900-2010, as well as projections for 2010-2050, for the same two sets of groupings of countries. We follow this with estimates for the contribution of nutrition on child mortality for 1900-2010 (data are not available to project this number forward to 2050). We briefly consider the sensitivity of the results to the assumptions made. The sixth and final section discusses the findings and presents conclusions.

Empirical evidence of the effect of height on earnings, and height on mortality

Many studies have noted that taller individuals earn more, and that height is associated with higher occupational status. There are also plausible biological reasons why better nutrition (of which height is a marker) is associated with higher productivity: both in physical labour, due to effects of improved nutrition on stamina and maximal work capacity, and in other occupations via well-known effects of improved nutrition on cognitive development. Even more powerful evidence comes from long-term longitudinal studies following up on controlled nutritional interventions. One trial in Guatemala involved a nutritious food supplement which demonstrated strong effects on wages and earnings of men in adulthood, particularly in children supplemented below the age of three (Hoddinott et al, 2008). Another trial in Costa Rica demonstrated the long-term impacts of an intervention involving iron supplements in infants (Lozoff et al, 2006).

We do not have data on birth weights or micronutrient status for populations in different regions extending over decades in the past. We can however find data on height over extended historical periods. Height for age is used as an indicator of chronic nutritional status, and achieved height of adults is sensitive to nutritional status during the vulnerable early years. Deficiencies in utero and prior to age three cannot completely be reversed by subsequent improvements in nutrition. The height data will be reviewed in the next section.

Fogel (1994) made early estimates of the contribution of better nutrition to economic growth, and calculated that it accounted for 30% of the increase of per capita income in the UK between 1790 and 1980, based on greater availability of food as well as reduced infection which increased the efficiency of use of food. He used data on height as well as estimates of calorie availability, and what he terms a technophysio modelling exercise.

A large number of studies have correlated earnings with height for adults, using a variety of specifications (see tables 1 and 2). When height is entered as in independent variable in earnings functions, there is general evidence of economic returns. Typically, higher returns are found when instrumental variables techniques are employed. These can improve the estimates if height is measured poorly, or if there is simultaneity.

Table 1. Effect of increased height on wages, developed countries

Reference	**Country**	**Results**	**% change in wages Per cm height ↑, men**
Case & Paxson	UK NCDS, born 1958	1 inch height leads to 2.3% ↑wages men, 1.9% women	0.9%
Case & Paxson	US PSID	1 inch height leads to 1.9% ↑wages men, 1.2% women	0.7%
Heinick	UK BHPS	No effect: others criticize and say height effects work through education & occupational choice	0%
Heineck 2005	Germany GSOEP	1 cm height males leads to 0.4% ↑ wage	0.4%
Kortt & Leigh 2009	Australia	1 cm height males leads to 0.3% ↑ wage	0.3%
Persico et al 2004	UK NCDS Born 1958	1 inch height leads to 2.2% ↑ wage	0.9%
Persico et al 2004	US NLSY	1 inch height leads to 1.8% ↑ wage	0.7%
Sargent & Blanchflower 1994	UK NCDS, born 1958	1 cm height leads to 0.27% ↑ wage	0.3%
Twins study			
Behrman & Rosenzweig 2001	US	1 inch height women leads to 3.5-5.5% ↑ wage	1.4% to 2.2%
Note: Table constructed from literature survey in Gao & Smyth, 2010; all references in Gao & Smyth, 2010			

We would expect the effects to differ significantly between developed and developing countries. In industrialized countries it is estimated that 80% of the variation in height observed is genetic, and 20% reflects differences in the environment (Silvontoinen, 2003). However, it is likely that in developing countries with lower average heights a larger proportion of the variation observed reflects environment. We would also expect the estimates to differ between rural and urban areas. We would anticipate height to have greater effects on productivity in rural areas (if there are gains attributable to greater physical size and strength), whereas benefits occurring in urban areas are more likely to occur via cognitive skills and education.

Instrumental variables approaches can also help deal with simultaneous relationships between nutrition/health, schooling and cognitive skills, all of which can affect wages. Taller children are more likely to enter school earlier and stay in school longer, and hence part of the observed schooling effect may be attributable to height (i.e. preschool nutrition). Nutrition particularly prior to the age of three can affect cognitive skills, and cognitive skills may then affect schooling as well as wages. Schooling and nutrition both depend on possible unmeasured household characteristics which may also affect wages. Parents may make the education and health investment decisions simultaneously for their children, either investing more in schooling for those with higher cognitive skills (related to early childhood nutrition) if efficiency motives prevail, or investing less if equity motives prevail. See Alderman et al (2006) for a simple model of this form.

A more sophisticated model is provided by Behrman et al (2010). Here there are two periods (childhood and adolescence) in which parents can invest in physical capital (e.g. height) and human capital (education and/or cognitive skills), and there is more endogeneity. Such a model requires longitudinal data to estimate. Their results for Guatemala suggest that even in a low income and rural environment, the dominant effects of nutrition on productivity occur via cognitive improvements, or, as they characterize it, that the effects of nutrition occur primarily through brains and not brawn.

Twins data have also been used to explore the relationship. Case and Paxson (2008) summarize results from three other studies in developed countries. These suggest that environment accounts for 65% of the height-intelligence relationship and genes 35% (using comparisons of monozygotic and dizygotic twins). Note that this is a higher effect for environment than that suggested by Silvontoinen (2003). Studies on monozygotic twins with different birth weights (reflecting differential nutrition in utero) find clear links between height and cognitive skills, and height and schooling.

Table 1 summarizes results from a literature survey by Gao and Smyth (2010), for eight studies for industrialized countries (the US, UK, Germany and Australia, where average height for adult men is currently about 178cm). The estimates presented are all using instrumental variables (IV), to account for errors in measurement of height and simultaneous relationships between height and income, and height and education. All the IV estimates are higher than the ordinary least squares (OLS) estimates. The median effect is a 0.55% increase in earnings per additional 1 cm of adult male height. The effect from a one study of twins is about three times higher.

Table 2 presents similar results for a sample of developing countries. The median effect (from 8 studies from Brazil, China, Cote d'Ivoire, Ghana, Philippines, Tanzania and Zimbabwe) is a 4.5% increase in earnings per additional 1 cm of adult male height. Mean height of adult males in these countries is approximately 170cm. The effect from the single longitudinal intervention study is about three times higher, for a population where adult male height is closer to 163cm. The studies in Table 2 include three of rural areas only, one of urban areas only, and the others include both. The studies also vary in the quality of the instruments used, which may help explain the variation in findings.

Previous studies have also determined that there is a relationship between nutritional status of children, and mortality risk. Pelletier et al (1994a) compare the predictive power of weight-for-age as compared to height-for-age and two other anthropometric indicators, using one prospective study. They conclude that the predictive power of the indicators varies. Height-for-age has greater predictive power two or three years after the child is measured, but other indicators have greater predictive power in the short term. Pelletier et al (1994b) develop very useful odds ratios for different categories of weight-for-age, using 8 prospective studies from developing countries. Severe malnutrition (weight-for-age less than 60% of the reference median) is associated with an odds ratio of 8.4; moderate malnutrition (as measured by weight-for-age 60 to 69% of the reference median) with a ratio of 4.6, and mild malnutrition (weight-for-age 70 to 79%) with a ratio of 2.5. In the model section we convert these to estimated odds ratio for height-for-age.

Table 2. Effect of increased height on wages, developing countries

Reference	**Country**	**Methods used**	**Results**	**% change in wages Per cm height ↑, men**
Gao & Smyth (2010)	12 Chinese cities, 2005, individuals 16+	IV: urban data	↑ height 1 cm for men increases earnings 4.5%; same for women increases earnings 7.3%	4.5%
Haddad & Bouis (1991)	Philippines, agricultural work	IV: rural data	Elasticity wages with height is 1.38	0.86%
Schultz 2002	Brazil, 1989 National survey	IV: national data		8-10%
Schultz 2002	Ghana 1987-9 Age 20-54	IV: national data		8-10%
Schultz 2003	Cote d'Ivoire 1985-7	IV: national data		11%
Thomas & Strauss 1997	Brazil 1989 National survey	IV: national data	1% increase in male height associated with 2.4% increase in wages	1.4%
Studies involving height & schooling				
Alderman, Hoogheven & Rossi (2008)	Tanzania, children born 1984-94	Longitudinal data, IV using short-run drought shocks: rural data	↑ height from 80% to 95% of median, leads to↑ schooling 0.93 years and annual salary 8%; ↑height from 85% to 100% of median leads to↑ schooling 0.85 years, and annual salary 7%: heights measured in children	Na (only child heights used)
Alderman, Hoddinott & Kinsey (2006)	Zimbabwe, children born 1977-87	Longitudinal data, IV using major drought, civil war shocks: rural data	Drought led to height/age 1.25 SD lower (3.4cm shorter) at adolescence: associated with 0.85 less years school achievement, and 14% lower lifetime earnings	4.12%
Longitudinal intervention studies				
Hoddinott et al, 2008	Guatemala, children born 1969-77	Longitudinal study following up controlled intervention in rural area	Intervention below age 3 resulted in 2.9cm ↑ in height, 46% ↑ in hourly wage for adult men; effect not significant for women	15.8%

A similar relationship holds for the developed countries, using historical data. Data for men and women (Bozzoli et al, 2009), and men (Schmidt et al, 1995), show that postneonatal mortality for children is correlated with achieved adult height for the same cohort 20 years later, for European countries in the second half of the twentieth century.

Height database: trends in height 1900-2010, and projections 2010-2050

A database of adult heights was assembled for this project, containing approximately 400 mean heights from cohorts of adult males (defined here as 18 or over), since 1900. Time series from 1900 to 2010 could be constructed (although not for every decade) for approximately 30 countries (19 in Europe, 2 in North America, 5 in Latin America, and 4 in Asia). There are also scattered data available for another 50 countries. The biggest gaps are for Africa, Australasia and the Middle East, where historical data are least available.

We focus on male height since female height data are less readily available (for example, some series rely on conscripts, where the data are exclusively for men). Female height is a strong predictor of male height (an R^2 of 0.95 was obtained by one of the authors when the natural log of male height was regressed on the natural log of female height, for a dataset containing male and female mean heights for 132 different samples, using data from Eveleth and Tanner 1976 and 1993). Empirical studies of the effects of height on income are also more readily available for men, since the proportion of women working in the wage labour market is smaller. Many of the benefits associated with improved women's nutrition (for example intergenerational effects via their children) are harder to measure, although Behrman et al (2009) provide useful estimates for Guatemala from the same longitudinal study of supplementation mentioned previously.

