

Nutritional and socio-economic predictors of adult height in 152 world populations

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Abstract:

Height is one of the most sensitive indicators of well-being because it combines the external influences of nutrition, economic wealth, health care, social equality, and other important socio-economic factors. The aim of this ecological study was to compare actual values of male and female height from 152 populations (except sub-Saharan Africa) with the mean supply of 47 food items from the FAOSTAT database (1995-2013) and mean values of seven socio-economic indicators (1995-2013). This comparison shows that economic wealth at the country level is only a mediocre correlate of physical growth because it is only loosely associated with the quality of nutrition and it does not reflect the social distribution of wealth. In a multiple regression model, the best predictors of stature are protein sources of the best and worst quality, and total fertility (which critically influences the amount of resources expended per child). In summary, these findings indicate that irrespective of crude economic statistics, the choice of specific nutrient sources and small family size are crucial factors determining the optimal physical development of children. Based on our data, we also believe that current international dietary recommendations regarding protein intake and protein quality would deserve serious re-evaluation.

Keywords: Height; Nutrition; Protein quality; Total fertility

Introduction

Height is a very important biological indicator of the quality of living conditions because it includes the role of nutrition and socio-economic factors that directly influence physical growth. For example, historical changes in the mean estimated stature in Northern and Central Europe have a characteristic pattern, with very short values in the Neolithic (when human nutrition depended on agriculture and low-quality proteins from cereals), and a dramatic increase during the late Eneolithic (3rd millennium BC), with the advance of the Corded Ware culture (Ehler & Vančata, 2009; Mummert et al., 2011; Ruff, 2018, p. 78-79). As already summarized by previous papers (Grasgruber et al., 2014; Grasgruber et al., 2016a), this sudden break can be connected with the spread of lactose tolerance and regular dairy consumption. Following the onset of the Industrial Revolution in the 19th century, height in the highly industrialized parts of Europe began to increase in an unprecedented way. Although the rising gross domestic product (GDP) per capita was the fundamental trigger of this trend, a more direct influence should be ascribed to changes in health care (reduced child mortality) and improved nutrition (Baten & Blum, 2012; Hatton, 2013).

Our ecological comparison of 105 populations (Grasgruber et al., 2016a) showed that the current height of young men in Europe, North Africa, Asia and Oceania is most strongly associated with the statistics of protein intake (supply) from the FAOSTAT database. The dominant role was played by dairy proteins, which naturally results from the high biological quality of their amino acid spectrum, and other nutrients in dairy products that are essential for bone growth (calcium, phosphorus, vitamin D) (see e.g. Black et al., 2002). The combination of ‘highly correlated proteins’ from dairy products, pork, eggs, beef and potatoes further increased correlation coefficients up to $r = 0.85$ in a sample of 93 populations. In contrast, cereals and legumes correlated negatively with height, and the shortest statures were typical of populations in the tropical belt of Asia where they were strongly associated with proteins from rice and legumes. In a multiple regression model incorporating 72 populations, the combination of three nutritional factors (‘highly correlated proteins’, cereal & legume proteins, total energy) explained by far the largest proportion of variance (adjusted $R^2 = 0.815$). The best model combining four nutritional and three socio-economic variables was only moderately better (adjusted $R^2 = 0.872$). At the same time, total fertility was a socio-economic factor with the strongest additive effect, followed by child mortality and urbanization.

As already indicated by the historical analyses mentioned above, GDP per capita did not have such a strong and direct influence on height in this ecological study. The explanation lies in the fact that the diet of wealthy Muslim and East Asian nations remains inferior relative to the diet of European nations, being characterized either by a low consumption of dairy products or the religious prohibition on pork, a relatively high consumption of cereals, and the dominance of low-quality meats (poultry). The unequal distribution of wealth (expressed by the Gini index) and

surprisingly low health-related expenditures in Muslim oil superpowers, relative to the high GDP per capita, are other factors that obviously contribute to short statures in these populations.

Interestingly, there also exist intriguing relationships of height with the frequency of paternal genetic markers (Y haplogroups) which must reflect “founder effects” in isolated human communities. Genetic predispositions associated with the spread of Y haplogroup I-M170 can illuminate the unexpectedly tall statures in the Western Balkan countries, which contrast with their unimpressive GDP per capita and mostly mediocre level of dietary protein quality (Grasgruber et al., 2017; 2019). On the other hand, Y haplogroups of Neolithic (Near Eastern) origin correlate negatively with stature in Europe. Certain Y haplogroups also show positive or negative correlations with height in North Africa, Asia and Oceania. These geographical tendencies based on Y haplogroups are being largely confirmed by studies of autosomal DNA (Berg et al., 2017). However, one persistent weakness of these autosomal studies is the omission of the most interesting region - the Western Balkans.

Although all these comparisons were only ecological, i.e. at the level of populations, it is important to emphasize that this fact does not diminish their biological relevance and importance. Realistically, without the use of long-term socio-economic and nutritional statistics, it is not possible to trace the influence of external conditions on the child’s growth, which may last up to ~20 years. Even current ideas about the nutritional needs of children are based on studies lasting only several days or weeks, whose accuracy and reliability are questionable. Indeed, recent research indicates that the actual protein recommendations of the World Health Organization (WHO) and other international bodies, which are based on short-term studies of nitrogen balance, underestimate the need for protein in children by almost two-fold (Elango et al., 2011). This agrees with our ecological data, because mean male height increases linearly with the supply of high-quality proteins, and no levelling-off of this trend can be observed (Grasgruber et al., 2016a).

The aim of the present study was to apply a similar ecological methodology on the American continent, which consists of 35 sovereign states and multiple dependent territories variously tied to Denmark, France, the Netherlands, the United Kingdom, and the United States¹. The total number of populations would thus increase by roughly four dozens and the larger size of this sample would enable a more precise evaluation of the role of environmental factors in the global context.

¹ Populations of North America, <https://www.populations-of-the-world.com/populations-of-north-america.html>. Populations of South America, <https://www.populations-of-the-world.com/populations-of-south-america.html>.

Methods

Collection of anthropometric data

Similar to two previous studies (Grasgruber et al., 2014; Grasgruber et al., 2016a), the data on measured body height in America were obtained from the most recent health and anthropometric surveys which ideally targeted young individuals aged 20-25 years. However, because the age range in the available surveys was not always ideal, we used all samples that incorporated young adults aged 18-30 years. The total age range of these studies was 18-44 years.

The search was performed independently of the NCD Risk Factor Collaboration (2016) which recently published a very extensive dataset incorporating the height of people born between 1896 and 1996 from 200 populations but not all sources listed in this study seemed to be sufficiently representative (see Appendix, p. 19-20 for a more detailed discussion). In general, only sovereign countries and territories with a population over 50,000 people were searched which guaranteed a reasonable availability of statistical data and reduced the chance of eccentric results. We always preferred large nationwide surveys including all social groups – anthropological surveys of school youth, measurements of conscripts, or official health surveys such as the STEPS [STEPwise approach to surveillance], or the DHS [Demographic and Health Surveys]. In several cases, when no other data were available, we used health surveys of urban populations that may somewhat overestimate the true population mean. University students or other privileged social groups were excluded, and studies with self-reported height were ignored as well. The minimum limit for the inclusion into our study was 50 measured individuals. The only exception is the survey from the Netherlands Antilles (Curaçao) which measured only 23 men. However, the measured height (175.2 cm) was supported by self-reported height from the same survey (175.9 cm, n=164). In several cases, the number of measured individuals was unknown but the data always came from nationwide surveys.

Together with Kosovo, Luxembourg, Macau, Malta, New Caledonia, and the Northern Mariana Islands (for which information on height was not available previously), and Montenegro (which was not included in the previous study because of temporal limitations of statistics), the total size of the male sample reached 152 countries/territories: 45 from Europe (Appendix Tables 1-3), 67 from North Africa, Asia & Oceania (Appendix Tables 4-5), and 40 from America (Table 1), leaving aside individual data for England, Northern Ireland and Scotland from which a weighted mean representing the United Kingdom was calculated. Two values of male height (for Afghanistan and Pakistan) were only estimated, based on studies performed in women and using male/female ratios from neighbouring countries (see Appendix, p. 14). The whole population mean (and not the mean

of the white population) is used for Australia, New Zealand and the United States. All the surveys were finished between 2002 and 2018.

Table 1. Male and female height in 40 American countries/territories sorted according to the height of males. For the list of references, see Appendix.

Country/territory	Age	Date	Men		Women		Source
			<i>n</i>	Height	<i>n</i>	Height	
Canada	20-39	2011-2015		177.7*		163.3*	Statistics Canada
Dominica	20-29	2007-08		177.4		164.8	STEPS 2007-08
St. Vincent & Grenadines	18-29	2013-2014	295	177.2	462	164.8	STEPS 2013-2014
Grenada	25-34	2010-11	131	177.0	182	164.3	STEPS 2010-11
USA (total population)	20-39	2011-2014	1,851	176.8**	1,885	163.5**	Fryar et al., 2016
UK: Cayman Islands	25-34	2012	103	176.6	176	161.8	STEPS 2012
Jamaica	20-29	2007-2008	172	176.1	375	163.5	National Survey 2007-2008
Trinidad and Tobago	25-34	2011	242	175.3	350	162.5	STEPS 2011
Neth. Antilles (Curaçao)	18-39	2013	23	175.2±7.3	53	165.0±6.0	Curacao Health Survey 2013
Uruguay	18-34	2013	279	174.8	445	161.3	STEPS 2013
Barbados	25-34	2012	52	174.7	95	164.3	STEPS 2012
UK: Bermuda	18-34	2014	89	174.7	106	163.6	STEPS 2014
St. Lucia	25-44	2012	322	174.7	577	164.0	STEPS 2012
Argentina (Rosario City) ^A	18-30	2011-2012	140	174.3±7.2	329	161.5±6.0	Zapata et al., 2016
Netherlands: Aruba	25-34	2006	51	173.9	61	160.8	STEPS 2006
Brazil	20-24	2008-2009	8,299	173.0	7,938	161.1	POF 2008-2009
USA: Puerto Rico (San Juan)	21-39	2005-2007	90	172.8±7.5	178	159.8±6.9	C. Perez et al., 2008
Denmark: Greenland (Inuit)	20-29	2005-2010	208	172.8	296	159.8	P. Bjerregaard – pers. comm.
Venezuela (Maracaibo)	20-29	2014	332	172.4±7.1	249	159.1±7.3	Bermúdez et al., 2016
Dominican Republic	20-25	2013	1,988	172.1±7.0	1,980	159.3±6.4	DHS 2013
Paraguay	20-29	2011	224	171.7±6.6	429	158.3±6.5	STEPS 2011
Bahamas	25-34	2012	211	171.5	254	162.2	STEPS 2011
Chile	19-29	2010-2011	273	171.5±6.7	388	158.3±6.3	ENCA 2010-2011
El Salvador (Santa Tecla)	20-29	2004-05	107	171.2±6.3	173	157.2±6.5	CAMDI 2003-06
Cuba	25-34	2010-2011		171.0		159.4	Bonet & Varona, 2015
Costa Rica (San José)	20-29	2004	116	170.9±6.8	205	157.0±5.9	CAMDI 2003-2006
Suriname	20-29	2013	381	170.9±7.5	655	158.8±7.4	STEPS 2013
St. Kitts and Nevis	25-34	2008	145	170.5	285	160.5	STEPS 2008
Haiti (Port-au-Prince)	25-34	2008-2009	76	170.4±9.8	50	160.6±6.4	El Mabchour et al., 2015
Nicaragua (Managua)	20-29	2003	238	169.0±6.4	205	155.6±5.9	CAMDI 2003-2006
Guyana	20-25	2009	585	168.9±8.7	889	156.4±7.9	DHS 2009
Colombia	20-24	2010	5,794	168.8±7.0	6,703	156.4±6.2	Ramírez-Velez et al., 2016
Mexico	20-25	2016	310	168.2	624	155.9	ENSANUT 2016
Panama	18-29	2010-2011	183	167.8±8.6	520	156.7±6.9	Mc Donald et al., 2015
Honduras (Tegucigalpa)	20-29	2003-2004	119	167.6±7.1	222	154.8±5.9	CAMDI 2003-2006
Belize	20-29	2005-2006	206	167.0±9.9	315	157.2±8.8	CAMDI 2003-2006
Bolivia	18	2005-2007	144	166.6±6.0	139	155.4±6.5	Botti et al., 2009
Ecuador	19-29	2011-2013	4,527	166.2	6,630	153.4	ENSANUT-ECU 2012
Peru	20-29	2010		165.5		153.1	Ramírez, 2016
Guatemala	20-24	2008-2009	851	161.9	2,534	148.7	ENSMI-2008/09

Notes: *A mean of 2011, 2013 and 2015. ** A mean of four ethnic groups (non-Hispanic white, non-Hispanic black, non-Hispanic Asian, Hispanic), corrected for their population size in the 2010 Census, <https://www.census.gov/prod/cen2010/briefs/c2010br-02.pdf>.

^A Other urban survey in Santa Rosa (the capital of the neighbouring province of La Pampa), performed between 2005-2009, documented practically identical median reference values for 18 year olds - 174.3 cm for boys and 161.1 cm for girls (Orden A.B. & Apezteguía M. C. (2014) Ann Hum Biol. 43(1), 9-17.)

In contrast to our previous studies, the present study also includes the height of women, which was missing from too many European countries in the first study (Grasgruber et al., 2014), and hence it seemed more meaningful to concentrate only on men. Female samples are now available for 149 populations (42 from Europe, 67 from North Africa, Asia & Oceania, and 40 from America), and are missing only for Bosnia and Herzegovina, Cyprus, and Norway. For 147 populations (including two regional studies from Bosnia and Herzegovina, and Norway), data on both sexes were available from the same study and hence enabled a maximally objective comparison of inter-sex differences. All data on the height of men and women are summarized in Dataset, Sheet 1.

Actual information on height was available even for Andorra² but the samples were small, and because only 31.9% of the examined participants were born in Andorra, these results did not seem to be meaningful for any analysis. No information on measured height was found for Wales, Antigua and Barbuda, and the U.S. Virgin Islands³. For three French territories in America (French Guiana, Guadeloupe, Martinique), no independent statistics were available, and hence they were not included in this study.

Nutritional statistics

Nutritional statistics of food consumption (supply) were again collected from the FAOSTAT database⁴ and were available for 136 out of 152 populations (36 out of 40 American populations) until 2013. Because these statistics describe the disappearance of food stocks in a particular country⁵, they inevitably overestimate true food consumption due to a certain proportion of food losses/waste, especially in affluent countries. Nevertheless, our experience with the FAOSTAT database in ecological analyses has been very impressive (see e.g. Grasgruber et al., 2016b), which shows that these data reflect inter-country differences in food consumption with remarkable accuracy.

A total of 29 variables were extracted: protein supply for 28 food items (g/day per capita) and total energy intake (kcal/day per capita) (see Dataset, Sheet 2). Several additional variables were subsequently computed from these data: proteins from ‘legumes total’ (including soybeans, which are otherwise classified among oil crops in the FAOSTAT database), combined supply of certain proteins (from rice & maize, dairy & pork etc.), proportion of protein energy in the diet (assuming

² 2a Enquesta Nutricional d’Andorra (ENA 2017-2018). (L. Serra-Majem – pers. communication)

³ There is a STEPS survey currently ongoing in Antigua and Barbuda (Ministry of Health – pers. communication), and a health survey in the U.S. Virgin Islands was to be finished in 2019 (E. S. Tull – pers. communication). The data will be available in 2020.