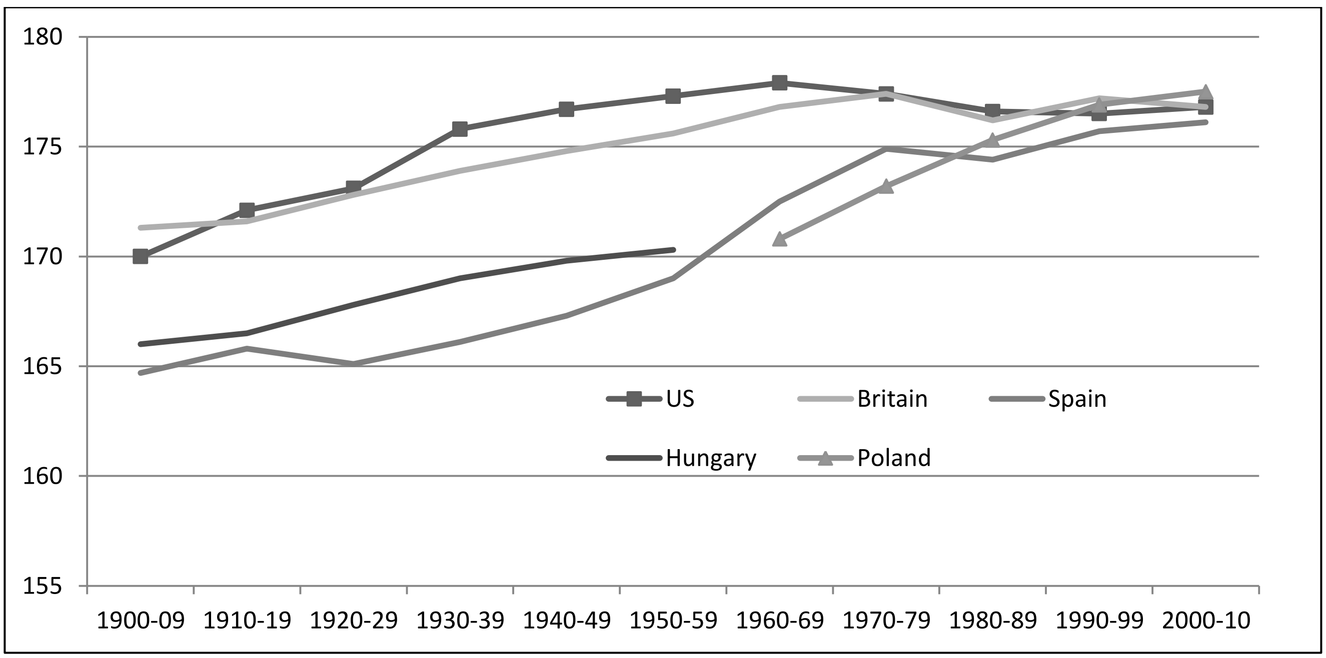
Figures 1 through 3 present trends for 11 indicator countries in 4 regions. These are countries with reasonably good time series data. Figure 4 presents our informed guesses for trends in those regions without historical data, namely Africa and West Asia. Figure 5 then presents trends for the five geographic regions included. Figure 6 presents the same data aggregated into developed and developing regions. Table 3 provides details and references for the data sources for the 11 indicator countries, and table 4 the underlying population weights applied to the indicator countries to construct the regional and developed/developing aggregates. We will first describe the trends observed, and then discuss the data limitations and qualifications.

Table 3. Source of data to obtain trends for representative countries.

Country	Population surveyed	Source	Years data collected	Age of subjects
Bolivia	national	Baten, 2010	1940, 50, 60, 70, 80	adult
Brazil	? ? national national	Monasterio & Signorini, 2008 Strauss & Thomas DATE? Baten, 2010 Monteiro et al, 1994	1910, 20 1930, 40 1950, 60, 70 1989	? ? Adult 22
China	Shandong province national	Zhen Wang and Cheng Ye, 2005 Yang et al, 2005	1956;72;85;2000 1992-2002	18 17
Colombia	Conscripts national	Meisel & Vega, 2007 Meisel & Vega, 2007 Meisel et al 2004	1910-20;20-30 1930-5;36-40;40-45;46-50; 50-55;56-60;60-65;66-70; 70-75;76-80;80-85; 2002	adult 18-48 18-22
Hungary	conscripts	Bodzsar and Zsakai, 1999	1900;05;10;15;20;25;35; 40;45;50;60;	adult
India	national national national	Guntupalli & Baten, 2006 Indian Council of Medical Research 1972 Deaton 2008	1915,16,17,18,19,20,21,22, 23,24,25,26,27,28,29,30,31, 32,33,34,35,36,37,38,39,40, 41,42,43 1972 2005-6	Adult 18 20
Japan	conscripts	Mosk, 1996	1901-10;11-20;21-30;31-40;41-50;51-60;61-70;71-80;81-90	18
Poland	conscripts	Bielicki and Szklarska, 1999 Bielcki et al, 2005	1965;76;86;95 2001	19 19
Spain	Conscripts National	Maria-Dolores & Martinez-Carrion, 2009 Garcia &Quintana-Domeque, 2007	1901-05;06-10;11-15;16-20;21-25;26-30;31-35;36-40;41-45;46-50; 1951-5;56-60;61-65;66-70; 71-5;76-80	21 adult
South Korea	Prisoners Students	Choi and Schwekendiek, 2009 Pak, 2004	1900-10;05-15;10-20;15-25;20-30; 1965;70;75;80;85;90;95; 2000	20-40 17-18
UK	Conscripts National National	Rosenbaum et al, 1985 Hatton & Bray, 2010 NHS 2008	1931-5;36-40;41-5;46-50; 51-55;56-60; 61-5;66-70;71-5;76-80 1996	Adult Adult 25-44
US	national	Steckel, 2006	1900,10,20,25,30,35,40,45, 50,55,60,65,70	adult

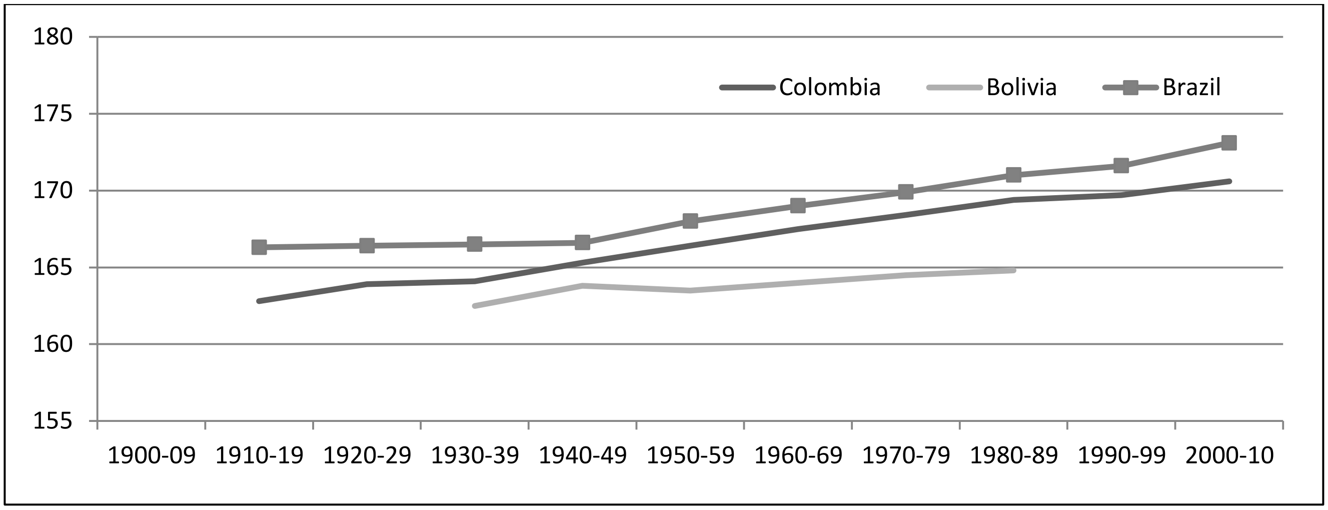
In 1900, adult male heights in Northern and Western Europe (represented by the UK) and the US and Canada (represented by the US) had already attained a mean of 170cm or more, and heights have grown at a rate approximately 1cm per decade to the end of the century, consistent with fairly slow but steady economic growth around 2% per capita per annum (Figure 1). Heights in Southern Europe (represented by Spain) began somewhat lower (165cm) and took off around World War II but grew faster and were still a couple of cm lower by the end of the century (Figure 1). Height data for Eastern Europe are more fragmentary. Data for Hungary (prior to 1960) and Poland (starting in 1965) are similar to the pattern for Spain, but catch up with the UK by the end of the century. The one national data point for Hungary after 1960 (in the 1980s) is in line with data for Poland at a similar date, suggesting that switching from Hungary to Poland mid-century does not do great violence to the trend.

Figure 1. Trends in adult male height (in cm), representative countries from North America, Northern, Southern and Eastern Europe, 1900-2000



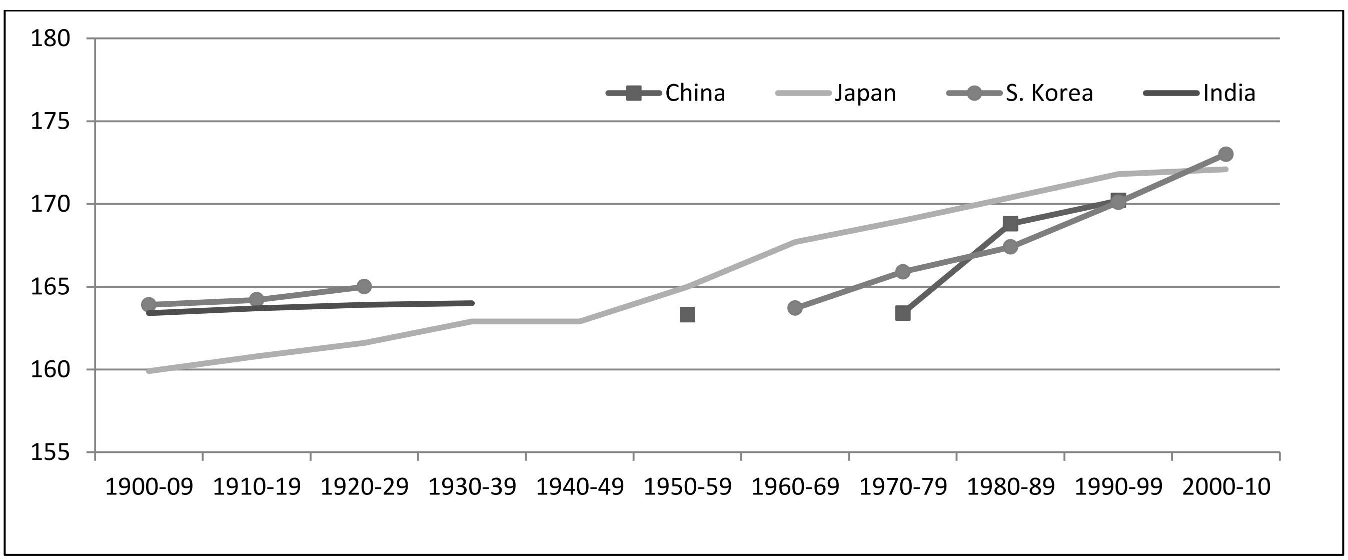
In Latin America (Figure 2) heights in the richer countries (e.g. Brazil) started out somewhat similar to Spain (Argentine men – not presented – were if anything taller than those from Spain). Men in the poorer countries (represented by Bolivia) have heights about 5cm below those of the richer countries (i.e. Brazil), and Colombia represents the trend for the intermediate countries. The trends for Mexico (not presented, due to a big gap in the data from 1970 to 2000 inclusive) are similar to those for Colombia. We do not have separate data for the Caribbean, however the population of this region is quite small. Over the whole century, the increase in height for Latin America averaged about 1cm per decade, but there is greater variability consistent with a greater variation in economic growth both across countries and between decades, and the poorer countries lag increasingly further behind.