⁴ Food Supply - Crops Primary Equivalent. <http://www.fao.org/faostat/en/#data/CC>. Food Supply - Livestock and Fish Primary Equivalent. <http://www.fao.org/faostat/en/#data/CL>.

⁵ Concepts and definitions used in food balance sheets. <http://www.fao.org/3/X9892E/X9892e02.htm>.

4.1 kcal per gram of protein), and protein ratios. Altogether, the analysis included 47 food items. In all cases, a mean for the period 1995-2013 (19 years) was computed.

Independent statistics of food supply for eight populations were incomplete and available for 8-17 years: Belgium (2000-2013), Libya (1995-2011), Luxembourg (2000-2013), Montenegro (2006-2013), the Netherlands Antilles (1995-2010), Palestine (1996-2011), Serbia (2006-2013), and Syria (1995-2011). However, all these populations fitted well the graphic comparisons of height and nutrition, which shows that this time period was sufficient to capture the characteristic diet of each country.

Socio-economic statistics

Our analysis includes a total of nine socio-economic statistics (Dataset, Sheet 3). Seven of them were drawn from the World Bank database⁶ and their mean values were also computed for the period 1995-2013 (Table 2). In addition to socio-economic variables examined in the previous paper, we used even the gross national income (GNI) which serves as an alternative to the gross domestic product (GDP). Whereas GDP takes into account the total value of goods and services produced within a country, GNI combines GDP with incomes obtained from foreign investments, but excludes incomes payable to non-residents⁷. Therefore, a high GDP/GNI ratio indicates that a significant proportion of a country's production is controlled by foreign non-residents, whereas a high GNI/GDP ratio betrays high foreign investments. Data on the Human Development Index (HDI) and the Inequality-adjusted Human Development Index (IHDI) for 2013 were taken from the website of the United Nations Development Programme (UNDP)⁸.

The period 1995-2013 is relatively the most advantageous in terms of long-term data availability but many national statistics are still unavailable or incomplete. Especially information regarding the Gini index and the IHDI is scarce, and the temporal availability of the Gini index varies greatly from country to country. Because economic data such as GDP, GNI and health expenditure usually show fast upward time trends, missing values could fundamentally distort the computed mean, and hence all populations with missing years were excluded from the comparison of these statistics. Complete data for all years were often missing even for total fertility, but because trends in total fertility change more slowly over time, the respective country was included, when it had at least one value available from the first half (1995-2003/4) and the second half (2004/5-2013) of the examined time period (Bermuda, Marshall Islands, Serbia). Only the statistics of child mortality and urbanization were always complete for all years, provided that they were available. For the

⁶ The World Bank. Data. Indicators. <http://data.worldbank.org/indicator>.

⁷ Gross National Income (GNI). <https://www.investopedia.com/terms/g/gross-national-income-gni.asp>.

⁸ United Nations Development Programme (UNDP). Human development reports. Table 2: Trends in the Human Development Index, 1990-2015. <http://hdr.undp.org/en/composite/trends>.

Netherlands Antilles, which dissolved in 2010, we used the World Bank statistics for Curaçao (which were only available for urbanization).

Table 2. The list of independent variables used in this study and their sources.

Variable	Period	Total number of populations available	Source
Nutrition (44 food items)	1995-2013 (mean)	136	FAOSTAT
GDP per capita ^a , by PPP* (current international USD)	1995-2013 (mean)	136	The World Bank
GNI per capita ^b , by PPP* (current international USD)	1995-2013 (mean)	128	The World Bank
Health expenditure per capita, by PPP* (constant 2011 int. USD)	1995-2013 (mean)	133	The World Bank
Child mortality under 5 years (per 1,000 live births)	1995-2013 (mean)	137	The World Bank
Total fertility rate (total births per woman)	1995-2013 (mean)	145	The World Bank
Urban population (% total)	1995-2013 (mean)	150	The World Bank
Gini index	1995-2013 (mean)	115	The World Bank
Human Development Index (HDI)	2013	136	UNDP
Inequality-adjusted Human Development Index (IHDI)	2013	106	UNDP
ALL STATISTICS		93	

Notes: *PPP = purchasing power parity. ^a GDP = gross domestic product. ^b GNI = gross national income.

Demographic statistics and genetic data

Similar to two previous studies, the present study tested the relationship between height and genetic factors in America. Nevertheless, this time we preferred genetic studies of autosomal DNA (ancestry informative markers) because American populations are subject to extensive mixing and consist of three main ancestral groups (European, African, Native American). Altogether, these autosomal studies were found for 32 populations and were based mostly on selected single nucleotide polymorphisms (SNPs) (see Dataset, Sheet 4). In addition, height was compared with the statistics of self-reported racial/ethnic affiliation that included even mixed ancestry (Lizcano-Fernandez, 2005; Latinobrómetro, 2011; Adhikari et al., 2017).

Statistical analyses

Complete statistics of all variables were available for only 93 populations (Table 2). Because the Gini index and IHDI were the variables with by far the least number of data, they were used only for additional comparisons and our analyses concentrated on seven socio-economic indicators and nutrition. First, simple Pearson linear correlations were conducted with seven socio-economic indicators alone (for 119 populations in men and 116 in women), and then with 47 nutritional variables (for 136 populations in men and 133 in women). Six socio-economic factors (excluding GNI per capita, which is basically interchangeable with GDP per capita), and nutrition were then used for a multiple regression (for 119 populations in men and 116 in women). Multiple regressions were also performed separately in three individual regions (Europe; North Africa, Asia & Oceania;

America). Because the number of genetic data for American populations is limited, an analysis including these data was performed separately as well. In addition, to test the influence of economic wealth on some relationships, the sample of 136 countries for which data on GDP per capita were available, was divided into three tertiles (each including 45, 46, and 45 populations, respectively). All these analyses were performed using the statistical software Statistica 12.0.

Results

Height in 152 world populations

The distribution of men's values in 152 populations is displayed in Fig. 1. More detailed maps of America and Europe are included in the Appendix (Appendix Figs. 1-2). The average of these 152 male populations is 172.9 cm (median 173.0 cm). Europe is by far the tallest (178.1 cm, median 178.5 cm). North Africa, Asia & Oceania (170.0 cm, median 171.1 cm) and America (171.9 cm, median 171.9 cm) are lagging behind considerably. Men from Timor-Leste are the shortest (160.0 cm), and recent surveys such as the DHS 2016 indicate that their height has decreased by ~1 cm during the last decade. The tallest men live in the Netherlands (183.8 cm) but their secular trend has already stopped (Schönbeck et al., 2012). The range of men's extremes is therefore 22.2 cm. The same countries appeared at both ends of the men's height spectrum in the study of the NCD Risk Factor Collaboration (2016).

Nevertheless, some caution is needed, when interpreting the tall values from the Netherlands. The local education system is compulsory up to the age of 16-18 years⁹ and data on older subjects are obtained outside the general school system. Pooled values of Dutch men aged 20-21 years give a mean of 183.8 cm but Dutch boys aged 18 years are only 182.4 cm tall (Schönbeck et al., 2012). At the same time, Montenegrin high schoolers aged 17-20 years reach 182.9 cm (when corrected for population size in individual regions) (Popović, 2017). Therefore, it is possible that young Montenegrin males may actually be the tallest in the world.¹⁰ Also noteworthy is the global maximum at the level of regions which we recently documented in their peers from neighbouring Dalmatia (183.7 cm) (Grasgruber et al., 2019).

The average of 149 female samples is 160.4 cm (median 160.6 cm), and women from Europe (165.0 cm, median 165.4 cm) are again much taller than women in North Africa, Asia & Oceania

⁹ Rijksoverheid [The Government of the Netherlands]. Leerplicht [Compulsory education]. <https://www.rijksoverheid.nl/onderwerpen/leerplicht>.

¹⁰ After World War II, Nilotic tribes from contemporary South Sudan were by far the tallest in the world, with mean values ranging between 178.7-184.9 cm. However, at present, there are no reliable data from this region, except for the measurements of refugees, who reach much shorter statures, probably as a result of wars and famines (See Grasgruber et al., 2019). All current information is based only on anecdotal reports by travellers.

(158.0 cm, median 158.4 cm) and America (159.6 cm, median 159.8 cm). The shortest women can be found in Guatemala (148.7 cm) and the tallest in the Netherlands (170.5 cm) – a difference of 21.8 cm. At the same time, 18-year old Dutch girls (169.7 cm) still have a significant height advantage over their Montenegrin peers aged 17-20 years (168.8 cm). Although the study of the NCD Risk Factor Collaboration (2016) also identified Guatemalan women as the shortest, the tallest female sample came from Latvia (169.8 cm) which seems doubtful because young women from the Latvian Health Survey 2014 (n=636) reached only 167.3 cm.

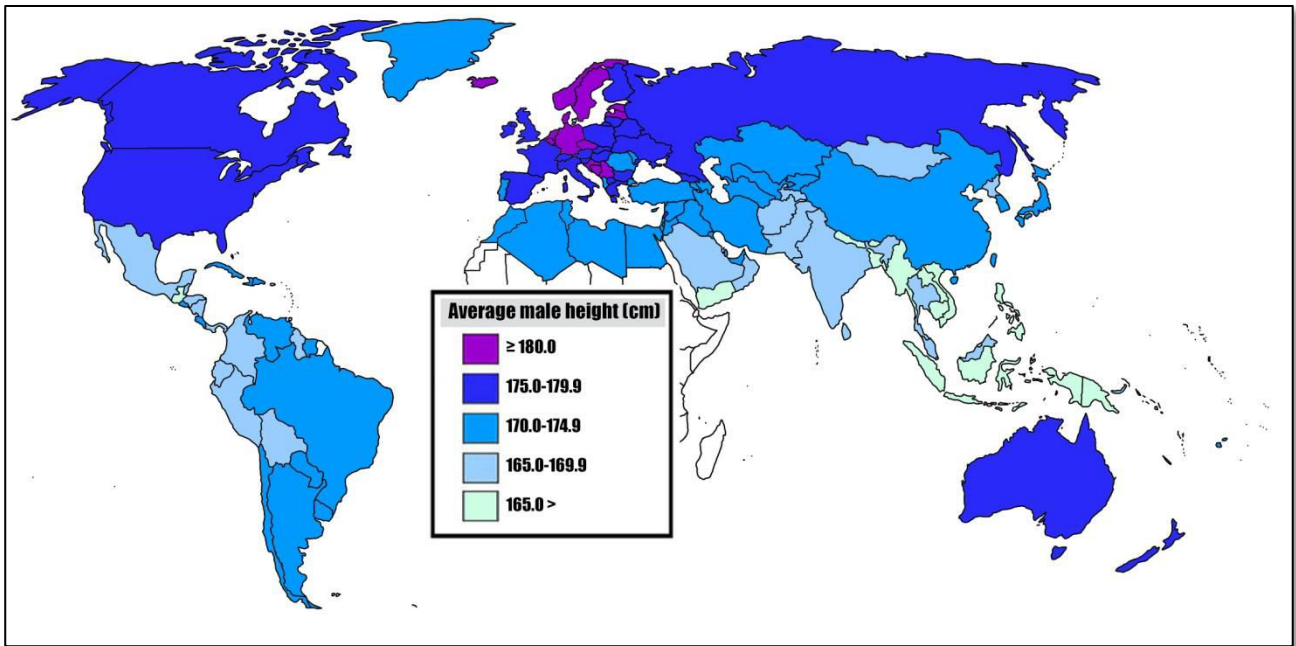


Figure 1. Distribution of the average male height in 152 world populations.

Male height in 40 American populations is also very variable, from 161.9 cm in Guatemala to 177.7 cm in Canada (15.8 cm). Men from Guatemala are actually the second shortest in our total sample after Timor-Leste, and the difference between men from Guatemala and neighbouring El Salvador reaches 9.3 cm. This is the largest inter-country gap that we have documented so far.¹¹ The range of extreme values in women is even larger – from 148.7 cm in Guatemala to 165.0 cm in Curaçao (a 16.3 cm differential).

¹¹ Nevertheless, mean heights in the CAMDI surveys (which included El Salvador and five other Mesoamerican countries) were mostly based on urban or suburban populations, and are probably overestimated because nationwide averages are strongly influenced by short-statured indigenous populations from rural areas. Because Guatemala and El Salvador have by far the highest proportion of the Native American population in Mesoamerica, it can be expected that the difference between urban means and nationwide means is also the highest in the region. This can be illustrated by the CAMDI survey from Villa Nueva, a suburban area of Guatemala City, which documented an average height of 164.2 cm in men (n=94) and 153.4 cm in women (n=209) in the age category of 20-29 years (A. Barcelo – pers. communication). This is 2.3 cm and 4.7 cm more than in the nationwide survey ENSMI-2008/09. Indigenous men in the ENSMI-2008/09 were 5.8 cm shorter and indigenous women were 5.1 cm shorter than the rest of the Guatemalan population.

Male height vs. GDP per capita & GNI per capita

Despite the different methods of calculation, there is a nearly perfect linear correlation between GDP per capita and GNI per capita in the sample of 119 populations ($r = 0.99$, $p < 0.001$), and even in the sample of 128 populations for which both these variables are available ($r = 0.99$, $p < 0.001$) (Appendix Fig. 3). This means that these two indicators are completely interchangeable as a measurement of living standards. However, both correlate with male height only weakly (Table 3; Figs. 2-3). There are two main reasons: First, wealthy Asian countries such as Brunei, Kuwait, Macau, and the UAE [United Arab Emirates] are characterized by a low quality diet, relative to their very high GDP and GNI, and their wealth is also unevenly distributed. The second reason lies in the large gap between the former ‘Western’ countries and the countries of the former Communist bloc. The latter are much taller than their economic wealth predicts, which can be attributed to the combination of good nutrition and genetic factors.

Table 3. Correlation between male height and seven socio-economic factors (a sample of 119 populations for which all variables are available).

	Europe			North Africa, Asia & Oceania			America			WORLD TOTAL		
Populations (n)	40			48			31			119		
	Mean	r	p	Mean	r	p	Mean	r	p	Mean	r	p
GDP per capita	22,402	0.43	0.006	13,495	0.31	0.032	11,415	0.52	0.003	15,947	0.45	<0.001
GNI per capita	21,826	0.46	0.003	13,418	0.30	0.038	11,061	0.51	0.003	15,630	0.44	<0.001
Health expenditure	1,839	0.47	0.002	641	0.54	<0.001	858	0.45	0.012	1,100	0.60	<0.001
Child mortality	11.0	-0.57	<0.001	38.7	-0.61	<0.001	27.7	-0.43	0.016	26.5	-0.69	<0.001
Total fertility rate	1.68	-0.11	0.48	2.91	-0.42	0.003	2.61	-0.72	<0.001	2.38	-0.70	<0.001
Urban population (%)	68.7	0.27	0.09	50.3	0.64	<0.001	62.0	0.07	0.71	59.5	0.52	<0.001
Human Development Index	0.84	0.57	<0.001	0.70	0.69	<0.001	0.73	0.53	0.002	0.76	0.76	<0.001

Positive relationships				Negative relationships			
$r \geq 0.700$	$p < 0.001$	$p < 0.01$	$p < 0.05$	$p < 0.05$	$p < 0.01$	$p < 0.001$	$r \geq 0.700$

Male height vs. health expenditure

Health-related expenses are a very meaningful causal factor influencing physical growth because they are related to the level of health care, sanitation and disease prevalence. Infectious diseases exhaust children’s growth capacity (Hatton, 2013). Figure 4 reveals that per capita health expenses in some populations with very high GDP/GNI per capita (Brunei, Kuwait, the UAE) are disproportionately low, roughly around the European average. This shows that the superior wealth of these populations does not translate into similarly high standards of health care. In fact, this striking asymmetry is typical even of other wealthy Arab and Southeast Asian countries (Appendix Fig. 4). As a result, these countries are no longer outliers (as in the graphic comparison of GDP/GNI per capita) and health expenditure per capita is a much stronger correlate of male height in the global sample (Fig. 4).

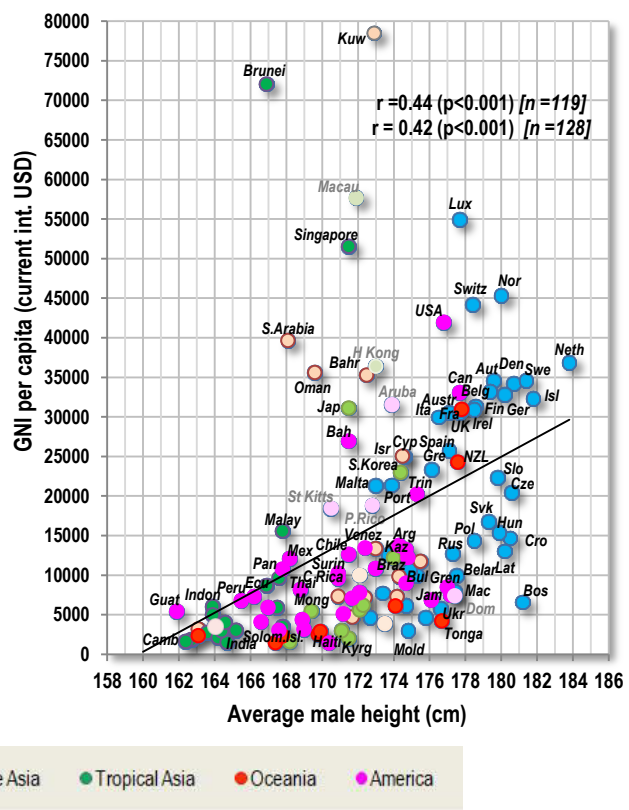
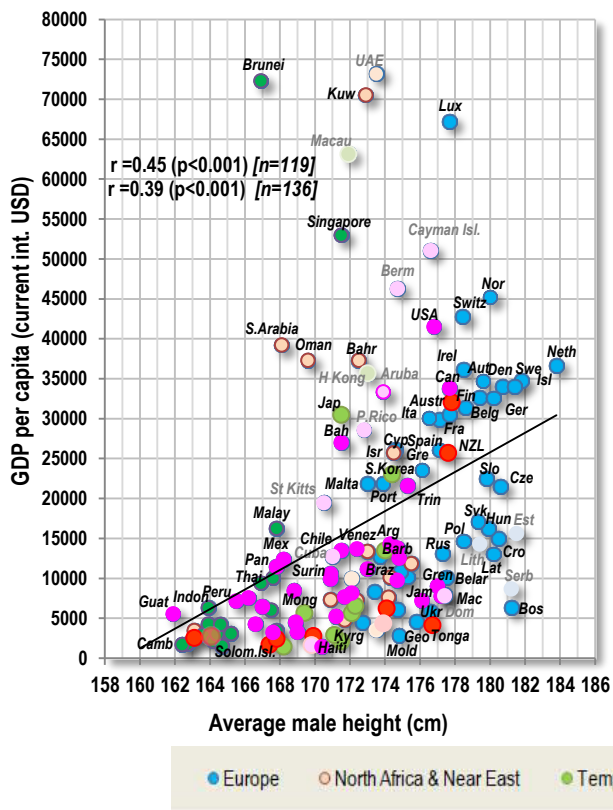


Figure 2. Relationship between male height in 136 populations and the gross domestic product (GDP) per capita (by purchasing power parity, current international USD; 1995-2013). Populations with incomplete data that were not included in the joint analysis of seven socio-economic factors (119 populations) are shown in matt colours.

Figure 3. Relationship between male height in 128 populations and the gross national income (GNI) per capita (by purchasing power parity, current international USD; 1995-2013). Populations with incomplete data that were not included in the joint analysis of seven socio-economic factors (119 populations) are shown in matt colours.

Male height vs. child mortality under 5 years

This factor reflects even more directly the presence of infectious diseases and hence it is not surprising that it correlates with male height even more strongly than health expenditure (Fig. 5). It would be logical to assume that low child mortality is determined by the quality of health care and economic wealth, but neither health expenditure per capita ($r = -0.59, p < 0.001$), nor GDP per capita ($r = -0.59, p < 0.001$) are the strongest negative correlates of child mortality among the seven socio-economic indicators in 119 populations. By far the strongest is HDI ($r = -0.84$) (Appendix Fig. 5). Health expenditure has a relationship with child mortality only up to a certain point, roughly equivalent to 1500-2000 USD per capita (Appendix Fig. 6). These observations indicate that health expenditure is not the main factor that influences child mortality. Besides HDI, the second strongest correlate is total fertility ($r = 0.70, p < 0.001$) (Appendix Fig. 7) and nutrition (see below). A very plausible explanation of this finding is that families with multiple children have insufficient resources to provide them with adequate nutrition and health care.¹²

¹² Nevertheless, the direction of causal relationships between child mortality and total fertility can be bilateral because high child mortality inevitably leads to high fertility. Appendix Fig. 7 indicates that disproportionately high rates of child mortality are typical of South Asian and other countries, which are characterized by poor nutrition and a high incidence of poverty.

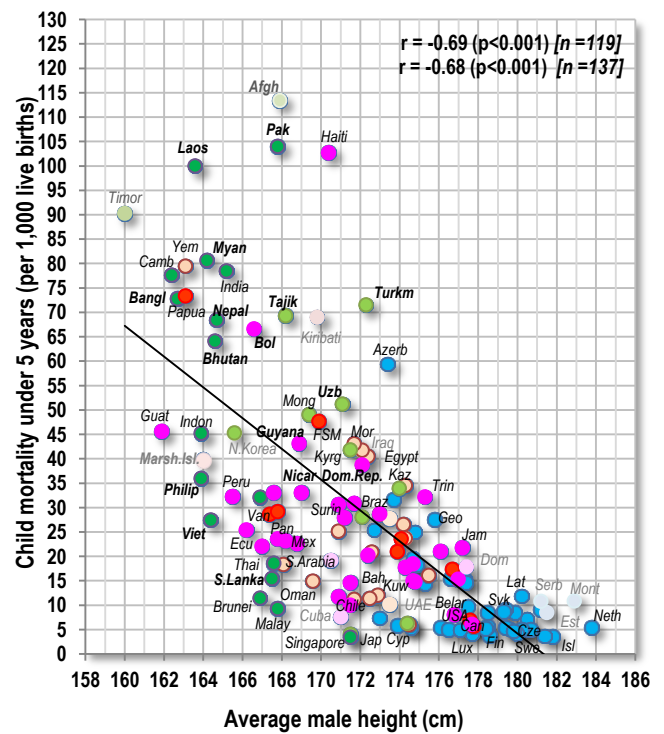
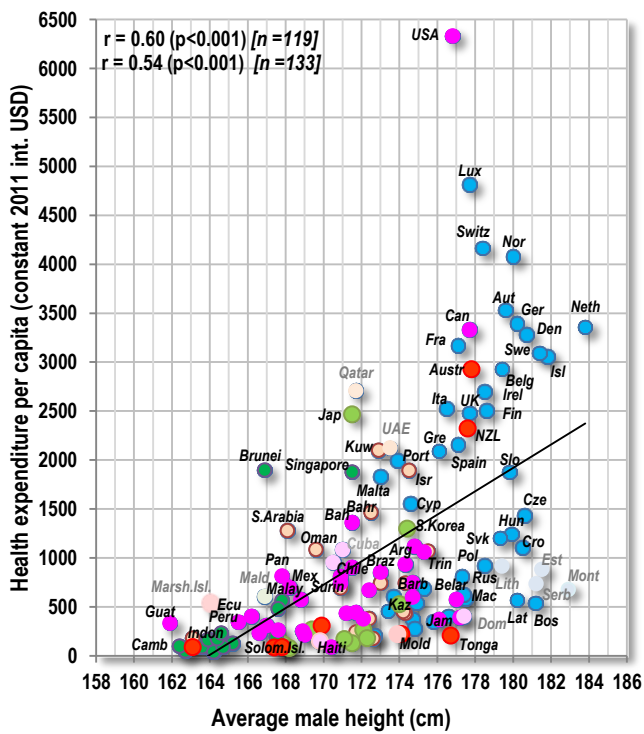


Figure 4. Relationship between male height in 133 populations and health expenditure per capita (by purchasing power parity, constant 2011 international USD; 1995-2013). Populations with incomplete data that were not included in the joint analysis of socio-economic factors (119 populations) are shown in matt colours.

Figure 5. Relationship between male height in 137 populations and child mortality under 5 years (per 1,000 live births; 1995-2013). Populations with incomplete data that were not included in the joint analysis of socio-economic factors (119 populations) are shown in matt colours.

Male height vs. total fertility rate

The importance of total fertility as a predictor of living conditions in the family is further supported by the fact that it is the second strongest socio-economic correlate of male height in the sample of 119 populations ($r = -0.70$, $p < 0.001$) (Fig. 6). However, in a direct comparison with child mortality, if a maximum available number of 135 populations for both variables were used, total fertility would correlate more weakly ($r = -0.65$ vs. $r = -0.68$). This r-value would further decrease to $r = -0.63$, if all 145 countries with available fertility rates were taken into account. The strongest (negative) correlate of total fertility is HDI ($r = -0.74$, $p < 0.001$). This would make sense because in addition to the indicators of health care and economic wealth, HDI includes education, a factor that has a major effect on lower fertility in women (see below). Fertility apparently does not play any role in Europe, where fertility rates are generally very low.

Male height vs. urban population (%)

Urbanization enables better access to superior nutrition and health care. Therefore, it can be expected that urbanization will also have a causal relationship to stature. The data are available for

the highest number of populations (n=150) but the relationship of urbanization with male height is only moderately strong (Fig. 7). Furthermore, the effect of urbanization is visible only in North Africa, Asia and Oceania, where we observe extremes between the weakly urbanized region of tropical Asia, and the almost completely urbanized city states such as Hong Kong, Macau, and Singapore. Judging from our data, urbanization is tightly tied with HDI ($r = 0.78, p < 0.001$), and it increases with both GDP and GNI per capita ($r = 0.66, p < 0.001$). On the other hand, it has a negative relationship with child mortality ($r = -0.64, p < 0.001$).

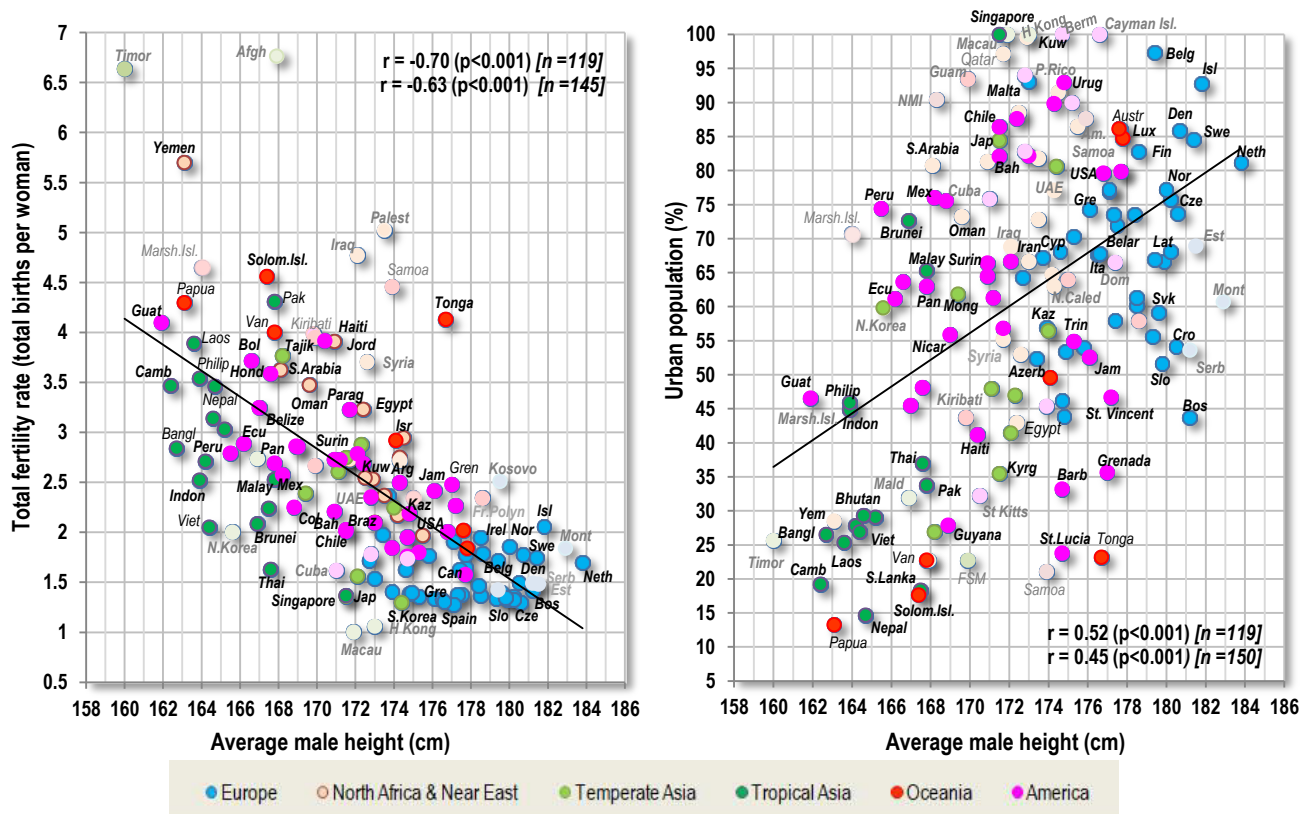


Figure 6. Relationship between male height in 145 populations and total fertility rate (total births per woman; 1995-2013). Populations with incomplete data that were not included in the joint analysis of socio-economic factors (119 populations) are shown in matt colours.

Figure 7. Relationship between male height in 150 populations and % urban population (1995-2013). Populations with incomplete data that were not included in the joint analysis of socio-economic factors (119 populations) are shown in matt colours.

Male height vs. Human Development Index (HDI)

Out of all seven socio-economic factors, HDI is most strongly correlated with male height ($r = 0.76, p < 0.001$) (Fig. 8). HDI is calculated from the statistics of life expectancy, education (years spent in the education system) and GNI per capita. Life expectancy expresses the quality of health care and low child mortality. Education may translate into better childcare and lower fertility rates (Martin, 1995). Economic wealth is the general indicator of living conditions. Therefore, HDI largely merges multiple factors examined in this study and similar to body height, it appears to be a very good indicator of the quality of life and social development. Still, even HDI cannot explain a significant

part of the variance in height because many wealthy and well-developed Asian populations (e.g. Singapore, Japan) are considerably lagging behind Europe, and they are even shorter than the poorest European populations such as Georgia and Moldova.