Figure 2. Trends in adult male height (in cm), representative countries from South America, 1900-2000



In Asia (Figure 3), we see the remarkable increase in height in the Asian "tiger" economies as they entered the phase of rapid modern economic growth, starting around 1950 for Japan, around 1960 for Korea, and around 1970 for China. Prior to this, average heights had been around 163cm (and even lower for Japan in 1900). For India, even by 2000 recent economic growth has not yet manifested in increased height at the national level. The "tiger" economies experienced increases in height of up to 3cm per decade during the fast growth periods, when per capita income was growing at 7% per capita per annum or even more.

Figure 3. Trends in adult male height (in cm), representative countries from Asia, 1900-2000



To put the developing country data from the twentieth century into perspective, note that in the UK mean height for adult men was 160cm as late as 1750 (Steckel, 2008), 168.9cm by 1800, and was only 0.4cm more by1900. In France as late as 1800 mean height was 164cm and life expectancy was only 34 years. The US was an exception, in that mean height was already 170cm by 1710 and (after various fluctuations) the same in 1900 (Steckel and Floud, 1997).

We next use the data on individual indicator countries to represent regional trends. This requires strong assumptions, given the data gaps: however the fact that heights track economic growth and life expectancy (Steckel 1995) provides some support for these assumptions. The population weights are provided in Table 4.

Table 4. Representative countries, associated population weights for modeling, and regional nutrition groupings

Country	Dev'ed/ Dev'ing	Geographic Region	Weight	Region represented (nutritional grouping)
Brazil	Dev'ing	Latin America	0.021	**Brazil**
Colombia	Dev'ing	Latin America	0.045	**Latin America and Caribbean (LAC)** excluding Brazil
Subtotal: LAC			**0.066**	
China	Dev'ing	Asia	0.220	**China**
India	Dev'ing	Asia	0.269	**South/Southeast/South Central Asia**
Japan	Dev'ed	Asia	0.026	**Japan**
South Korea	Dev'ing	Asia	0.020	**East Asia** (excluding China and Japan)
West Asia	Dev'ing	Asia	0.020	Use Eastern Europe with 50-year lag
Australasia	Dev'ed	Asia	0.005	Represent with North American data
Subtotal: Asia			**0.560**	
Hungary/Poland	Dev'ed	Europe	0.087	**Eastern Europe**
Spain	Dev'ed	Europe	0.043	**Southern Europe**
UK	Dev'ed	Europe	0.087	**Northern Europe**
Subtotal: Europe			**0.217**	
US	Dev'ed	North America	0.068	**North America:** also Australasia
Subtotal: North America			**0.068**	
Africa	Dev'ing	Africa	0.088	No data: assume little change over the century, heights remain below 170cm
Subtotal: Africa			**0.088**	
TOTAL: World			**1.000**	

Note: populations weights used are for 1950 (mid-century) throughout. Source UNESA (2009); see also UNESA (2009) for countries included in regional groupings

North America is represented by the US (the data for Canada are similar: and Mexico is included with Latin America and the Caribbean for our purposes). The trend for Europe is a weighted average of Northern and Western Europe (using UK data), Southern Europe (using Spain) and Eastern Europe (using data for Hungary/Poland).

Brazil has its own time series, and the rest of Latin America and the Caribbean is represented by Colombia (Colombia has the best time series, and also tracks Mexico well for those years when data are available). We assume that the richer countries (where men are taller) such as Chile and Argentina are balanced out by the poorer countries in the region such as Bolivia, Haiti, the Dominican Republic, Guatemala, El Salvador, such that Colombia is a reasonable average.

For South-central and Southeast Asia, we assume that the data for India represent the situation across that entire region prior to the initiation of modern economic growth, i.e. that height was around 163cm and changed little. There was almost no time trend in India prior to 1940, and for two isolated years (1972 and 2005-6) for which later data are available (not visible on the chart) heights remained the same as during the period 1900-1940.

In the East Asian countries, prior to the initiation of modern economic growth, heights were similar to those in India (even lower than India in the case of Japan prior to 1930). For those economies which experienced the takeoff into modern economic growth, such as Japan, Korea and China, heights grew rapidly.

In Western Asia (Iran being the most populous country) we use the trend for Eastern Europe lagged 50 years reflecting a later start to modern economic growth, which is consistent with men's heights in Iran around 2000 of about 170cm (Figure 4). The Asian regional average therefore reflects a weighted average of the economic takeoff which began in Japan, and spread to Korea (and Taiwan, Singapore, Hong Kong), followed by China (and Thailand and Malaysia). Economic takeoff has still not affected heights in South Asia and the remaining countries in Southeast Asia. Takeoff in Western Asia followed (with a lag) the takeoff in Eastern Europe, i.e. at a similar time to that in Japan.

Figure 4. Assumed trends in adult male height (in cm) for areas missing historical data, 1900-2000

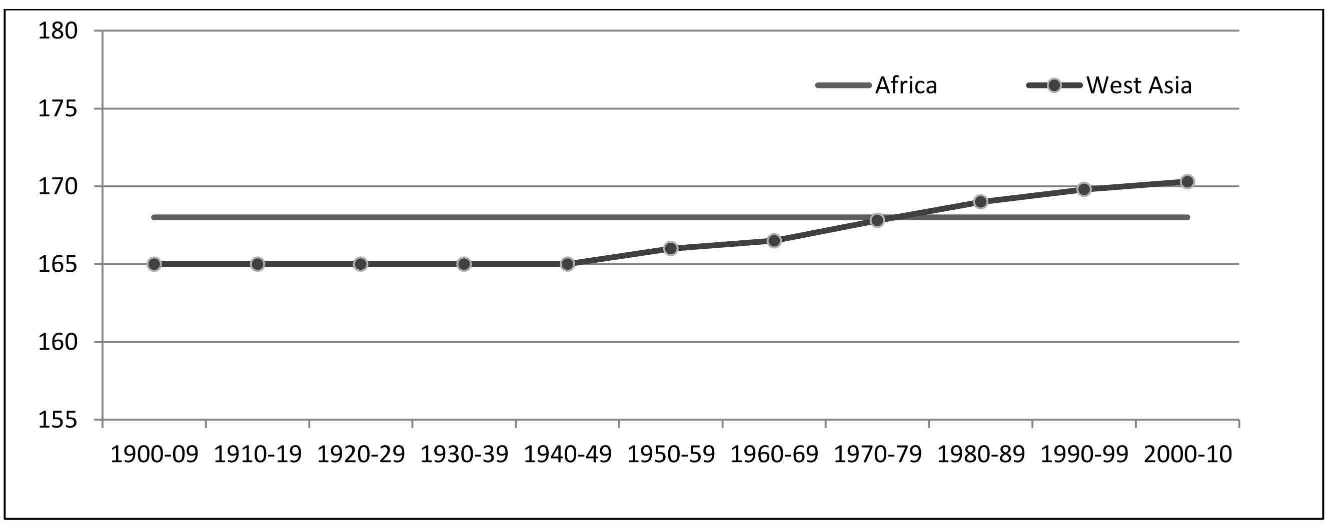
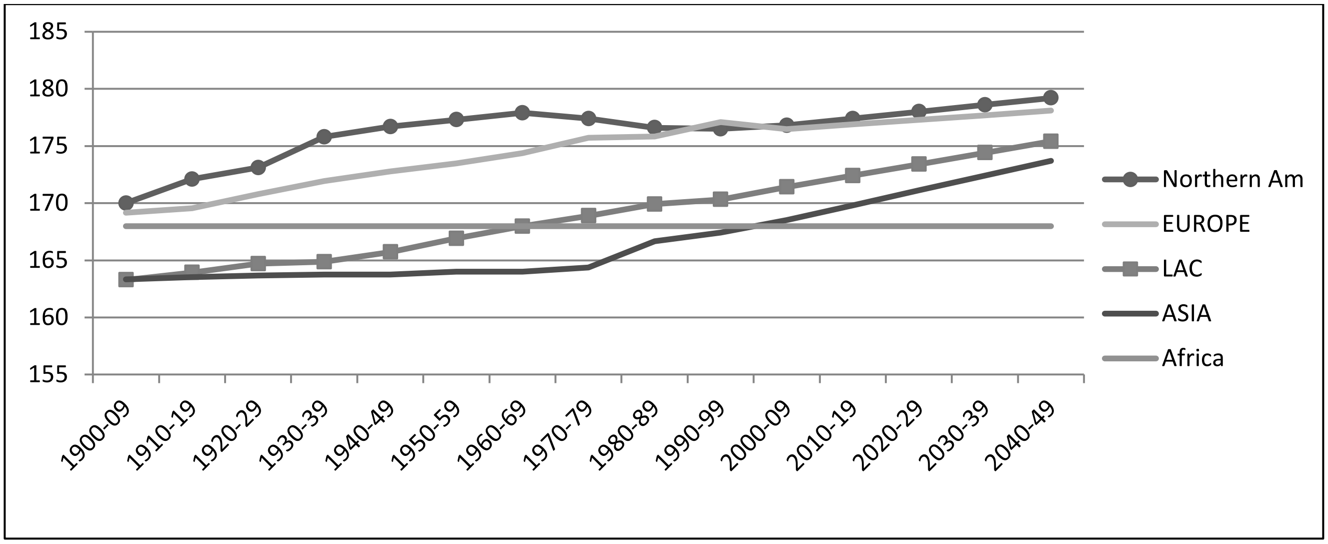


Figure 5. Estimated trends in adult male height (in cm) by region, 1900-2010, and projections 2010-50