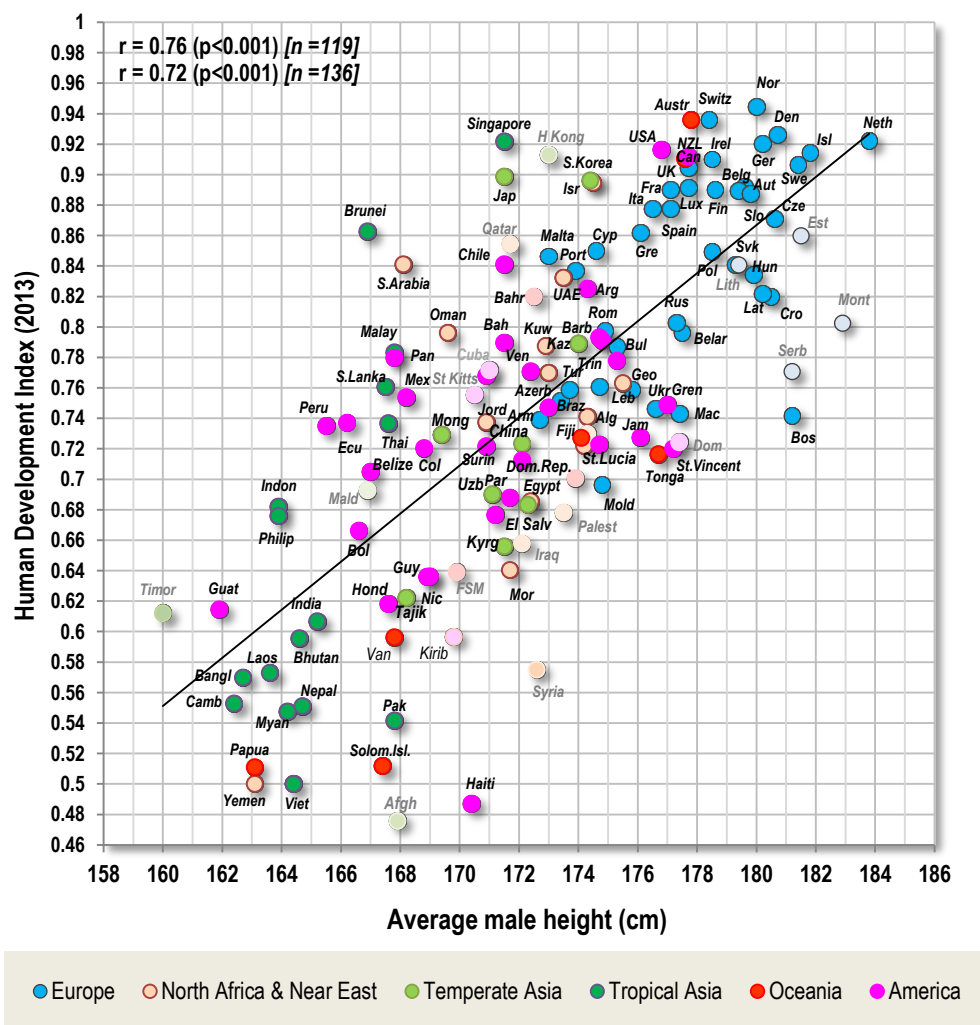


Figure 8. Relationship between male height in 136 populations and the Human Development Index (for 2013). Populations with incomplete data that were not included in the joint analysis of socio-economic factors (119 populations) are shown in matt colours.

Male height vs. nutrition

Nutrition was analysed independently of socio-economic factors, in a sample of 136 populations for which the statistics of food supply were available (Table 4). The strongest positive correlates of male height are dairy proteins ($r = 0.75$), total protein and total energy (Appendix Figs. 8-10). Among other individual protein sources besides total dairy, the highest correlation coefficients above $r > 0.50$ were found in cheese, potatoes, pork, and eggs (Appendix Figs. 11-13). The strength of this relationship further increases, when combinations of various proteins are used: dairy & potatoes ($r = 0.76$), dairy & eggs ($r = 0.77$), dairy & pork ($r = 0.78$), dairy, pork & eggs ($r = 0.786$) (Appendix Figs. 14-15), and especially dairy, pork, eggs & potatoes ($r = 0.793$) (Fig. 9). These

results are thus very similar to those from our previous paper, except that beef dropped out of the five most strongly correlated proteins.

Table 4. Relationship between male height and food consumption (supply) in 136 populations.

	Europe			North Africa, Asia & Oceania			America			TOTAL SAMPLE		
Populations (n)	44 (mean: 178.1 cm)			56 (mean: 170.1 cm)			36 (mean: 171.7 cm)			136 (mean: 173.1 cm)		
	Mean	r	p	Mean	r	p	Mean	r	p	Mean	r	p
PROTEIN SUPPLY (g/day per capita)												
Dairy total	19.3	0.47	0.001	6.9	0.55	< 0.001	10.0	0.51	0.001	11.7	0.75	< 0.001
Cheese	7.5	0.47	0.001	1.2	0.51	< 0.001	2.9	0.51	0.002	3.7	0.67	< 0.001
Milk	9.1	-0.10	0.514	4.5	0.45	< 0.001	5.9	0.15	0.398	6.3	0.46	< 0.001
Eggs	3.3	0.23	0.138	1.9	0.44	< 0.001	1.8	0.01	0.947	2.3	0.52	< 0.001
Meat total	22.2	0.28	0.068	14.8	0.61	< 0.001	20.2	0.62	< 0.001	18.6	0.58	< 0.001
Beef	5.8	0.06	0.688	3.7	0.63	< 0.001	6.4	0.30	0.079	5.1	0.39	< 0.001
Mutton & Goat meat	1.1	-0.13	0.402	1.9	0.37	0.005	0.7	0.33	0.048	1.3	0.09	0.296
Pork	8.2	0.45	0.002	2.5	0.16	0.245	3.2	0.41	0.013	4.5	0.57	< 0.001
Poultry	6.4	0.03	0.859	6.0	0.51	< 0.001	9.7	0.61	< 0.001	7.1	0.30	< 0.001
Fish & Seafood	5.6	0.20	0.184	6.8	-0.01	0.927	4.6	0.48	0.003	5.8	0.04	0.649
Pelagic marine fish	2.2	0.21	0.166	2.9	0.01	0.923	1.8	0.38	0.022	2.4	0.02	0.816
Freshwater fish	0.7	0.29	0.055	1.0	-0.38	0.004	0.4	0.12	0.479	0.7	-0.17	0.046
Pelagic & Freshwater fish	2.9	0.27	0.082	3.8	-0.09	0.528	2.2	0.42	0.011	3.1	-0.02	0.776
Offals	1.9	0.07	0.660	1.4	0.37	0.005	1.2	-0.08	0.624	1.5	0.31	< 0.001
ANIMAL PROTEINS	52.7	0.39	0.008	31.7	0.59	< 0.001	38.1	0.67	< 0.001	40.2	0.68	< 0.001
Cereals total	30.1	-0.53	< 0.001	31.9	0.02	0.861	23.4	-0.33	0.047	29.0	-0.10	0.258
Wheat	24.9	-0.57	< 0.001	19.3	0.53	< 0.001	12.0	0.59	< 0.001	19.2	0.42	< 0.001
Rice	0.8	-0.40	0.006	9.6	-0.65	< 0.001	5.2	-0.33	0.048	5.6	-0.67	< 0.001
Maize	2.1	-0.09	0.560	2.0	-0.37	0.005	5.4	-0.52	0.001	2.9	-0.29	< 0.001
Fruits	1.2	-0.01	0.925	1.1	0.33	0.013	1.5	0.19	0.260	1.2	0.18	0.037
Oilcrops	0.8	0.12	0.455	2.4	0.06	0.656	1.4	0.02	0.906	1.6	-0.19	0.027
Legumes (excl. Soybeans)	1.7	-0.10	0.531	2.7	-0.03	0.821	4.6	-0.27	0.113	2.9	-0.26	0.002
Legumes total	1.8	-0.06	0.689	3.7	0.00	0.978	5.0	-0.28	0.099	3.4	-0.31	< 0.001
Starchy roots	3.2	0.20	0.200	1.8	0.08	0.577	1.9	0.29	0.088	2.3	0.34	< 0.001
Potatoes	3.2	0.20	0.198	1.0	0.40	0.002	1.2	0.06	0.724	1.8	0.58	< 0.001
Treenuts	0.6	-0.02	0.917	0.5	0.41	0.002	0.2	0.24	0.165	0.4	0.29	< 0.001
Vegetables	3.7	-0.44	0.003	3.3	0.46	< 0.001	1.9	0.35	0.036	3.1	0.30	< 0.001
PLANT PROTEINS	44.0	-0.44	0.003	45.0	0.22	0.111	36.8	-0.16	0.355	42.5	0.03	0.752
TOTAL PROTEIN	96.8	0.19	0.213	76.7	0.72	< 0.001	74.9	0.60	< 0.001	82.7	0.71	< 0.001
ENERGY SUPPLY (kcal/day)												
TOTAL ENERGY	3181.8	0.17	0.259	2723.2	0.73	< 0.001	2699.5	0.55	< 0.001	2865.3	0.70	< 0.001
% PROTEIN ENERGY	12.4	0.13	0.408	11.5	0.44	< 0.001	11.3	0.43	0.008	11.7	0.49	< 0.001
COMBINATIONS OR RATIOS OF PROTEIN SUPPLY												
Rice & Legumes total	2.6	-0.18	0.251	13.3	-0.60	< 0.001	10.1	-0.39	0.019	9.0	-0.68	< 0.001
Rice, Maize & Legumes total	4.7	-0.15	0.330	15.3	-0.66	< 0.001	15.5	-0.64	< 0.001	11.9	-0.71	< 0.001
Rice & Maize	2.9	-0.15	0.339	11.6	-0.72	< 0.001	10.6	-0.71	< 0.001	8.5	-0.73	< 0.001
Dairy, Pork, Fish & Seafood	33.1	0.50	< 0.001	16.1	0.35	0.009	17.8	0.67	< 0.001	22.1	0.68	< 0.001
Dairy & Beef	25.1	0.38	0.010	10.6	0.63	< 0.001	16.4	0.47	0.004	16.8	0.71	< 0.001
Dairy & Potatoes	22.5	0.51	< 0.001	7.9	0.55	< 0.001	11.2	0.49	0.003	13.5	0.76	< 0.001
Dairy, Pork, Eggs & Beef	36.5	0.49	< 0.001	14.9	0.69	< 0.001	21.4	0.48	0.003	23.6	0.77	< 0.001
Dairy & Eggs	22.6	0.49	< 0.001	8.7	0.62	< 0.001	11.9	0.48	0.003	14.0	0.77	< 0.001
Dairy, Pork, Eggs, Beef & Potat.	39.8	0.50	< 0.001	15.9	0.69	< 0.001	22.6	0.47	0.004	25.4	0.78	< 0.001
Dairy & Pork	27.5	0.56	< 0.001	9.3	0.60	< 0.001	13.2	0.57	< 0.001	16.2	0.78	< 0.001
Dairy, Pork & Eggs	30.8	0.56	< 0.001	11.2	0.63	< 0.001	15.0	0.53	< 0.001	18.5	0.79	< 0.001
Dairy, Pork, Eggs & Potatoes	34.0	0.58	< 0.001	12.2	0.65	< 0.001	16.2	0.51	0.002	20.3	0.79	< 0.001
... / Rice & Maize	27.24	0.37	0.014	3.44	0.39	0.003	3.21	0.51	0.002	11.08	0.57	< 0.001
Dairy & Pork / Wheat	1.22	0.62	< 0.001	1.05	-0.40	0.003	1.23	-0.06	0.747	1.15	-0.11	0.206
Dairy & Pork / Cereals	0.99	0.61	< 0.001	0.33	0.53	< 0.001	0.60	0.59	< 0.001	0.62	0.73	< 0.001
% ANIMAL PROTEINS	53.6	0.47	0.001	39.1	0.48	< 0.001	49.3	0.61	< 0.001	46.5	0.59	< 0.001

Positive relationships				Negative relationships			
$r \geq 0.700$	$p < 0.001$	$p < 0.01$	$p < 0.05$	$p < 0.05$	$p < 0.01$	$p < 0.001$	$r \geq 0.700$

Among the negative correlates, rice protein is by far the strongest ($r = -0.67$, $p < 0.001$), before proteins from legumes and maize (Appendix Figs. 16-18). The combination of proteins from rice &

legumes ($r = -0.68$), rice, maize & legumes ($r = -0.71$) and especially rice & maize ($r = -0.73$, $p < 0.001$) (Fig. 10) produces even somewhat higher values than rice protein alone.

Similar to the previous study (Grasgruber et al., 2016a), these results show that height in developing regions outside Europe is more closely associated with protein quantity (total protein) and total energy intake, whereas the relationships documented in Europe can better be explained by differences in protein quality, i.e. amino acid scores according to the FAO/WHO [Food and Agriculture Organization/World Health Organization] standard 1985. This is understandable because the daily consumption of protein and its proportion in the everyday diet (Appendix Fig. 19) has its limits and in wealthy countries, at high levels of protein intake, it is the mean quality of consumed protein that matters. Consumption (supply) rates of individual foodstuffs differ as well, with Europe relying much more on dairy and pork, and much less on rice and other plant foods.

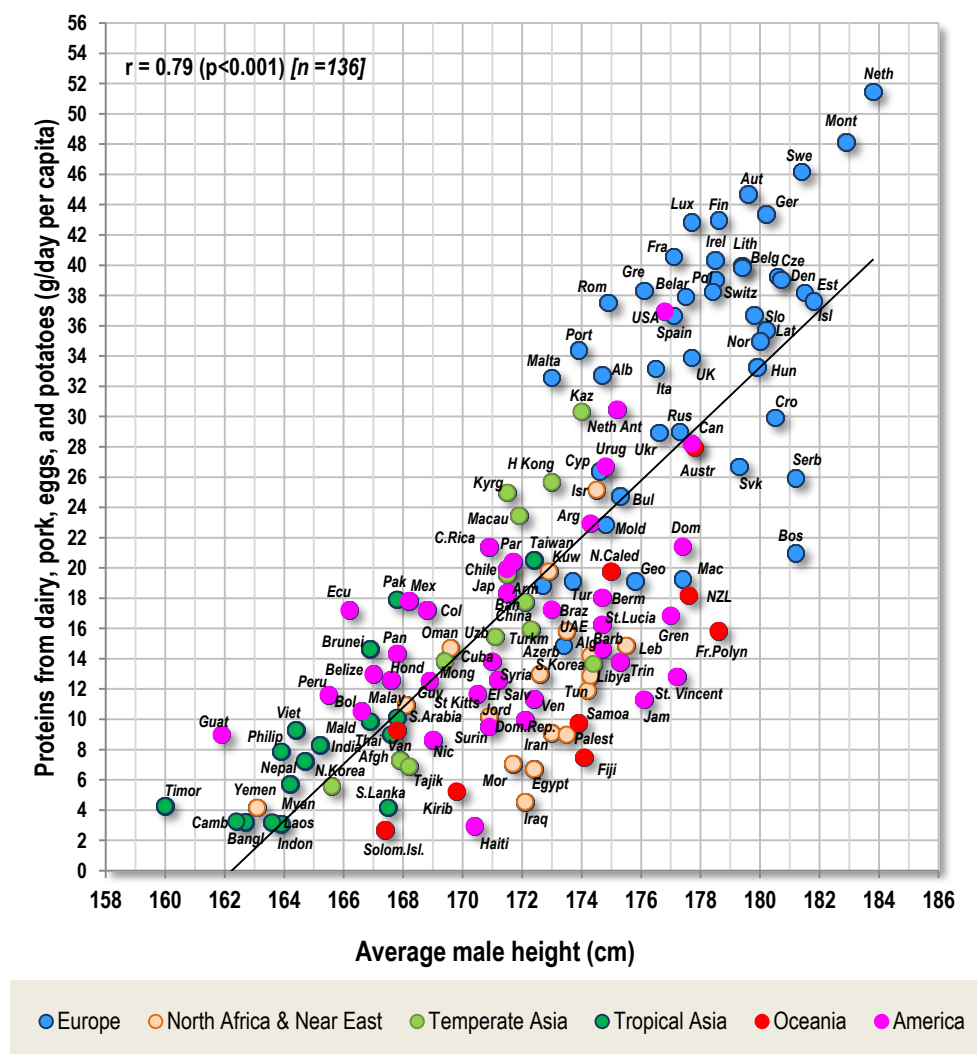


Figure 9. Relationship between male height in 136 populations and the mean combined supply of proteins from dairy, pork, eggs and potatoes (g/day per capita, FAOSTAT 1995-2013).

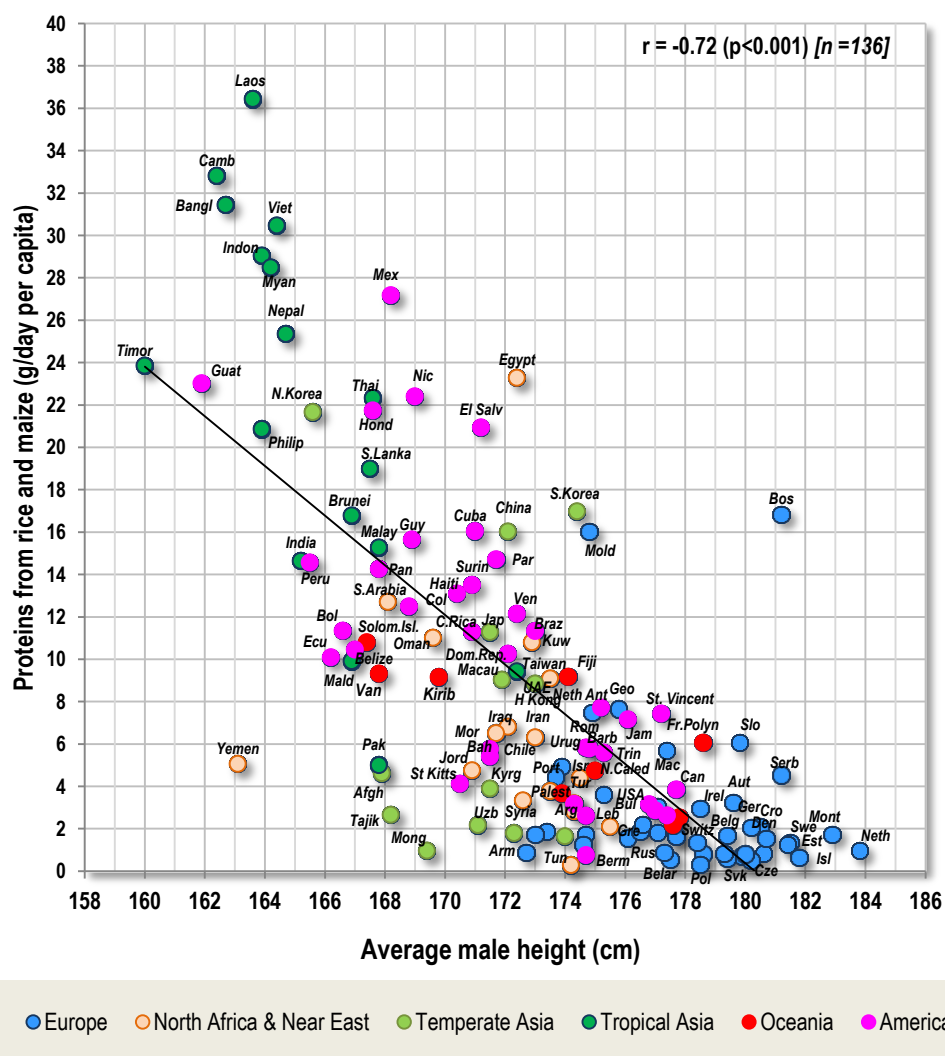


Figure 10. Relationship between male height in 136 populations and the mean combined supply of proteins from rice and maize (g/day per capita, FAOSTAT 1995-2013).

Populations in East and Southeast Asia have no tradition of dairy consumption because of widespread lactose intolerance, and pork is prohibited in Muslim countries for religious reasons, which must inevitably weaken its ecological relationship with stature in North Africa and Asia. The fact that poultry (Appendix Fig. 20) and beef (Appendix Fig. 21) have a positive relationship with height outside Europe, but not in Europe, is in accordance with the lower amino acid score of chicken meat (0.93) and beef (1.02), when compared with pork (1.14).¹³ There are also big differences in the biological quality of fish species. In general, it seems that fish & seafood proteins have a positive relationship with height only up to a certain point (Appendix Fig. 22).

All these factors can explain why relationships between male height and nutrition are not stable across all three predefined regions. Only dairy proteins (including cheese) and animal proteins

¹³ Mutton & lamb meat has an even higher amino acid score (1.15) but the mean global supply of mutton & goat meat is apparently negligible.

consistently correlate positively with male height.¹⁴ In contrast, rice protein is the only item that invariably correlates negatively, although its negative correlation in Europe is probably only spurious because the mean supply is very small (0.8 g/day per capita). Plant proteins, whose major source is wheat, generally appear to have some benefits only in non-European populations, but after the mean male height of ~172-174 cm is reached, their supply starts to correlate negatively with stature (Appendix Fig. 23-24), and animal proteins clearly dominate (Appendix Figs. 25-26).

The present study also confirms our previous finding that economic wealth is not strongly associated with food items that are identified as the best predictors of physical growth. In a sample of 126 populations, GDP per capita correlates most positively with animal proteins ($r = 0.67$), meat proteins ($r = 0.66$), and total protein ($r = 0.62$), but not so much with dairy proteins ($r = 0.45$), pork protein ($r = 0.43$), or the four proteins from dairy, pork, eggs, and potatoes ($r = 0.50$, $p < 0.001$). Nevertheless, some nutritional variables show strong relationships with other socio-economic factors, the most significant of them being that between HDI and animal proteins ($r = 0.83$, $p < 0.001$ in 129 populations). Child mortality is strongly negatively associated with total energy ($r = -0.71$, $p < 0.001$) and animal proteins ($r = -0.70$), and positively associated with low-quality rice & maize proteins ($r = 0.45$, $p < 0.001$) in a sample of 129 populations. These relationships are certainly meaningful but their strength may also be influenced by the high collinearity of these food items with HDI.¹⁵

An alternative comparison, in which 126 populations are compared within tertiles of GDP per capita (Appendix Table 6), confirms the importance of the sheer intake of protein and energy in developing countries, and the rising importance of high-quality protein sources in developed countries. Also noteworthy are the correlations between various types of meat (pork, beef, poultry) and height in the 1st tertile, which again reflect differences in amino acid scores according to the FAO/WHO standard 1985.

Trends in protein consumption

During the last two decades, the positive secular trend of height started to show signs of stagnation in multiple 'Western' countries, including the Netherlands, where no difference was observed between boys and girls measured in 1997 and 2009 (Schönbeck et al., 2009). Besides the possible exhaustion of the genetic potential, some other hypotheses were proposed, such as the onset of

¹⁴ These relationships are less consistent in milk, despite the fact that milk is the major source of dairy proteins, and its amino acid score (1.22) is higher than that of cheese (1.10). The explanation undoubtedly lies in the fact that milk is the cheapest source of dairy proteins and its consumption rates are very high in relatively poor countries with suboptimal dietary quality. A typical example is Albania where the official mean supply of milk protein (22.5 g/day per capita) is currently the highest in the world but the mean supply of cheese protein (3.3 g/day per capita) is negligible. Albania also has a low ratio between proteins from dairy & pork/wheat (0.80) which is the strongest dietary predictor of height in Europe.

¹⁵ Indeed, only total energy retains moderate significance ($p = 0.017$) after adjusting for the HDI. The significant relationship with child mortality completely disappears both in animal protein ($p = 0.63$) and rice & maize proteins ($p = 0.96$).

unhealthy dietary habits (Komlos, 2010). The FAOSTAT statistics of per capita protein supply from 17 ‘Western’ countries support this assumption. Although total protein supply is currently higher than during the 1960s, the mean biological quality of proteins in the diet started to decline in the mid-1980s. More concretely, these statistics indicate that the consumption of dairy products and red meats decreased, whereas the consumption of cereals gradually increased (Fig. 11). The mean ratio between high-quality proteins from dairy and pork, and low quality proteins from wheat reached a peak in 1982 and 1985 (1.83), but in 2013, it was back to the level of 1966 (1.47). Furthermore, we can observe similar tendencies even in other wealthy ‘non-Western’ countries such as Japan and the UAE where the supply of animal proteins markedly decreased during the last two decades (see Grasgruber et al., 2016a).

This phenomenon can primarily be linked with the introduction of nutritional recommendations aimed against saturated fats, first in the United States (1977), and then in the United Kingdom (1983) and other countries. Ironically, these recommendations have been enforced by politicians, not dietitians (Taubes, 2001), being based on flawed health statistics (Grasgruber et al., 2016b), and due to the lack of any clinical evidence, they should have never been introduced (Harcombe et al., 2015). Worse, the rising proportion of cereals and sweeteners in the diet contributed to the epidemic of obesity and diabetes. However, Fig. 11 also indicates that the consumption of cereals was increasing in parallel with poultry and cheese - frequent ingredients of fast foods. Either way, the wealthiest countries of the world have reached a point when wealth does not contribute to the improvement of diet but actually leads to its deterioration.

Figure 12 compares temporal changes in the supply of dairy and pork proteins in seven American countries between 1961 and 2013, relative to the Netherlands. The supply of these proteins has increased most significantly in Grenada, Dominica, and Cuba, and decreased most markedly in Canada, Nicaragua, and Bermuda. No change has occurred in the United States but the proportion of low-quality cereal proteins in the diet is currently higher than in 1961 (see Grasgruber et al., 2014). The mean supply in 41 American countries/territories (including Antigua and Barbuda, which was not included in the present study) has increased only marginally between 1961 and 2013 (from 10.9 to 14.3 g/day per capita), and despite a remarkable increase in mean heights between birth cohorts 1896 and 1996 (10.8 cm on average – from 6.0 cm in the United States to 15.4 cm in Greenland) (NCD Risk Factor Collaboration, 2016), many American countries lag as much as 15-20 cm behind the tallest European nations.

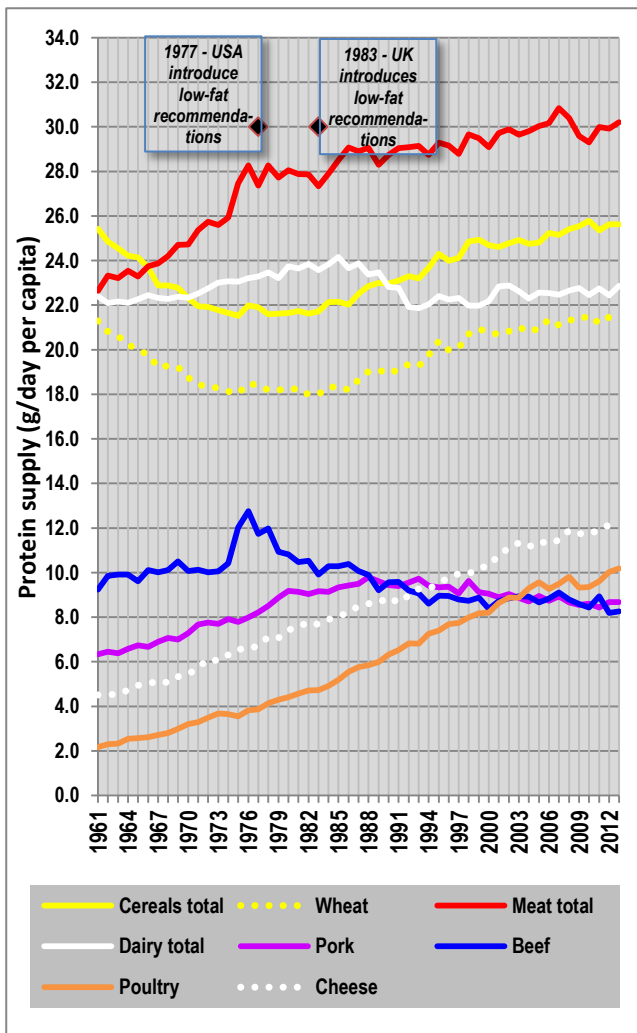


Figure 11. Average protein supply in 17 'Western' countries* between 1961-2013.

*Australia, Austria, Belgium/Luxembourg, Canada, Denmark, Finland, France, Germany, Iceland, Ireland, the Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom, United States.

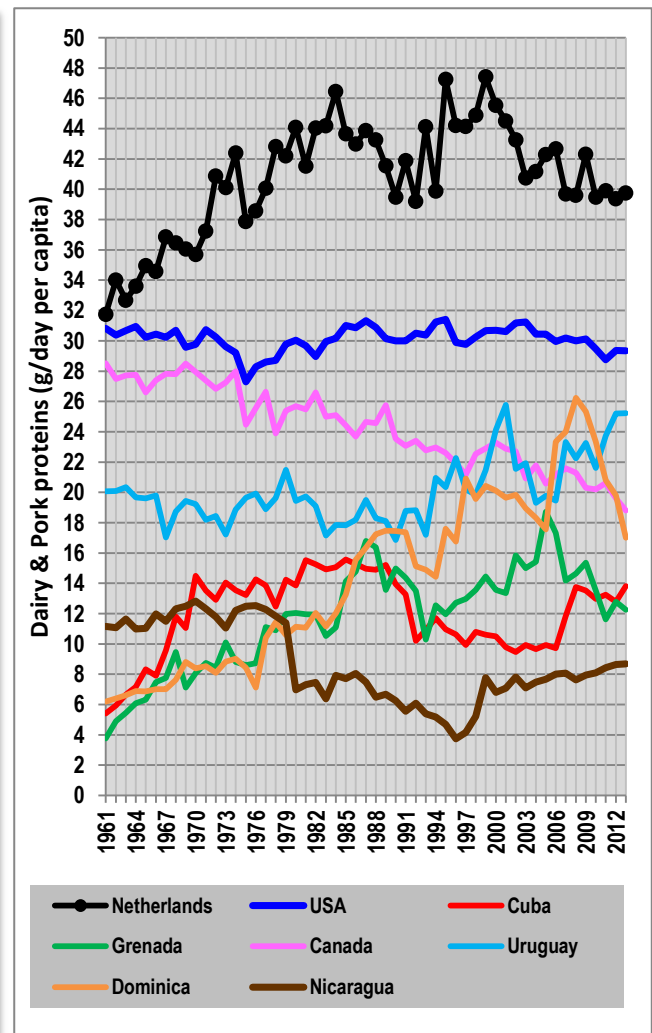


Figure 12. Supply of proteins from dairy & pork in seven American countries between 1961-2013, compared with the Netherlands.