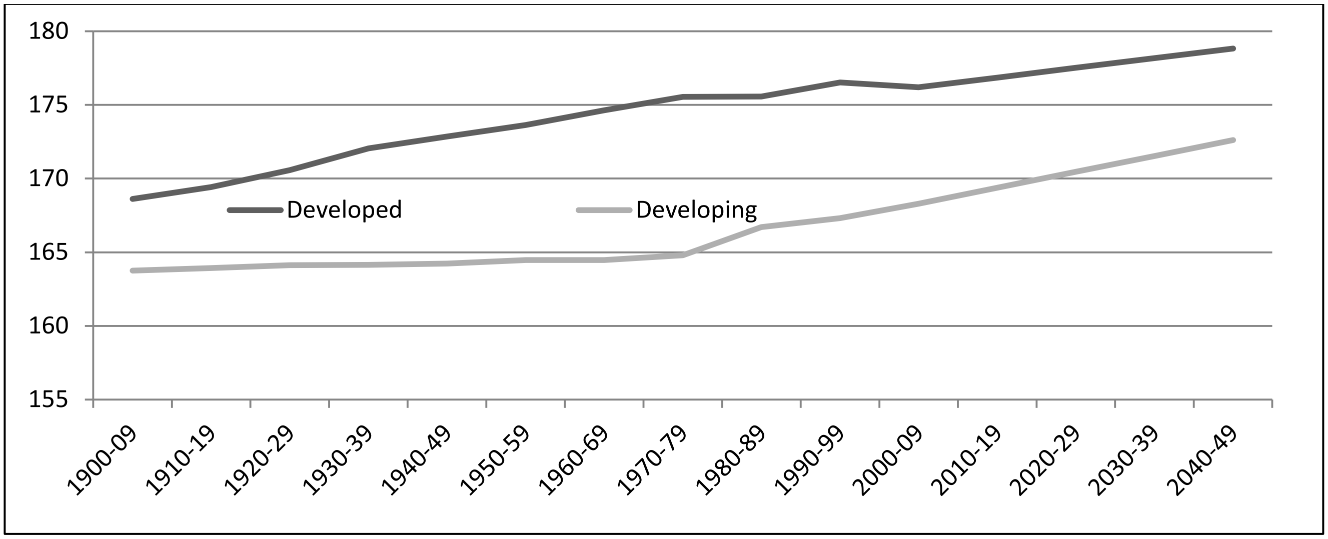
For Africa, even for the modern period there are very limited data. The South African Demographic and Health Survey 1998 is one exception (DHS, 1998), which provides national data for adult men (with a mean of 168cm). Similar surveys for other African countries provide data for adult women but not men, and most other studies provide data for samples which are not nationally representative. We assume that mean heights in Africa did not change significantly, and remain below 170cm by 2010 (Figure 4). Some support for this assumption comes from Deaton (2007), who examines the height of women born between 1950 and 1980 for Africa (using Demographic and Health Survey data), where no improvement is detectable.

Finally, there are no time series data for Australasia. We assume heights in New Zealand and Australia tracked those of the US over the century which would be consistent with data on migration patterns, economic growth, and modern height. We do not have separate sources for Micronesia, Polynesia and Micronesia, but these populations are a very small fraction of the world.

Figure 5 presents the trends for the five geographic regions used in this project. Figure 6 displays the same data aggregated into developed and developing regions. These two figures also include projections to 2050, for which the estimation method is explained further below in this section.

Two major data limitations should be borne in mind. First, the population surveyed is as far as possible national data for adult men or conscripts (for whom series are often quite good): see table 3. There are frequently data available for subpopulations which are not representative. Data for particular ethnic groups are often available (e.g. in Mexico, Bolivia, US), or selected occupations (government workers, railway workers, employees of a particular firm, students), or selected cities or regions. We have avoided using these data, other than to confirm broad patterns, since they are not representative of the population. Members of ethnic groups or disadvantaged groups such as prisoners may be systematically shorter than the average, and other groups such as students or government employees may be systematically taller. Only for Korea were we forced to use a less than preferable series (prisoners up to 1930, and students aged 17-18 from 1965 to 2000).

Figure 6. Estimated trends in adult male height (in cm), developed and developing countries, 1900-2010, and projections 2010-2050



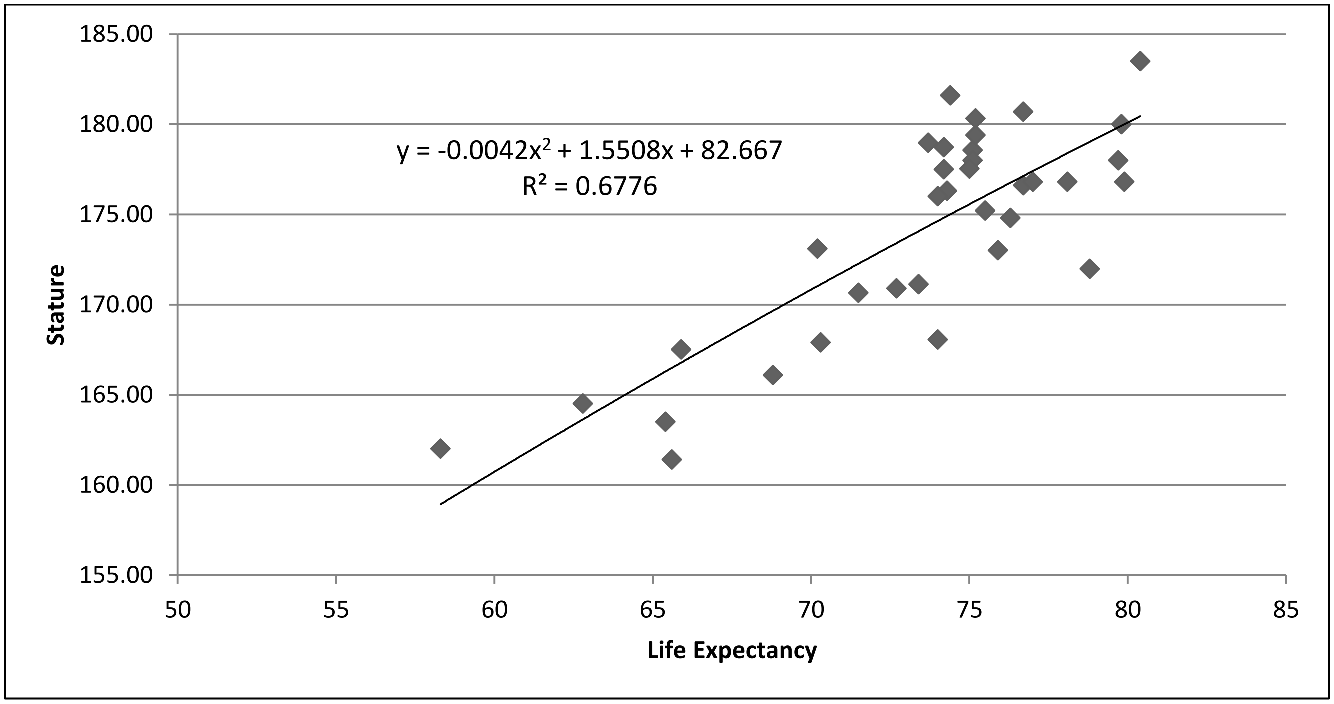
Second, the age of the men surveyed matters. Ideally we would want a consistent series for men in their twenties who have completed their adolescent growth spurt. Although in well-nourished populations this would be completed prior to age 18, in less well-nourished populations this might occur in the early twenties. Series for men aged 18 (and possibly conscripts, depending on the age of conscription) might therefore slightly overstate nutrition improvements over the century. Series for all adult males will reflect changes in young men or conscripts, but with a lag. The current adult male working age population consists of men who recently completed their growth within the last decade, those who completed their growth one to two decades ago, two to three decades ago, and three to four decades ago, with appropriate weights dependent on population growth rates and normal retirement age. We have not made this further data refinement.

For the projections 2010-2050, we need forecasts of height. Three options to forecast are available: (1) extrapolate existing time series of height; (2) use projections of per capita GDP; and (3) develop a model of height and life expectancy. The first two options are unsatisfactory because the time series of height are lacking for a large share of countries, and second, GDP is notoriously difficult to forecast. Forecasts of life expectancy are widely available and arguably are more reliable than GDP. Moreover life expectancy and height are direct measures of health, whereas GDP per capita is only one determinant of human growth.

We estimate the relationship using data from 35 countries (from four of the five regions here) that conducted national height studies in recent years. There are many height studies for sub-Saharan Africa but unfortunately they cover only local populations or ethnic groups, and regrettably there are no data from these countries in our model. Estimates of life expectancy are readily available for every country since 1960 (*World Development Indicators*, World Bank, 2010). Ideally we would compare life expectancy in the year that young adult men were measured but some height studies included a wider range of ages such as 19-39. In these situations we approximated the desired life expectancy using an estimate for several years prior to the year the study was conducted, ranging from 5 to 15 years depending upon the age range of adults.

Prior studies have found that the relationship between life expectancy and average height is approximately linear (Steckel 1995; 2000). Here we use a quadratic function because ultimately there is an upper limit to height that does not apply (or applies less so) to life expectancy. Put another way, future gains in life expectancy for rich countries will come from falling mortality rates at older ages, but height reflects conditions in childhood, at ages where mortality rates are now exceptionally low. We then anticipate diminishing returns of life expectancy on height. Figure 7 provides a scatter diagram and the estimating equation.

Figure 7. Scatter diagram and equation used for height projections.



In making projection we caution that extrapolations beyond the range of evidence can be hazardous, particular in polynomial models. We think this problem is notable at the lower end of forecast life expectancies, some of which are below 55 years. Unfortunately, this applies to almost all of sub-Saharan Africa for both 1950 and 2000. The heights for sub-Saharan Africa projected by the model for 2050 are too low to be credible – ranging from below 150cm for the countries with the lowest life expectancy, to barely over 170cm. We simply project forward the same height for Africa as for the twentieth century.

Our projections are that the 5cm differential between heights in developed and developing countries which existed in 1900, and which widened to 10cm in 1960, diminishes again by 2050 (Figure 6). Heights in Latin America catch up to within 3cm of those in the West by 2050, and in Asia to within 5cm, while (by assumption) there is no change in Africa (Figure 5).

Model

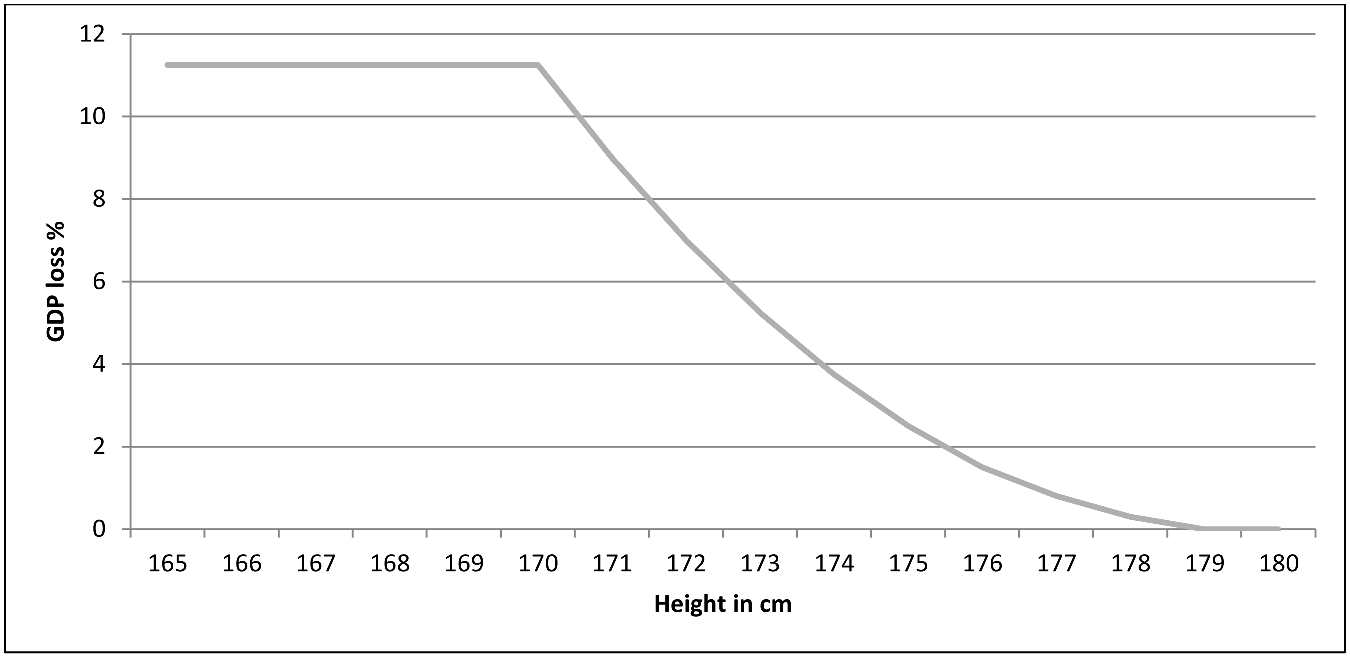
In this section we first model the effect of nutrition (as measured by height) on economic productivity. We then model the effect on mortality (a human cost of undernutrition). This requires strong assumptions. Less technically-minded readers may wish to gloss over this section and proceed to the results.

We assume that the effects of height on productivity and hence economic growth can be captured by the effects of height on wages (earnings), and further that these effects act on the share of wages in national income (approximately 50%). This is a conservative assumption, since it is possible that better nourished individuals with higher cognitive skills could increase the rate of technical change, or could enhance the productivity of other complementary factors of production.

We use the empirical estimates surveyed previously and summarized in tables 1 and 2. At a height of 178cm the median effect of height on wages is 0.55% per cm, and at a height of 170 cm the effect is 4.5% per cm. We do not have evidence on how this effect tapers off, other than some estimates of curvature in the relation of height with schooling for children in Alderman et al (2008). We therefore assume a linear relation between the wage coefficient and height, between 170cm and 178cm (namely 4.5% at 170 cm, 4% at 171 cm, 3.5% at 172 cm, etc, up to 0.5% at 178cm and zero thereafter). We also assume conservatively that there are no additional losses in productivity per cm of height lost below 170cm.

If we then aggregate these losses, at a height of 170cm (compared to 179cm) the cumulative loss in wages is 22.5%; at 171 cm 18%; at172 cm 14%; at 173cm 10.5%; at 174cm 7.5%; at 175cm 5%; at 176cm 3%; at 177cm 1.5%; and at 178cm 0.5%. The assumed loss function as a % of GNP (plotted against current height) is depicted in Figure 8. The loss function as a % of GNP allows for the assumption that lost earnings (attributable to poor nutrition) affect only labour income, approximately half of total GNP (Lübker, 2007). It also assumes that a given point in time, the percentage loss of earnings for those women who work in the market labour force, is the same as for men.

Figure 8. Assumed GDP loss (%) with height (cm)



We lack two sets of data to do a separate analysis for women. First, there are fewer data on women's heights (the data on conscripts do not include women). Second, the studies reported in table 2 do not always include the effect of women's height on earnings. Women's market earnings are however typically less than half (in some regions much less than half) of total market earnings, and hence the overall losses (being based on the market labour share in national income) are less sensitive to women's than men's earnings.

These assumed productivity losses described above are then combined with the height trends and projections for each geographical region (Figure 5) and the developed/developing grouping (Figure 6) to give estimated productivity losses as % of national income.

Undernutrition (as represented by height) affects not only economic productivity, but there are human costs in terms of increased mortality. We do not have data on child height-for-age worldwide throughout the entire twentieth century, unfortunately. Stein et al (2010) examine longitudinal data on over four thousand children from five cohorts in three developing regions. They conclude that birth length and conditional length at 12 months (i.e. growth since birth) were the most strongly correlated with adult height, and that "Growth failure prior to age 12 months) was most strongly associated with adult stature".
Hence we use achieved adult height as an indicator for height in early childhood, and as such as an indicator for child mortality risk.

We then have to make three sets of assumptions, in order to associate mean adult height with odds ratios of post-neonatal mortality. The assumptions are described in the next three paragraphs.

We first assume that the standard deviation of adult height does not change as mean population height changes. Although some researchers have suggested that the standard deviation of height may depend on the degree of inequality within a society (e.g. Deaton, 2008), there is no evidence to suggest that it varies with height per se. We then calculate (using normal tables) the proportion of the population who would fall below two standard deviations from the reference population mean, at each mean height in increments of 1cm from 163cm to 176.86cm. Hence we have constructed estimates of the proportion of the child population severely or moderately malnourished on a height-for-age basis (SMM: HA), inferred from mean adult male height (column 2, table 5).

Table 5. Construction of estimated proportion of child mortality attributable to malnutrition, at different levels of achieved mean adult male height.

Mean Height	% of pop SMM:HA	% of pop SMM:WA	% WA<60	% WA 60-69	%WA 70-79	PAR
176.86	2.30	0.00	0.000	0.000	13.590	0.169
176	2.94	0.24	0.000	0.000	13.684	0.170
175	4.01	1.10	0.000	0.000	14.029	0.174
174	5.37	2.20	0.000	0.000	14.467	0.178
173	7.08	3.58	0.000	0.000	15.019	0.184
172	9.18	5.28	0.000	0.000	15.696	0.191
171	11.7	7.31	0.000	0.000	16.508	0.198
170	14.69	9.73	0.000	0.000	17.472	0.208
169	18.14	12.52	0.000	0.860	18.584	0.236
168	22.06	15.68	0.000	2.193	19.848	0.274
167	26.43	19.22	0.000	3.680	21.257	0.311
166	31.21	23.08	0.386	5.306	22.798	0.360
165	36.32	27.21	1.146	7.044	24.445	0.414
164	41.68	31.54	1.943	8.867	26.173	0.461
163	47.21	36.01	2.765	10.748	27.956	0.503

See text for calculation method and explanation of column titles.

We then link statistically the proportion moderately or severely malnourished using height for age, with the same group using the weight-for-age measure, in both cases using the z-score measure. Height for age reflects chronic nutrition status, whereas weight-for-age combines the effects both of chronic and acute nutritional status. Using data for 2006 (UNICEF, State of the World's Children), we regress the proportion severely or moderately malnourished using weight-for-age (SMM:WA) on the proportion severely or moderately malnourished using height-for-age (SMM:HA). The 2006 data were used rather than the most recent data, since these use the same NCHS-WHO growth standards as for the Pelletier et al (1994b) calculation   The equation estimated is:

SMM:WA = -2.14 + .808 SMM:HA
F statistic (1,114) = 373.29; Adjusted R-squared is 0.7640;

We then apply this equation to the data in column 2, Table 5, to estimate the proportion severely or moderately malnourished using weight-for-age (SMM:WA). The result is given in table 5, column 3.

We then apply Pelletier et al's (1994b) conversion equations to convert the proportion moderately and severely malnourished using the z-score, to the different categories of malnutrition using the % of median methodology (using the WHO-A methodology, Table 6 of Pelletier et al, 1994b). The equations are:

- WA < 60 = (WHOA1 < -2Z X 0.184) – 3.86 (severe malnutrition)
- WA 60-69 = (WHO A1 < -2Z X 0.421) – 4.41 (moderate malnutrition)
- WA 70-79 = (WHO A1 < -2Z X 0.399) + 13.59 (mild malnutrition)

The calculated proportions are provided in columns 4, 5 and 6, respectively, table 5. If the predicted proportion in a category is negative, we set this to zero.

Finally, the PAR (population-attributable risk) for malnutrition deaths is:

$$\mathrm{PAR} = \frac{(7.4\ \mathrm{X}\ \mathrm{WA}\ <\ 60)\ +\ (3.6\ \mathrm{X}\ \mathrm{WA}\ 60-69)\ +\ (1.5\ \mathrm{X}\ \mathrm{WA}\ 70-79)}{1\ +\ (7.4\ \mathrm{X}\ \mathrm{WA}\ <\ 60)\ +\ (3.6\ \mathrm{X}\ \mathrm{WA}\ 60-69)\ +\ (1.5\ \mathrm{X}\ \mathrm{WA}\ 70-79)}$$

This uses the odds ratios from Pelletier et al (1994b), which we assume remained constant across the century. The calculated PAR is given in column 7 of table 5 and displayed in Figure 9. We would expect the PAR based on height for age to provide a lower estimate of the mortality risk due to malnutrition, than if using actual weight-for-age data. Weight for age incorporates additional risks of death due to temporary food shortages which affect primarily weight-for-height, in addition to the risks which are correlated with chronic undernutrition and measured by height-for-age.

Table 6 shows the data used for the calculations, namely the under-five mortality rates, birth rates and population by region and by decade. The sources, and assumptions required to interpolate data prior to 1950, are described beneath the table. We are not able to project the human costs forward after 2010: although we have projected heights, we do not have the necessary projections of mortality rates.

Child deaths in the twentieth century predominantly occur in the developing countries. However, it is important to note that consistent improvements in height only began in Western Europe and North America after 1900. In the US in 1850 infant mortality rates were as high as 200 per '000, higher than regional averages for Asia in 1960 and in Africa in 1980. In Austria, between 1820 and 1870 rates fluctuated between 250 and 310 per '000 (falling to 252 by 1880) (Corsini and Viazzo, 1993), well above rates for any region in the twentieth century except Africa. Thus the twentieth century patterns in developing countries likely existed in developed countries in the nineteenth century.