Male height vs. Gini index and Inequality-adjusted human development index (IHDI)

As already noted in the 'Methods' section, these two socio-economic indicators are available from a limited number of populations (Figs. 13-14) and their inclusion leads to some changes of correlation coefficients. More concretely, in the comparison of nine socio-economic and three nutritional variables in 93 populations (Table 5), the r-values of GDP and GNI per capita disproportionately increase because the Gini index and IHDI are not available for some wealthy populations that constitute outliers in Figs. 2-3. Even the correlation between height and urbanization increases, but other relationships remain more or less stable.

Table 5. Correlation between male height and nine socio-economic & three nutritional factors.

	Seven socio-economic variables & Nutrition			...& Gini index			...& I HDI			...Gini index & I HDI		
	Mean	r	p	Mean	r	p	Mean	r	p	Mean	r	p
Populations (n)	113			101			96			93		
SOCIO-ECONOMIC FACTORS												
GDP per capita	15,873	0.47	<0.001	14,510	0.66	<0.001	15,114	0.66	<0.001	15,061	0.66	<0.001
GNI per capita	15,572	0.46	<0.001	14,151	0.67	<0.001	14,754	0.67	<0.001	14,705	0.68	<0.001
Health expenditure	1,122	0.61	<0.001	1,127	0.63	<0.001	1,182	0.63	<0.001	1,193	0.63	<0.001
Child mortality	26.0	-0.67	<0.001	25.9	-0.68	<0.001	26.1	-0.72	<0.001	25.6	-0.71	<0.001
Total fertility rate	2.34	-0.72	<0.001	2.32	-0.73	<0.001	2.30	-0.74	<0.001	2.29	-0.73	<0.001
Urban population (%)	60.3	0.53	<0.001	60.4	0.58	<0.001	61.2	0.60	<0.001	61.5	0.59	<0.001
Human Development Index	0.76	0.76	<0.001	0.76	0.79	<0.001	0.76	0.80	<0.001	0.76	0.80	<0.001
Gini index				37.9	-0.54	<0.001				37.6	-0.53	<0.001
Inequality-adjusted HDI							0.63	0.83	<0.001	0.64	0.83	<0.001
PROTEIN SUPPLY (g/day per capita)												
Dairy	12.0	0.75	<0.001	12.5	0.77	<0.001	12.7	0.78	<0.001	12.9	0.77	<0.001
Dairy, Pork, Eggs & Potatoes	20.6	0.81	<0.001	21.4	0.82	<0.001	21.8	0.83	<0.001	22.1	0.83	<0.001
Rice & Maize	8.8	-0.73	<0.001	8.5	-0.71	<0.001	8.7	-0.73	<0.001	8.6	-0.72	<0.001

Positive relationships				Negative relationships			
$r \geq 0.70$	$p < 0.001$	$p < 0.01$	$p < 0.05$	$p < 0.05$	$p < 0.01$	$p < 0.001$	$r \geq 0.70$

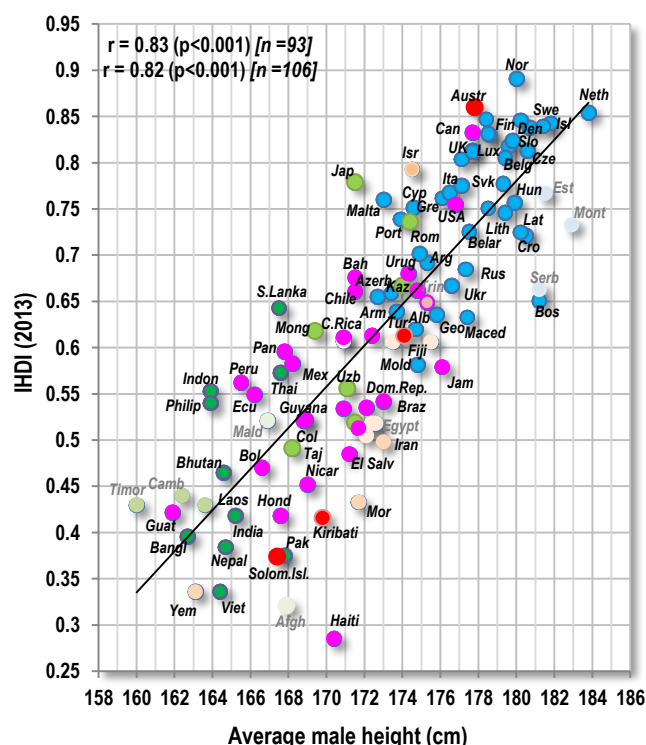
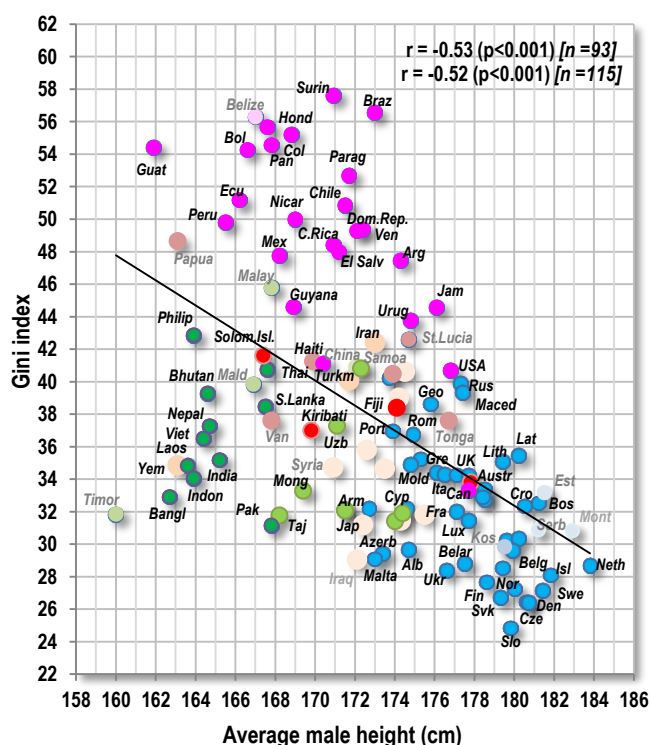


Figure 13. Relationship between male height in 115 populations and the Gini index (1995-2013). Populations with incomplete data that were not included in the joint analysis of nine socio-economic and three nutritional factors (93 populations) are shown in matt colours.

Figure 14. Relationship between male height in 106 populations and the inequality-adjusted Human Development Index (IHDI) (2013). Populations with incomplete data that were not included in the joint analysis of nine socio-economic and three nutritional factors (93 populations) are shown in matt colours.

The most interesting observation is the fact that IHDI is the most strongly correlating socio-economic variable in these comparisons, and it can even match the predictive power of nutrition. The considerable social inequalities (high Gini indices) in America are also worth noting. Because the biological effect of the Gini index depends on the overall wealth of the respective country, it is not so surprising that the correlation between height and the Gini index differs when the examined countries are divided according to GDP per capita. More concretely, it reaches $r = -0.58$ ($p = 0.001$) within the 1st tertile (28 countries) and $r = -0.61$ ($p < 0.001$) within the 2nd tertile (41 countries) but only $r = -0.33$ ($p = 0.035$) within the 3rd poorest tertile where data from 42 countries are available. In other words, social inequality does not play such a big role at generally high levels of poverty.

Table 6. Multiple regression models of male height (total sample of 119 populations).

Models	Socio-economic variables only			Nutrition only		All 9 variables		
	(1a)	(1b)	(1c)	(2a)	(2b)	(3a)	(3b)	(3c)
	Parsimonious	All	Optimal	Parsimonious	Optimal	Parsimonious	All	Optimal
Dairy, Pork, Eggs & Potato protein				$b^* = 0.56$ $r = 0.64$ $p < 0.001$	$b^* = 0.43$ $r = 0.47$ $p < 0.001$	$b^* = 0.33$ $r = 0.40$ $p < 0.001$	$b^* = 0.24$ $r = 0.25$ $p = 0.007$	$b^* = 0.26$ $r = 0.31$ $p < 0.001$
Rice & Maize protein				$b^* = -0.37$ $r = -0.48$ $p < 0.001$	$b^* = -0.35$ $r = -0.47$ $p < 0.001$	$b^* = -0.39$ $r = -0.54$ $p < 0.001$	$b^* = -0.37$ $r = -0.50$ $p < 0.001$	$b^* = -0.38$ $r = -0.54$ $p < 0.001$
Total energy					$b^* = 0.20$ $r = 0.26$ $p = 0.004$		$b^* = 0.14$ $r = 0.18$ $p = 0.064$	$b^* = 0.14$ $r = 0.18$ $p = 0.056$
GDP per capita		$b^* = -0.26$ $r = -0.24$ $p = 0.011$	$b^* = -0.27$ $r = -0.24$ $p = 0.008$				$b^* = -0.10$ $r = -0.12$ $p = 0.21$	
Health expenditure per capita		$b^* = 0.24$ $r = 0.20$ $p = 0.035$	$b^* = 0.23$ $r = 0.19$ $p = 0.036$				$b^* = 0.06$ $r = 0.06$ $p = 0.56$	
Child mortality		$b^* = -0.08$ $r = -0.07$ $p = 0.46$					$b^* = -0.08$ $r = -0.10$ $p = 0.31$	$b^* = -0.10$ $r = -0.13$ $p = 0.17$
Total fertility rate	$b^* = -0.33$ $r = -0.35$ $p < 0.001$	$b^* = -0.28$ $r = -0.29$ $p = 0.002$	$b^* = -0.30$ $r = -0.32$ $p < 0.001$			$b^* = -0.32$ $r = -0.44$ $p < 0.001$	$b^* = -0.24$ $r = -0.30$ $p = 0.001$	$b^* = -0.26$ $r = -0.35$ $p < 0.001$
Urban population (%)		$b^* = -0.05$ $r = -0.06$ $p = 0.54$					$b^* = -0.08$ $r = -0.11$ $p = 0.25$	$b^* = -0.08$ $r = -0.13$ $p = 0.18$
IHDI	$b^* = 0.51$ $r = 0.50$ $p < 0.001$	$b^* = 0.53$ $r = 0.29$ $p = 0.002$	$b^* = 0.55$ $r = 0.38$ $p < 0.001$				$b^* = 0.09$ $r = 0.06$ $p = 0.52$	
Variables (n)	2	6	4	2	3	3	9	6
Adj. R ²	0.612	0.627	0.631	0.723	0.740	0.775	0.782	0.784
p-value	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$

Note: b^* = beta coefficients; r = partial correlations; p = probability values.

Positive relationships			Negative relationships		
$p < 0.001$	$p < 0.01$	$p < 0.05$	$p < 0.05$	$p < 0.01$	$p < 0.001$

Multiple regression analysis: Male height

Because GNI per capita largely duplicates with GDP per capita, the former variable was excluded and multiple regression of male height was performed only with six socio-economic variables and nutrition in a sample of 119 populations (Table 6). The results demonstrate quite convincingly the

fundamental role of nutrition. In fact, the optimal model of socio-economic variables (adjusted $R^2 = 0.631$) (1c) explains less variance than the combination of two most important nutritional variables (adjusted $R^2 = 0.723$) (2a). Interestingly, HDI is the strongest predictor in model (1c) but it loses significance after nutrition is included. This observation points to the strong connection between HDI and high-quality nutrition. Total fertility remains the only socio-economic factor with some appreciable additive effect, and significantly contributes to the parsimonious model derived from all nine variables (adjusted $R^2 = 0.775$) (3a). Total energy, child mortality and urbanization further improve an optimal model (3c), but only negligibly to adjusted $R^2 = 0.784$.

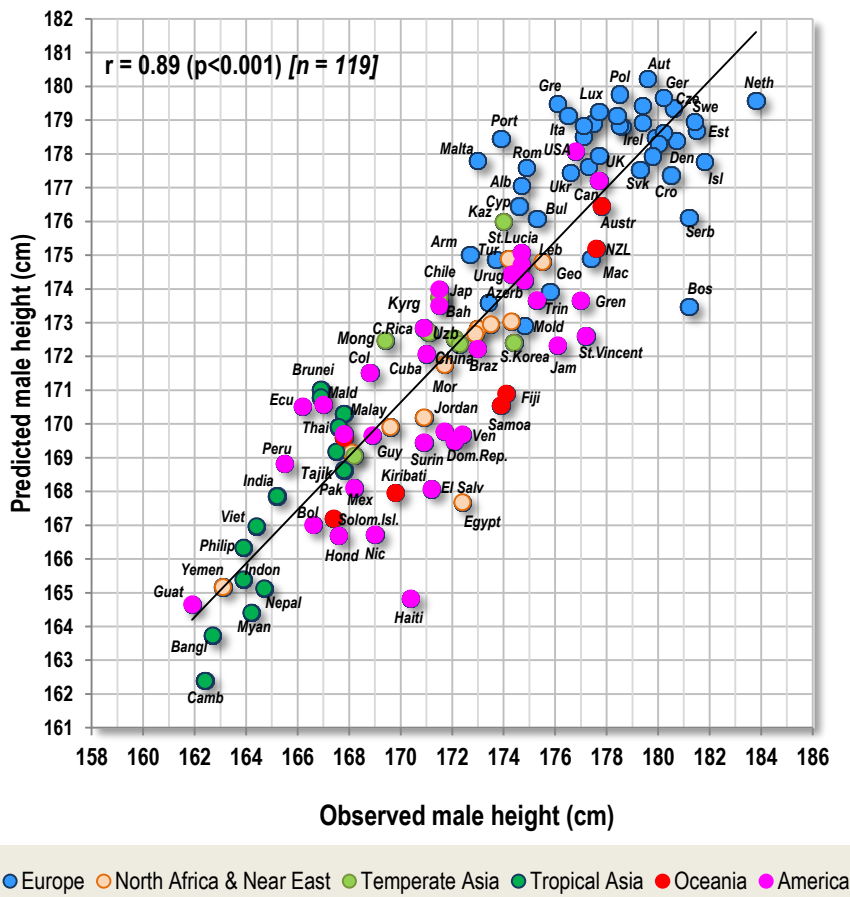


Figure 15. Relationship between observed and predicted male height in 119 populations, based on the best regression model (3c) in Table 6.

The explanatory power of this best regression model (3c) is very good, but not as good as in the previous study dealing with male stature in Europe, North Africa, Asia, and Oceania (adjusted $R^2 = 0.872$). Figure 15 and Appendix Table 7 show that countries such as Bosnia & Herzegovina (+7.7 cm), Haiti (+5.6 cm) and Serbia (+5.1 cm), are much taller than this model predicts. In contrast, Malta (-4.8 cm), Portugal (-4.5 cm) and Ecuador (-4.3 cm), are much shorter.

After the addition of the Gini index and the replacement of HDI with IHDI, the optimal regression model (adjusted $R^2 = 0.794$) would work with seven variables (dairy, pork, eggs & potato

protein; rice & maize protein; total energy; child mortality; total fertility; IHDI; the Gini index) in 96 populations. The parsimonious model (adjusted $R^2=0.782$) would include three variables (dairy, pork, eggs & potato protein; rice & maize protein; total fertility). This result again confirms the key role of nutrition and total fertility.

Table 7. Multiple regression models of male height (regions).

Europe			North Africa, Asia, Oceania			America			
Models	(1)	(2a)	(2b)	Models	(1a)	(1b)	Models	(1a)	(1b)
	Optimal	Parsim.	Optimal		Parsim.	Optimal		Parsim.	Optimal
Populations (n)	43	42	42	Populations (n)	44	44	Populations (n)	32	32
Dairy & Pork protein / Wheat protein ratio	b* = 0.49 r = 0.45 p = 0.003		b* = 0.23 r = 0.28 p = 0.086	Total protein			Dairy, Pork, Fish & Seafood protein		
				Total energy	b* = 0.50 r = 0.73 p < 0.001	b* = 0.62 r = 0.73 p < 0.001			
				Rice & Maize protein	b* = -0.52 r = -0.77 p < 0.001	b* = -0.50 r = -0.76 p < 0.001	Rice & Maize protein	b* = -0.71 r = -0.71 p < 0.001	b* = -0.51 r = -0.59 p < 0.001
Genetics (Y haplogroup I-M170)		b* = 0.39 r = 0.51 p < 0.001	b* = 0.45 r = 0.62 p < 0.001						
Genetics (Neolithic Y haplogroups E, G, J)		b* = -0.54 r = -0.63 p < 0.001	b* = -0.24 r = -0.32 p = 0.051						
GDP per capita			b* = -0.81 r = -0.35 p = 0.030	GDP per capita		b* = -0.23 r = -0.36 p = 0.026	GDP per capita		
Health expenditure per capita				Health expenditure per capita		b* = 0.25 r = 0.31 p = 0.065	Health expenditure per capita		b* = 0.26 r = 0.31 p = 0.098
Child mortality	b* = -0.24 r = -0.23 p = 0.14			Child mortality		b* = 0.11 r = 0.19 p = 0.27	Child mortality		
Total fertility rate				Total fertility rate	b* = -0.23 r = -0.46 p = 0.002	b* = -0.19 r = -0.38 p = 0.022	Total fertility rate		b* = -0.63 r = -0.55 p = 0.002
Urban population (%)				Urban population (%)		b* = -0.27 r = -0.32 p = 0.056	Urban population (%)		
HDI			b* = 0.76 r = 0.39 p = 0.016	HDI		b* = 0.22 r = 0.25 p = 0.14	HDI		b* = -0.44 r = -0.35 p = 0.061
Variables (n)	2	2	5	Variables (n)	3	8	Variables (n)	1	4
Adj. R²	0.426	0.627	0.721	Adj. R²	0.840	0.865	Adj. R²	0.488	0.634
p-value	p < 0.001	p < 0.001	p < 0.001	p-value	p < 0.001	p < 0.001	p-value	p < 0.001	p < 0.001

Note: b* = beta coefficients; r = partial correlations; p = probability values.

Positive relationships			Negative relationships		
p < 0.001	p < 0.01	p < 0.05	p < 0.05	p < 0.01	p < 0.001

Table 7 displays regression models of nutrition and six socio-economic variables in individual regions. In Europe, the predictive power of the optimal model (1) consisting of nutrition and child mortality is quite weak (adjusted $R^2 = 0.426$), but it increases dramatically after the genetic factors (Y haplogroups) are included (up to adjusted $R^2 = 0.721$) (2b). In fact, the parsimonious model (2a) consists only of two genetic variables. The importance of nutrition and Neolithic Y haplogroups in the optimal model (2b) is compromised which suggests that Neolithic Y haplogroups are largely a proxy for inferior nutrition associated with the symbol of the Neolithic revolution - wheat.

In 44 populations of North Africa, Asia and Oceania, the combination of total energy, rice & maize protein and total fertility plays by far the biggest role (adjusted $R^2 = 0.840$), and the addition of another five variables has only a very small effect (adjusted $R^2 = 0.865$). The situation in 32 American populations is very similar. Proteins from rice & maize are the most important factor, and their combination with total fertility explains 60.4% variability. Health expenditure and the HDI increase the explanatory power of the optimal model rather marginally to 63.4%.

Female height

The correlates of female height are displayed in Appendix Tables 8-10 and Appendix Figs. 27-29. When compared with men, the general tendencies are very similar, although the correlation coefficients are almost always weaker. This trend towards weaker r-values in women persists even when men and women are compared within the same number of populations (data not shown). The most likely explanation lies in the fact that height means in women differ less than height means in men (see below). Some noticeable differences between men's and women's results can be found only in the regression models (Appendix Tables 11-12) where total fertility does not emerge among significant predictors of female height at the regional level, and the most consistent socio-economic factor is HDI. Also noteworthy is the stronger predictive role of Y haplogroup R1a-M420 in European women, which must primarily be ascribed to the taller statures of women in the Baltic states, relative to the local men. Otherwise, we do not observe any fundamental differences between sexes.

Male height vs. female height

The comparison of male and female height was performed with a sample of 147 populations for which data on both sexes come from the same study. The correlation is very high ($r = 0.96$, $p < 0.001$) (Fig. 16) and the mean difference between men and women is 12.4 cm (13.1 cm in Europe, 12.0 cm in North Africa, Asia and Oceania, 12.3 cm in America). The mean male-female ratio is 1.077 (1.079 in Europe, 1.076 in North Africa, Asia and Oceania, 1.077 in America). There are no obvious geographical trends in this sex gap (Fig. 14) but both the male-female difference ($r = 0.54$, $p < 0.001$) and the male-female ratio ($r = 0.32$, $p = 0.001$) increase with rising male height. In other words, the taller the population height mean (or the height of men, respectively), the higher the sexual dimorphism in stature.

Male height can be predicted by the equation "*Male height* = $-2.855 + (1.0949 * \textit{Female height})$ ". Female height can be predicted by the equation "*Female height* = $13.553 + (0.84999 * \textit{Male height})$ ". Therefore, at the male height of 160 cm, the mean height of females will be approximately 149.6 cm (a difference of 10.4 cm). At the male height of 180 cm, women will be

approximately 166.6 cm tall (a difference of 13.4 cm). This means that height differences among women will be smaller than in men, which is also evidenced by the lower standard deviation of 147 female samples (± 4.5 cm), when compared with corresponding 147 male samples (± 5.1 cm).

The male-female differences in height did not show any particularly strong correlations with the examined variables. Although it was suggested that these sex differences are primarily influenced by nutrition because male stature requires more high-quality proteins to fully express its genetic potential (Gray & Wolfe, 1980), the main positive correlate in a sample of 115 populations (including nutrition and six socio-economic variables) was always HDI ($r = 0.53$, $p < 0.001$ with the male-female difference, $r = 0.35$, $p < 0.001$ with the male-female ratio). The role of proteins from dairy, pork, eggs and potatoes was substantially weaker ($r = 0.43$, $p < 0.001$, and $r = 0.22$, $p = 0.016$). Dietary factors did not appear among the strongest negative correlates either; it was always total fertility ($r = -0.44$, $p < 0.001$, and $r = -0.27$, $p = 0.003$) and child mortality ($r = -0.50$, $p < 0.001$, and $r = -0.35$, $p < 0.001$) that reached the highest correlation coefficients.

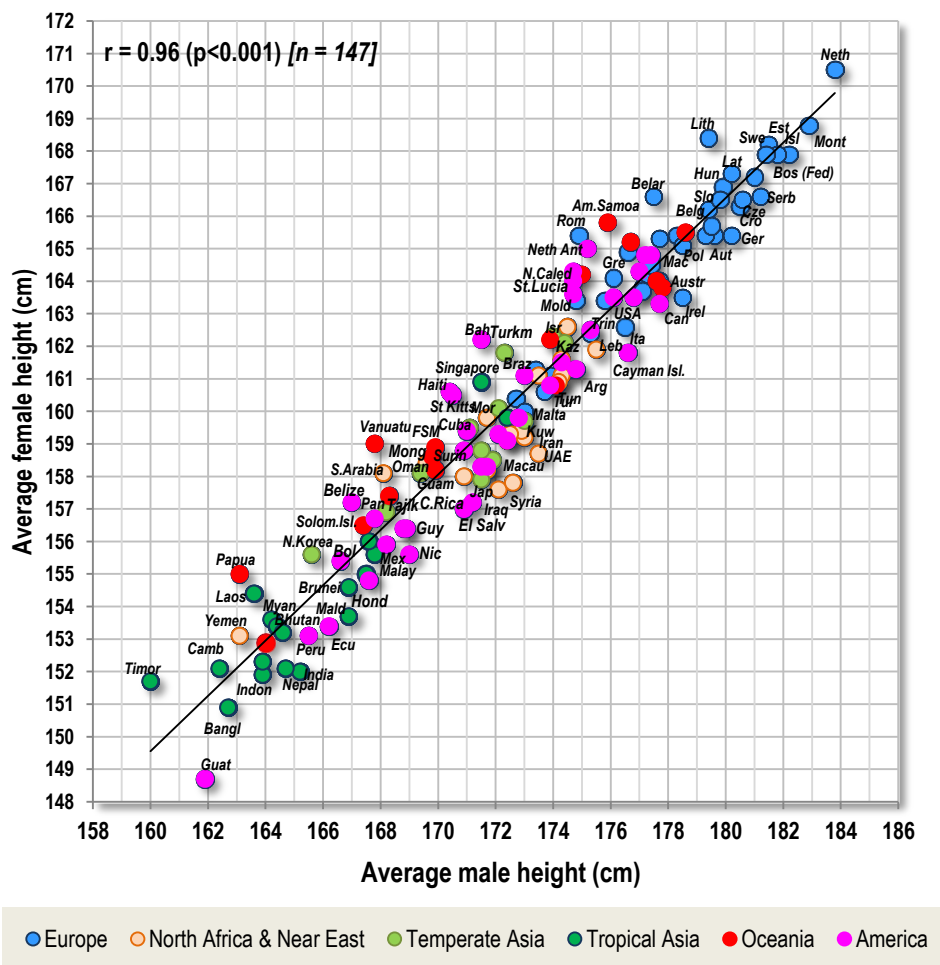


Figure 16. Relationship between male and female height in 147 populations where male and female data are available from the same study.

America: Male height vs. racial and ethnic composition

As stated in the ‘Methods’ section, American populations trace their genetic ancestry to three main groups (Native American, European, African) that are subject to mutual mixing which is particularly intense in tropical Latin America (e.g. Brazil). This situation complicates any genetic comparisons at the population level because the proportion of genetic ancestry in individuals is extremely variable (Bryc et al., 2010; Reich et al., 2012; Homburger et al., 2015), and hence only very large samples including all ethnic and social groups are representative.

The use of these three genetic sources (see Dataset, Sheet 4) is mostly sufficient, although in Canada, Trinidad and Tobago, and the United States, a significant part of the population belongs to the category ‘other’.¹⁶ Some genetic studies have used East Asians as a fourth source population and have found an unexpectedly high East Asian admixture in certain countries, but this may be an artefact of the Native American ancestry. On the other hand, we can suppose that in other studies, East Asian admixture was classified as Native American.

Table 8. Correlations between male height and self-reported racial/ethnic affiliation in America.

America total (Adhikari et al., 2017)	<i>n</i>	Europeans		Africans		Europeans & Africans		Native Americans	
	38	0.14 (<i>p</i> = 0.40)		0.44 (<i>p</i> = 0.005)		0.64 (<i>p</i> < 0.001)		-0.33 (<i>p</i> = 0.044)	
Latin America (Lizcano-Fernandez, 2005)	<i>n</i>	Creoles*	Mulattos	Blacks	Blacks & Mulattos	Blacks, Mulattos & Creoles*	Mestizos	Native Americans	Native Americans & Mestizos
	20	0.68 (<i>p</i> = 0.001)	0.27 (<i>p</i> = 0.26)	0.25 (<i>p</i> = 0.29)	0.28 (<i>p</i> = 0.24)	0.73 (<i>p</i> < 0.001)	-0.37 (<i>p</i> = 0.11)	-0.83 (<i>p</i> < 0.001)	-0.71 (<i>p</i> < 0.001)
Latin America (Latinobarometro, 2011)	<i>n</i>	Whites	Mulattos	Blacks	Blacks & Mulattos	Blacks, Mulattos & Whites	Mestizos	Native Americans	Native Americans & Mestizos
	18	0.64 (<i>p</i> = 0.004)	0.39 (<i>p</i> = 0.11)	0.31 (<i>p</i> = 0.21)	0.37 (<i>p</i> = 0.13)	0.74 (<i>p</i> < 0.001)	-0.46 (<i>p</i> = 0.058)	-0.77 (<i>p</i> < 0.001)	-0.76 (<i>p</i> < 0.001)

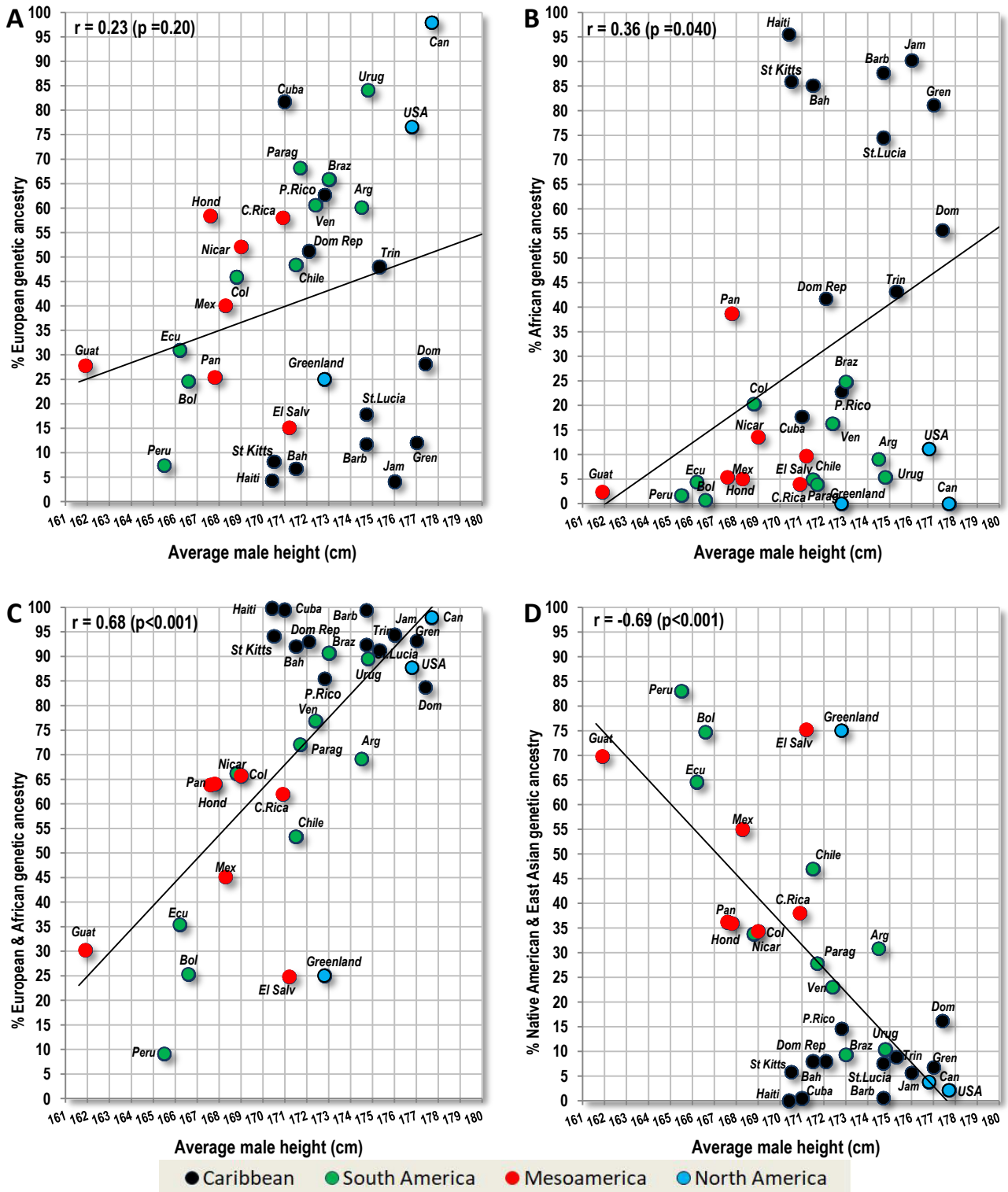
*Note: The term “creoles” (*criollos*) is largely identical with “white” and represents descendants of Europeans.