Figure 9. Estimated population-attributable risk due to child malnutrition

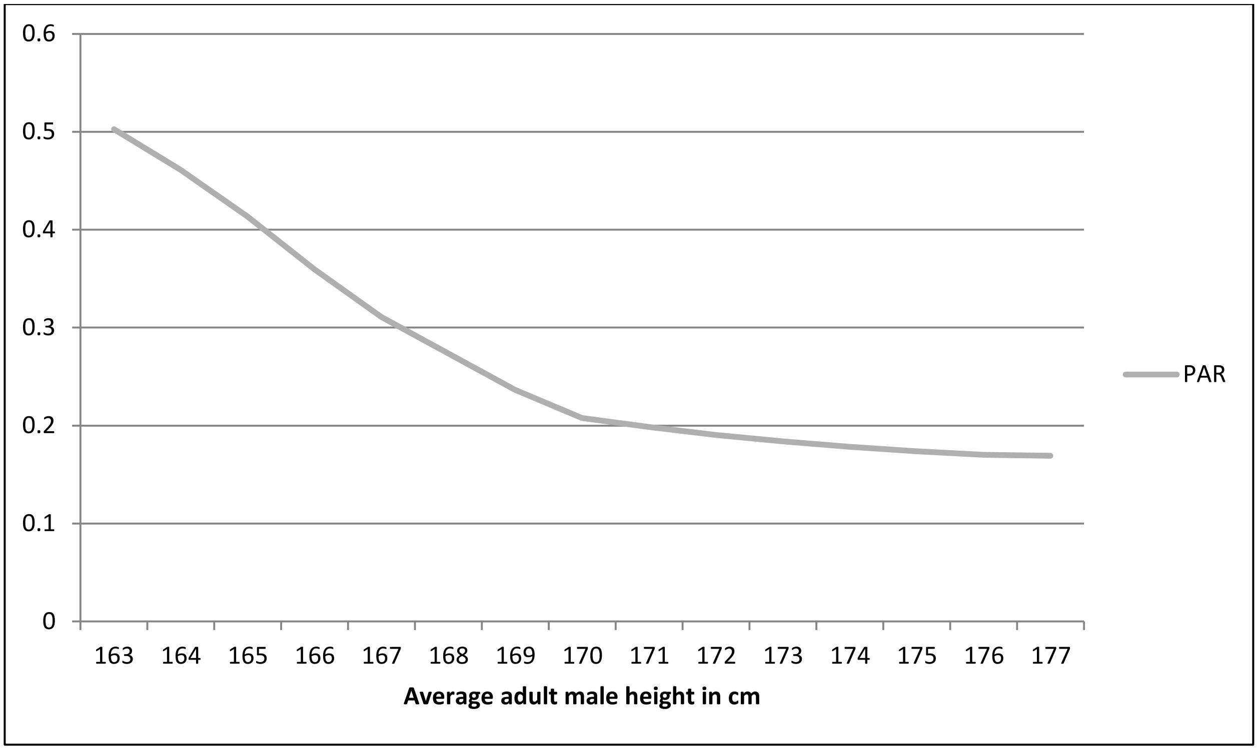


Table 6. Selected demographic variables, by region, selected years 1900 to 2000.

	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000
1. U5MR Per '000											
Africa	259	259	259	259	259	259	250	215	180	158	151
Asia	217	217	217	217	217	217	188	147	114	86	82
NAmerica	132	120	109	111	99	82	36	26	15	10	9
LAmerica	151	151	151	151	151	151	131	105	71	48	42
Europe	181	153	112	86	67	58	48	35	27	20	18
2.Pop (m)											
Africa	110.00	121.14	133.41	160.79	193.80	227.27	285.05	366.79	496.22	640.72	822.37
Asia	877.87	959.35	103.61	1136.92	1247.60	1415.69	1709.88	2145.03	2696.89	3225.87	3759.36
NAmerica	81.84	99.47	115.68	129.21	144.33	171.62	204.32	231.28	256.46	290.29	329.06
LAmerica	64.61	76.76	89.98	108.13	129.95	167.32	219.65	286.47	370.55	445.92	526.75
Europe	429.14	480.22	488.35	533.82	583.52	547.46	604.46	656.20	696.04	741.24	748.07
3.Birthrate per '000											
Africa	48	48	48	48	48	48	47.6	46.2	44.8	40.6	37.2
Asia	42	42	42	42	42	42	39	33.7	28.9	25.1	20.3
NAmerica	32.3	31.5	27.6	21.1	19.4	24.6	22	15.7	15.5	15.5	13.8
LAmerica	42.5	42.5	42.5	42.5	42.5	42.5	41	35.2	30.7	25.3	21.2
Europe	30.8	28.9	27	25.1	23.2	21.5	19.1	15.7	14.4	11.5	10.2
4.Child death (m)											
Africa	1.368	1.506	1.659	1.999	2.409	2.825	3.398	3.638	3.997	4.120	4.620
Asia	8.009	8.745	9.444	10.363	11.372	12.918	12.512	10.618	8.893	6.932	6.248
NAmerica	0.349	0.376	0.348	0.303	0.277	0.346	0.162	0.094	0.060	0.045	0.041
LAmerica	0.415	0.493	0.577	0.694	0.834	1.076	1.181	1.057	0.807	0.537	0.464
Europe	2.389	2.128	1.481	1.155	0.901	0.684	0.549	0.358	0.270	0.169	0.135
TOTAL	12.528	13.248	13.509	14.514	15.794	17.849	17.802	15.765	14.027	11.803	11.508
5.Maln'n death (m)											
Africa	0.222	0.244	0.269	0.324	0.390	0.458	0.550	0.589	0.647	0.667	0.748
Asia	2.403	2.256	2.437	2.674	2.934	3.333	3.228	2.740	1.654	1.289	0.900
NAmerica	0.044	0.043	0.038	0.031	0.028	0.035	0.017	0.010	0.006	0.005	0.004
LAmerica	0.124	0.136	0.142	0.171	0.180	0.200	0.191	0.152	0.102	0.068	0.056
Europe	0.344	0.268	0.178	0.132	0.097	0.074	0.059	0.037	0.028	0.017	0.014
TOTAL	3.136	2.947	3.063	3.331	3.630	4.100	4.046	3.527	2.437	2.046	1.722
Share of all attrib. to maln'n	0.250	0.222	0.227	0.229	0.230	0.230	0.227	0.224	0.174	0.173	0.150

Sources and assumptions:

Block 1: under 5 mortality rate

Source: Ahmad et al (2000), for the five year periods beginning 1955-59 to 1995-9, using population weights to aggregate WHO regions to the five regions used here. Europe B (WHO category) uses data for Austria to extend the data back to 1900 (Corsini and Viazzo, 1993); Europe A and C (WHO category) uses data for the UK to do a similar calculation (Hicks and Allen, 1999). These data are for infant mortality, and we add an additional 15% to estimate under-five mortality, using the ratio for the UK from Hatton (2009). North America uses data for the US we use data on mortality under 14 from Cutler and Meara (2001), which slightly overestimates the rate for under 5's. For the remaining regions, we assume that the rate remained constant between 1900 and 1950.

Block 2: population

Source: Maddison (accessed 2011).

Block 3: birth rates

Source: UNESA (accessed 2011), for data from 1950 onwards. The WHO regions have to be aggregated into the broader regions used in this analysis, using population weights. Prior to 1950, birth rates for the US from Haines (accessed 2011). For Europe, the rate for 1900 for Western Europe was used from Maddison (2006) and a linear trend from 1900 to 1950 to interpolate values for 1910, 1920, 1930 and 1940. For the other regions, the rate was assumed not to have changed from

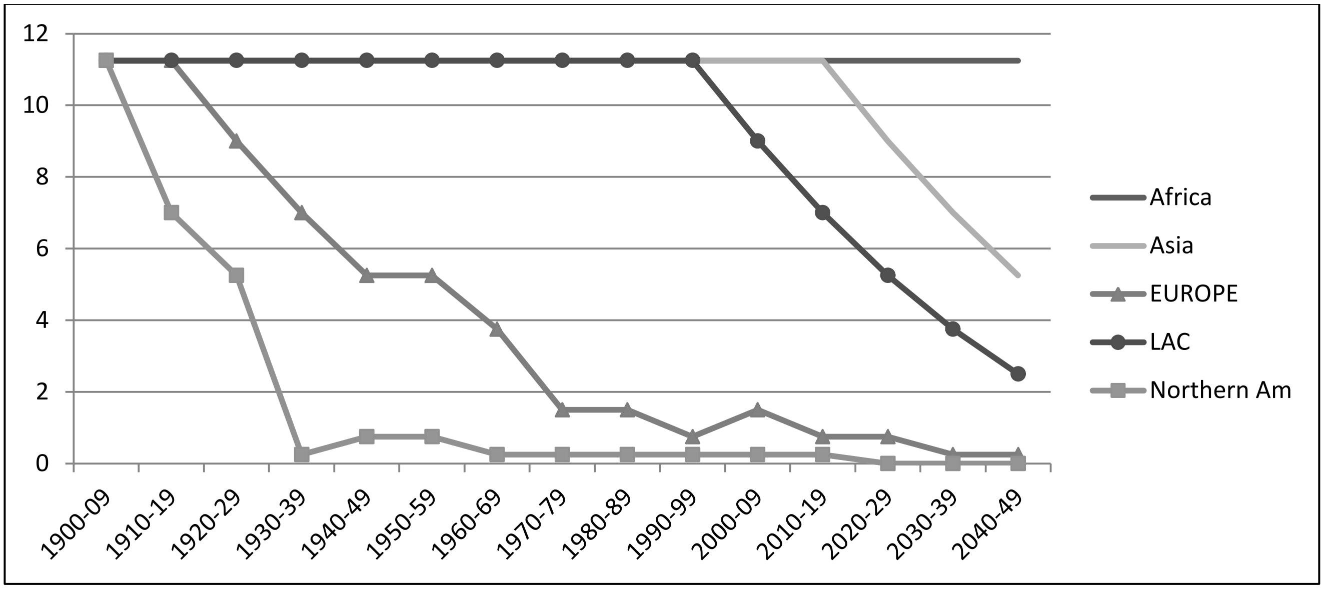
1900 to 1950, which is consistent with data provided in Maddison (2006) for India, China, Brazil and Mexico.
Block 4:
Child deaths calculated from U5MR X birthrate X population size
Block 5:
Child deaths attributable to malnutrition calculated as follows: we use achieved adult height 20 years in the future to obtain PAR. For 1990 and 2000 we use PAR estimated from child height-for-age from UNICEF 2000, to be consistent. However, this yielded PARs higher than 1980, hence we used the 1980 PARs for 1990 and 2000 instead. We assume that 40% of child deaths occur in the first month, based on WHO (2010), and that the relative risks from Pelletier et al (1994b) can be applied to the other 60%. (In practice, Pelletier et al, 1994b, derived those rates from ages 6 months to 5 years; but it is the first month which is most critical to exclude).

Results: economic and human costs of undernutrition

Figure 10 shows the trends in economic losses by region, and Figure 11 for the developed/developing countries and world aggregate, for 1900-2010, as well as projections for 2010 to 2050. Economic losses attributable to poor nutrition were already negligible in North America by the 1930's, and in Europe overall by the end of the 20th century. Losses in Northern Europe virtually disappeared as the post war babies reached adulthood, and similarly by 2000 in Eastern and Southern Europe.

In the developing world, although productivity losses began to diminish in individual countries, progress was not widespread enough to see any decrease at the level of the region until the turn of the 21st century, when improvements in Latin America became evident. The improvements in Asia become evident as of 2020, and significant improvements are visible in both Latin America and Asia by 2050. According to our assumptions, no improvement is seen in Africa even by 2050.

Figure 10. Estimated % of GNP lost due to poor nutrition, geographic regions, 1900-2010, and projections 2010-50



Global productivity losses start to decline at the beginning of the twentieth century (Figure 11), since productivity losses are weighted by GDP and not by population, and hence reflect heavily the situation of the developed regions. As the share in global GDP of the developing countries increases, particularly since 1970, global productivity losses increase again for almost four decades (since heights in these countries have not yet attained the level of North America). Once heights in Latin America attain 170cm in 2000, and in Asia in 2020, global productivity losses recommence their downward trend. Global losses average 8% over the twentieth century, and diminish to a projected 6% over the first half of the twenty-first century.

Figure 11. Estimated % of GNP lost due to poor nutrition, developed/developing regions and world, 1900-2010, and projections 2010-2050

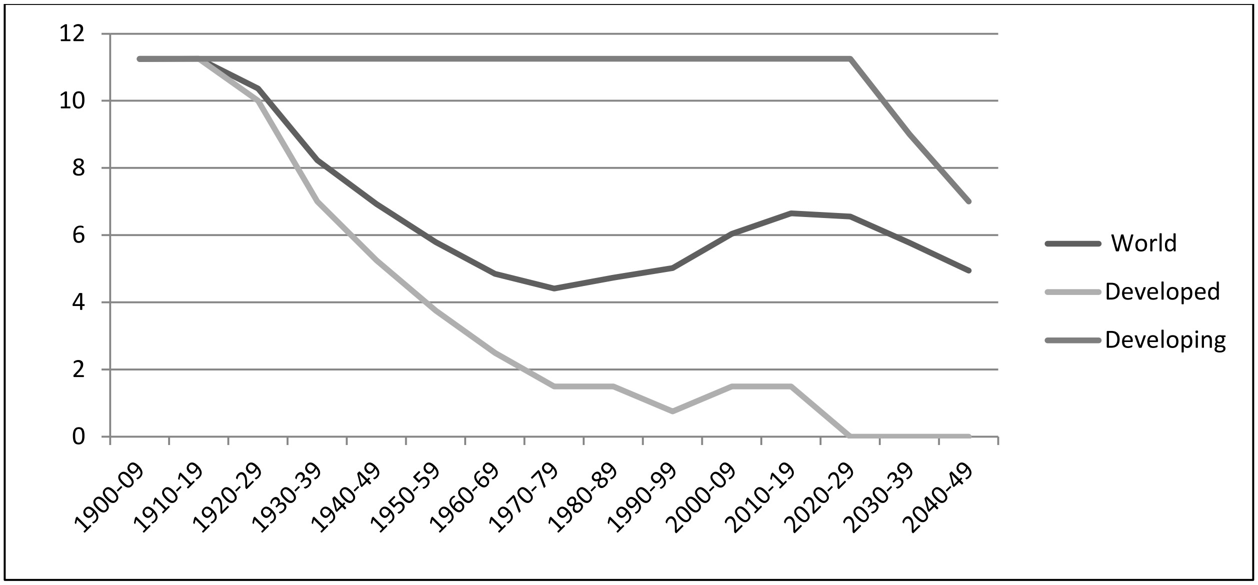


Table 7 provides some indications as to how sensitive these results are, to the assumptions made. The assumptions made of the relationship between height and productivity (Figure 8) have a major effect, as do assumptions as to how the effect of male height on individual productivity, translates into an effect of overall height on GDP. Assumptions which have a medium effect include our use of height as a measure of nutrition (which omits effects of higher calorie intake by adults, and higher micronutrient intake by children and adults), and the assumption that the benefits for women are similar to those for men. Assumptions which have the least impact include those concerning heights in Africa (since Africa contributes only about 3% of world GDP over this period), and errors in measurement of height trends.

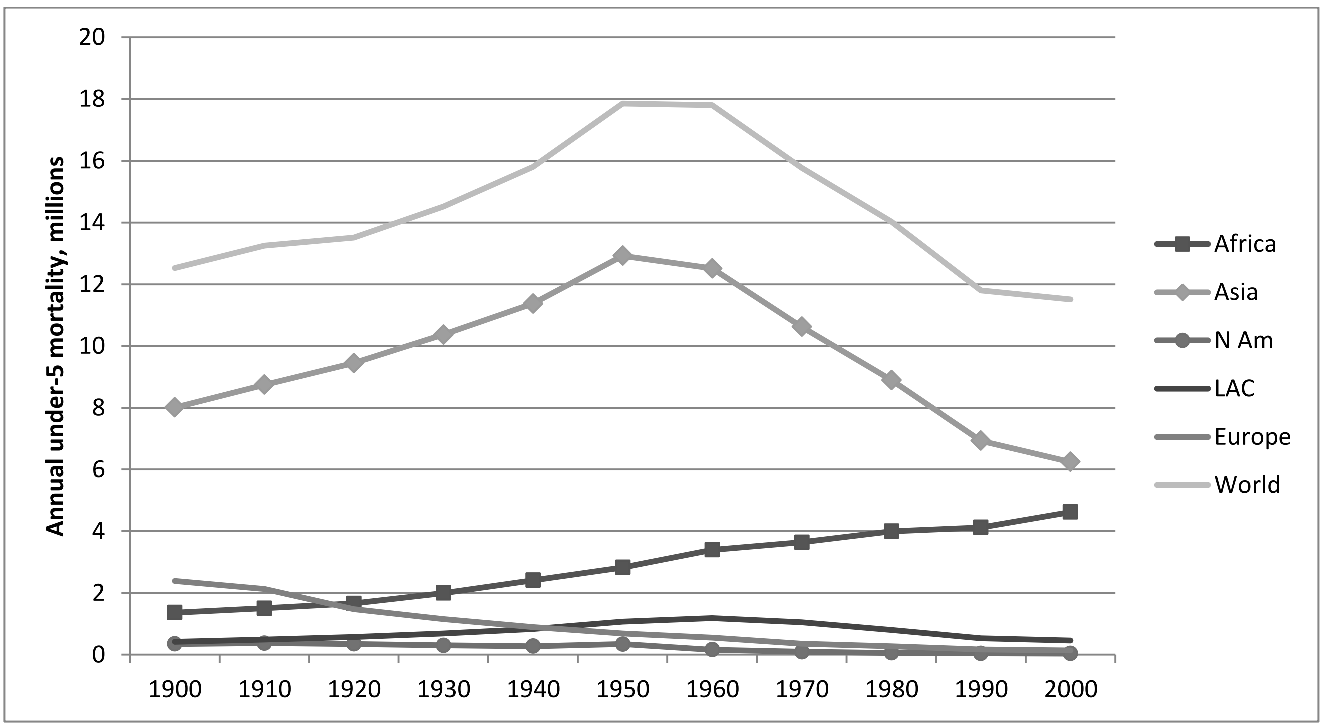
Table 7. Sensitivity analysis of effect of varying assumptions, on estimates of economic losses.

Assumption	Impact
There are additional productivity losses associated with heights below 170cm (e.g. Hoddinott et al, 2008 find that early childhood food supplements are associated with an additional 2.9cm of adult height, 45% higher wages, at mean height around 163cm for men	Gains/losses 2X larger
Benefits of improved productivity affect all of GDP, not just the wage share (one-half)	Gains/losses 2X larger
Benefits of improved height for women have no effect on productivity (who are on average one-third of labour force)	Gains/losses 50% smaller
Using data on young men overstates the improvement in height (hence productivity) of the whole labour force	Gains/losses 25% smaller (depending on structure of labour force by age, and rate of nutritional improvement)
Additional nutritional productivity losses attributable to improvements in calorie intake and micronutrient intake which do not manifest in improved height	Gains/losses 25% larger or possibly more

Heights in Africa do not stay constant over the 150 year period	World GDP gains/losses at most 10% larger/smaller (1 percentage point change in world GDP): Africa accounts for 3% of world GDP
GDP growth between 2010 and 2050 is higher or lower than expected	Will affect estimates, but by an undetermined amount: the effect on height is estimated via changes in life expectancy (which depend partly on income): however UN has not produced life expectancy variants to correspond

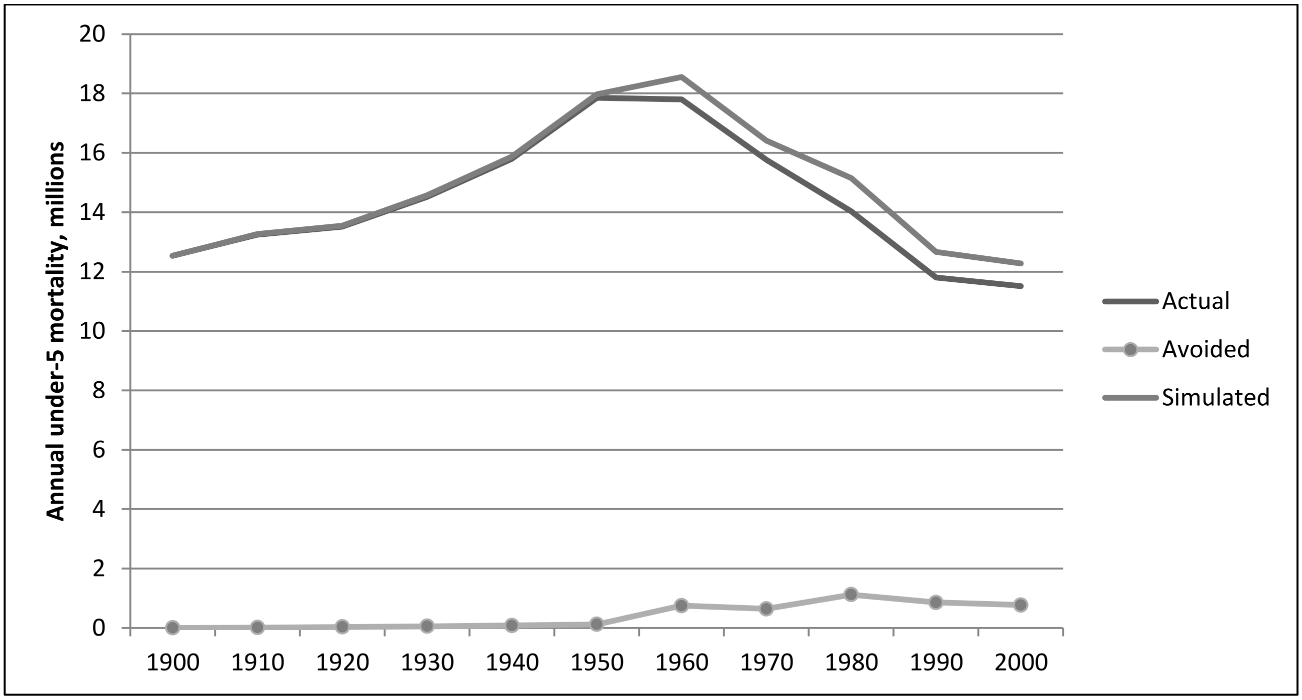
In addition to the economic losses, there are human costs of poor nutrition. Given the assumptions required, our results should be treated as broad orders of magnitude. Figure 12 presents trends in the annual number of under-5 deaths from all causes by region over the twentieth century. Figure 13 compares the total actual annual number, and our estimates of what this number would have been in the absence of nutrition improvements. Figure 14 breaks down the estimates of deaths avoided due to nutrition improvements, by region. The underlying numbers are available in Table 6.

Figure 12. Annual under-5 deaths (m), all causes (1900-2000)



The results show that the mortality due to undernutrition (as measured by height) is disturbingly large – accounting for a quarter of postneonatal child deaths from 1900 to 1970, on average 3-4 million child deaths annually. This only drops to 15% (and below 2m deaths annually) by 2000. Note that since we conservatively assume no height growth in Africa over the century, there is no improvement in child mortality attributable to nutrition for that region. There is also no improvement in North America, but for the opposite reason: heights were already sufficiently large by 1900 that further increases had no noticeable impact on further mortality reduction. (Note that some of the apparently surprising patterns – e.g. absolute decreases in annual lives saved due to nutrition improvements between 1960 and 1970, and between 1980 and 1990, are due to drops in birth rates).

Figure 13. Annual under-5 deaths (m), all causes (1900-2000)



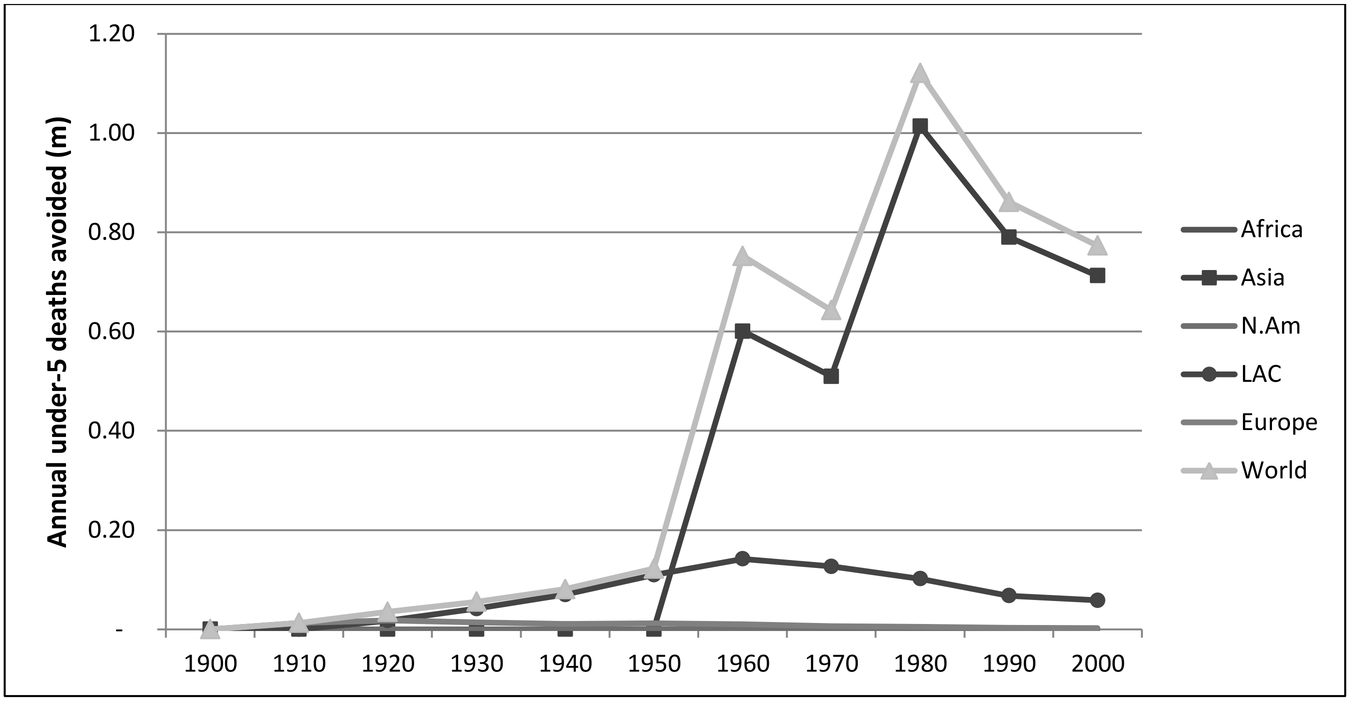
Note: Simulated means (actual plus avoided), i.e. deaths that would have occurred without nutrition improvements

Although there are substantial nutritional improvements in some regions in the twentieth century (primarily Europe and Latin America), these are regions with lower population, lower birth rates and lower child mortality. The end result is that these nutritional improvements save only about half a million lives a year worldwide prior to 1970, and just over a million worldwide thereafter, once nutritional improvements in Asia begin to take effect. We would expect major improvements between 2010 and 2050 as nutrition improves, particularly in Asia which is home to the majority of the world's children.

This estimate of mortality attributable to malnutrition focuses only on chronic malnutrition. In addition, there is a risk attributable to short term variations in nutritional status (associated with hungry seasons, periodic crop failures or famines). These affect weight-for-height and have separate effects on mortality. Our best estimate is that chronic malnutrition accounts for about three-quarters of the attributable risk due to malnutrition, based on the fact that our estimates around 2000 predict 1.7m under-five deaths annually. Black et al (2008) by comparison use weight for age (which combines both chronic and acute malnutrition) and a more robust methodology for the same year, and obtain a higher estimate of 2.2m under-five deaths due to undernutrition.

It is interesting to contrast the differences in patterns between the gains in economic productivity, with those in lives saved. The function linking GDP gains to height (Figure 8) models all the improvements occurring above a height of 170cm. By contrast, the function linking mortality risk to height (Figure 9) shows virtually all the improvement occurring at heights below 170cm. The improvements in height in the developed world have a large impact on world GDP growth (since these countries account for a large proportion of world GDP). By contrast, the improvements in height in the developed world have only a modest impact on world mortality improvements (since these countries account for a small proportion of world mortality).

Figure 14. Annual under-5 deaths (m) avoided, due to nutrition improvements (1900-2000)



Discussion and Conclusions

The estimates suggest that undernutrition has been a cause of a significant, slowly-declining, loss of global productivity. We estimate that this loss was 8% of world GDP over the twentieth century, and will decline to 6% of world GDP in the first half of the twentieth century. The losses are largely associated with impaired cognition which directly reduces productivity, with reduced educational attainment, as well as lower productivity of undernourished adults in manual work.

There is clearly some overlap between GDP gains in the twentieth century attributed to nutrition, and those attributed to increased education. Part of the improvement in nutrition allows children to stay longer in school, and part improves cognition and hence productivity even holding education level constant. Alderman, Hoddinott and Kinsey's (2008) estimates for Zimbabwe suggest that an increase in height from the 85th to the 95th percentile is associated with an extra 0.75 years of schooling (i.e. an extra 10cm in adult male height is associated with approximately one extra year in school). In the twentieth century, if heights increased on average by 10cm and education by 10 years for some regions, that implies that about a tenth of the schooling effect is nutrition-related, and equally somewhere between a quarter and a third of the nutrition effect is schooling-related. This gives a rough idea of the double-counting implicit in improved education and improved nutrition.

Similarly, there is overlap between health and nutrition as explanations of human costs (excess deaths). In the 35% of child deaths attributable to undernutrition, the immediate cause of death is often infection; however, a well-nourished individual could have survived.

The results are highly sensitive to the assumptions made regarding the effect of height (as a measure of nutritional status) and productivity. These assumptions likely could affect the results by an order of magnitude 4-8 times greater than variations in the assumptions made regarding height and mortality, errors in our estimates of height of adult males, and possible errors in the height projections to 2050.

Our results for productivity are lower than those of Fogel (1994) for the UK over the period 1790 to 1980. Fogel did not have access to the more recent econometric studies in Tables 1 and 2, and used a modelling exercise instead. Using height as a nutrition measure excludes the effect of higher calorie intake for adults on work output, as well as the benefits of improved micronutrient status on work output both directly and (via cognition and schooling) indirectly. Hence, our estimates are conservative. However, our estimates are somewhat larger than cross-sectional estimates of the costs of malnutrition for individual countries and regions at one point in time, since some of the effects take more than one generation to achieve.

We have carefully-controlled econometric studies of the effect of an additional centimetre of height, both for industrialized countries, and for countries with mean heights of 170cm for male adults. We do not, however, have good measures however of how the relationship tapers off as height increases (our assumption of a linear reduction in effect is not based on empirical evidence). We also do not have good measures of the effect at mean heights for male adults lower than 170cm. Unfortunately, mean heights for male adults in most of the developing world are below 170cm (often substantially below) for much of the twentieth century. The one longitudinal study available for Guatemala, where mean heights are around 163cm, suggests the effects on nutrition on productivity might be even larger at that height. We have not assumed additional losses of productivity as height falls further below 170cm, to be conservative.

The projections from 2010 to 2050 show much stronger impacts of improved nutrition on productivity, since our model is that heights of 170cm have to be attained, before productivity improves significantly. This happens in Latin America by 2000, and in Asia by 2020. Even by 2050, world economic losses attributable to undernutrition are still 5%. These are dominated by losses in Asia. Africa also likely has losses due to undernutrition, but the data on height for Africa are too limited to model the trends in this region; in any case Africa contributes only around 3% of world GDP over this period.

Our results for mortality using height are an underestimate of the effect of nutrition overall, since we measure chronic nutrition status (via height) and do not include the effects via weight-for-height, reflecting temporary food shortages and famines. Our own estimate is that these would add at least another third to the absolute losses. Our estimate of 41 million child deaths over the 20th century is a huge number (especially if we are correct about the additional deaths due to acute undernutrition, which would contribute an additional 20 million child deaths).

Although using height to measure nutrition underestimates both the productivity losses and the mortality losses, unfortunately there is no other measure that can be used for the whole century, nor for a global study. Despite the limitations of the measure, the differences between regions and by decades are very informative.

We have not touched at all on what could have been done to improve nutrition – and hence reduce child mortality, and increase world GDP – during the twentieth century. The cost-effectiveness of nutrition interventions is another big topic in itself (Horton, Alderman and Rivera, 2009).

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