Positive relationships			Negative relationships		
<i>p</i> < 0.001	<i>p</i> < 0.01	<i>p</i> < 0.05	<i>p</i> < 0.05	<i>p</i> < 0.01	<i>p</i> < 0.001

Despite these limitations, the tendencies of both genetic and self-reported ancestries are very clear: Male height tends to increase with the increasing proportion of European and African ancestry but it decreases with the increasing proportion of Native American (or East Asian) ancestry. The combination of European and African ancestry further substantially increases correlation coefficients (Table 8, Figs. 17A-17D). Greenland has a taller mean stature than expected, but the different genetic ancestry of the Inuit, who make up a separate genetic cluster distinct from other Native Americans (Reich et al., 2012), and the better living standards in this

¹⁶ In Trinidad and Tobago, 29.5% of inhabitants are classified as ‘(unmixed) other’, and are mostly of South Asian (Indian) origin. This can also explain why people from Trinidad and Tobago were found to have 48% European genetic ancestry, despite the fact that self-reported whites make up only 1.6% of the population.

Danish territory, where 82.6% of the population is nowadays urban, could easily explain this anomaly. The height of men in El Salvador is also somewhat anomalous but, as already explained in a footnote, the reason must lie in the suburban character of the population surveyed.



Figures 17A-17D. Correlations between male height and autosomal genetic ancestry in 32 American populations divided by geography. For sources, see Dataset, Sheet 4.

Table 9. Observed and predicted height in American populations, according to different regression models.

adj. R ²	OBSERVED HEIGHT	PREDICTED HEIGHT (and change compared to observed height)					
		Model 1 (28 populations)		Model 2 (28 populations)		Model 3 (23 populations)	
		0.609		0.747		0.818	
		dairy, pork, fish & seafood protein; rice & maize protein; total fertility		dairy, pork, fish & seafood protein; rice & maize protein; total fertility; Native American & East Asian ancestry		rice & maize protein; total fertility; Gini index; Nat. American & East Asian ancestry	
Argentina	174.3	173.8	0.5	172.8	1.5	172.4	1.9
Bahamas	171.5	174.6	-3.1	174.9	-3.4		
Barbados	174.7	174.7	0.0	175.4	-0.7		
Bolivia	166.6	168.3	-1.7	166.1	0.5	165.2	1.4
Brazil	173.0	172.1	0.9	173.0	0.0	172.4	0.6
Canada	177.7	176.0	1.7	176.3	1.4	178.4	-0.7
Chile	171.5	173.9	-2.4	171.7	-0.2	171.5	0.0
Colombia	168.8	171.4	-2.6	170.9	-2.1	170.6	-1.8
Costa Rica	170.9	172.4	-1.5	171.5	-0.6	171.7	-0.8
Cuba	171.0	171.5	-0.5	173.1	-2.1		
Dominican Rep.	172.1	170.6	1.5	172.0	0.1	172.4	-0.3
Ecuador	166.2	171.1	-4.9	168.8	-2.6	168.2	-2.0
El Salvador	171.2	168.2	3.0	166.1	5.1	167.4	3.8
Grenada	177.0	174.4	2.6	175.0	2.0		
Guatemala	161.9	164.7	-2.8	164.3	-2.4	163.7	-1.8
Haiti	170.4	167.2	3.2	170.4	0.0	171.7	-1.3
Honduras	167.6	166.6	1.0	167.9	-0.3	166.9	0.7
Jamaica	176.1	172.7	3.4	173.7	2.4	174.4	1.7
Mexico	168.2	167.4	0.8	167.3	0.9	168.5	-0.3
Nicaragua	169.0	167.2	1.8	168.2	0.8	169.4	-0.4
Panama	167.8	170.5	-2.7	170.4	-2.6	169.6	-1.8
Paraguay	171.7	169.5	2.2	170.5	1.2	169.3	2.4
Peru	165.5	169.6	-4.1	166.4	-0.9	167.0	-1.5
Saint Lucia	174.7	175.2	-0.5	175.3	-0.6	175.9	-1.2
Trin. and Tobago	175.3	174.0	1.3	174.2	1.1		
USA	176.8	176.3	0.5	176.9	-0.1	176.3	0.5
Uruguay	174.8	174.2	0.6	174.6	0.2	174.8	0.0
Venezuela	172.4	170.6	1.8	171.2	1.2	171.4	1.0

The roots of these trends must not necessarily be genetic, and they may result from differences in ethnic-specific dietary customs or social status, but a recent autosomal study confirmed that even at the level of individuals in five South American countries, higher European and African ancestry is associated with increased height, whereas higher Native American ancestry predicts shorter height (Ruiz-Linares et al., 2014). Although the authors did not directly test for any genetic loci associated with height, and found a significant effect of education and wealth on height, our data suggest that at the population level, these tendencies remain large even after nutritional and socio-economic variables are taken into account. A comparison of regression models (1) and (2) in Table 9 shows that the negative residual of predicted height is particularly high (> 4 cm) in countries of the Andean mountain range (Ecuador, Peru), and is reduced after the inclusion of the genetic factor (Native American & East Asian ancestry). In contrast, positive residuals are generally the highest in countries with the highest proportion of African ancestry (Jamaica, Haiti, Grenada). Only El Salvador is an exception and its observed height is much higher than predicted height. This again supports the suspicion that the height of Salvadoran men is overestimated.

The addition of the Gini index to the regression further improves the best model, although the number of usable countries is smaller ($n = 23$). It is thus possible that besides nutrition, total fertility, and genetics, some inter-population differences in America could be explained by social inequality. Nevertheless, the exclusion of the Gini index from Model 3 would still decrease its power rather marginally (to adjusted $R^2 = 0.785$), when compared with the exclusion of genetic variables (to adjusted $R^2 = 0.689$). Therefore, more data would be needed to assess these relationships objectively.

After an adjustment for genetic factors (Native American & East Asian ancestry), partial correlations of 47 nutritional and six socio-economic variables in 28 American populations mostly change only negligibly (Appendix Table 13). Perhaps the most noteworthy change is the decrease of r -values in poultry, fish & seafood, maize, GDP per capita, health expenditure, and total fertility. On the other hand, the r -values of potatoes and rice markedly increase. Thus, some of the examined variables may be spuriously associated with genetic factors, and genetics may mask the significant role of others, but the total picture is not changed in a fundamental way.

Discussion

The present study basically confirmed results from our last paper, which tested the relationship between male height and environmental factors in 105 populations (Grasgruber et al., 2016a). Here, it was nutrition ('highly correlated proteins', proteins from rice & legumes, and total energy) that explained by far the largest proportion of variance in a regression model. Out of three socio-economic factors in the optimal model, total fertility was obviously the most important.

After the addition of 40 American countries/territories and seven other populations that were not used previously, the strongest predictor of male height in a sample of 152 populations is again nutrition. Regression models incorporating complete data from 119 populations show that the combination of total energy with proteins correlating most positively (dairy, pork, eggs & potatoes) and most negatively (rice & maize) explains 74.0% of the variability in male height. Socio-economic factors (total fertility, child mortality, urbanization) improve the explanatory power to 78.4%, and total fertility clearly has the strongest effect. This also mirrors the result of the previous paper. In women, for whom data from 149 countries were available, we find essentially the same relationships.

If we were to pinpoint any notable differences, they lie in the combinations of protein sources (with beef losing its importance as a positive correlate of height, and the combination of rice & maize now being a slightly stronger negative predictor than rice & legumes). The explanatory power of the best regression model also substantially decreased, and as evidenced by regression

models in American populations, the cause should be sought in the significant role of genetic factors. The Gini index and IHDI are other important variables that could influence results in a significant way but their availability is still limited.

One of the most interesting practical observations is the identification of dairy, pork, and eggs as foods with the strongest positive relationship to stature which agrees remarkably well with their high protein quality (amino acid scores, AAS) according to the older FAO/WHO standard 1985 (children aged 2-5 years). Furthermore, the statistical strength of different types of meat (pork, beef, poultry) also mirrors their amino acid scores according to the FAO/WHO standard 1985. In contrast, these results do not accord so well with amino acid scores based on the new FAO/WHO standard 2007 (children aged 3-10 years) (Table 10). The proportion of isoleucine and valine in this new standard is slightly higher but the content of other essential amino acids was reduced, sometimes quite dramatically. The largest decrease occurred in the case of tryptophan, from 11 mg/1 g protein to 6.6 mg/1 g protein¹⁷. At the same time, tryptophan is the rarest essential amino acid in the human diet and it is contained in exceptionally high amounts in human milk (17 mg/1 g protein)¹⁸. Furthermore, according to the FAO/WHO 1985 standard, tryptophan is a limiting amino acid in many important protein sources (dairy and meat). As a result of these changes, the new FAO/WHO 2007 standard diminishes differences in protein quality among pork, beef, and chicken meat, and markedly increases amino acid scores of fish, which play a rather marginal role in the present study. Considering that dairy and pork emerge repeatedly as the key individual protein sources with high consumption rates (in Europe, in the total sample, and in the 1st tertile and 2nd tertile according to GDP per capita), the validity of the new FAO/WHO 2007 standard would certainly deserve re-evaluation.¹⁹

The problem of tryptophan can also have other interesting implications that relate to the unexpectedly positive role of potatoes in many statistical comparisons. Although this result may only be spurious, due to the low quality and low consumption rates of potato protein, it could have a meaningful rationale because potato protein contains the highest content of tryptophan out of all common food sources (16.5 mg/1 g protein)²⁰.

Another finding with potentially important implications is the linear increase in height with the increasing supply of proteins (and particularly proteins of the highest quality). This result obviously contradicts contemporary WHO guidelines regarding daily protein intake in children (~0.9

¹⁷ FAO Expert Consultation. 2011. Dietary protein quality evaluation in human nutrition. FAO food and nutrition paper, 92. <http://www.fao.org/ag/humannutrition/35978-02317b979a686a57aa4593304ffc17f06.pdf>.

¹⁸ Amino acid content in foods and biological data on proteins. <http://www.fao.org/docrep/005/AC854T/AC854T00.htm>.

¹⁹ The doubts about the correctness of the new FAO/WHO amino acid standard (2007) were further strengthened by our recent findings from Bosnia and Herzegovina where we observed a strong connection between the regional production of pork and the strikingly shorter statures of local Bosniak (Muslim) boys who do not consume pork for religious reasons (Grasgruber et al., 2017).

²⁰ Amino acid content in foods and biological data on proteins. <http://www.fao.org/docrep/005/AC854T/AC854T00.htm>.

g/kg/day)²¹ according to which children in affluent European countries should be in a state of permanent protein excess because their typical protein intake reaches ~2.7 g/kg/day (Börnhorst et al., 2014). Therefore, protein intakes exceeding WHO recommendations should not produce any additional growth. However, as already mentioned in the Introduction, even other authors maintain that the protein doses recommended by the WHO are deeply underestimated and correspond to normal protein intake in children from poor developing countries (Elango et al., 2011). Our practical experience also shows that protein intake in Czech children is far from optimal.²²

The reason for the persisting uncertainties regarding child nutrition lies in the fact that practical experiments of protein requirements in children are not performed due to ethical reasons, and the current standards are based on notoriously problematic tests of nitrogen balance in adults, lasting usually no longer than two weeks. In fact, Elango et al. (2011) explicitly stated that “No long-term studies exist to determine whether recommended [protein] intakes will maintain adequate health and/or meet the body’s needs for various physiologic and metabolic functions.” The observed discrepancies with our ecological data thus do not necessarily imply the inferiority of the ecological approach.

The identification of the strongest negative dietary correlates of height (rice and maize) also agrees with their low protein quality (according to both FAO/WHO standards) but it cannot be the sole factor because wheat is associated positively with height (up to a certain point), despite the fact that its amino acid score is much lower than in parboiled rice, and roughly the same as in maize. Although deep poverty and the general lack of food in rice & maize consuming regions may offer an acceptable explanation, it is noteworthy that the proportion of protein energy in rice (7.8%) and maize (9.5%) is substantially lower, when compared with wheat (12.1%)²³, and hence a higher amount of these cereals must be consumed per gram of complete protein. This is in accordance with the fact that rice & maize consuming regions are characterized by the lowest proportion of protein in the diet (Appendix Figure 19).

²¹ Protein and amino acid requirements in human nutrition.

https://apps.who.int/iris/bitstream/handle/10665/43411/WHO_TRS_935_eng.pdf?ua=1, p. 176.

²² Our unpublished data based on body composition measurements of ~2000 Czech high schoolers aged 18-21 years demonstrate that there are 2-4 cm differences in height between extremes of various social groups. Height correlates positively with the attendance of school lunches and the frequency of dairy consumption, whereas obesity is in an inverse relationship with these factors. In other words, there can be no talk about the alleged excess protein in the diet of European children, and obesity has nothing to do with overnutrition but, conversely, with a low-quality diet containing a high proportion of cereals and sweeteners. Ironically, these marked differences in height exist despite the fact that the current Czech protein recommendations exceed the WHO recommendations roughly 3-times, and are criticized as “excessive”.

²³ Food Supply - Crops Primary Equivalent. <http://www.fao.org/faostat/en/#data/CC>. The USDA.gov database (<https://ndb.nal.usda.gov/ndb/search>) lists approximately 9.8% energy from protein in parboiled white rice, 10.4% in white maize (corn) flour, and 13.6% in wheat flours.

Table 10. Amino acid scores (AAS) of 50 selected protein sources (animal foods, mushrooms and plants), according to different FAO/WHO standards. The data are not corrected for total protein digestibility (PDCAAS score) and individual amino acid digestibility (DIAAS score) which further disproportionately decrease the quality of plant proteins.

FAO/WHO standard 1985, age 2-5 years			FAO/WHO standard 2007, age 3-10 years		
	AAS	Limiting amino acid		AAS	Limiting amino acid
Fish (Flatfish)	1.250	tryptophan	Cheese (average)	1.464	methionine/cysteine
Fresh milk	1.247	tryptophan	Fish (<i>Clupeiformes</i>)	1.445	leucine
Pasteurized milk	1.222	lysine	Eggs (hen's)	1.442	leucine
Eggs (hen's)	1.200	lysine	Fresh milk	1.416	methionine/cysteine
Reindeer meat	1.183	methionine/cysteine	Fish (Flatfish)	1.377	leucine
Rabbit meat	1.180	leucine	Sharks	1.376	valine
Zebu-cattle meat	1.177	tryptophan	Pasteurized milk	1.366	methionine/cysteine
Molluscs	1.171	leucine	Soy (tempeh)	1.354	valine
Sterilized milk	1.166	methionine/cysteine	Fish (<i>Cypriniformes</i>)	1.309	leucine
Mutton & lamb meat	1.154	tryptophan	Fish (Eels)	1.300	histidine
Pork meat	1.142	leucine	Fish (<i>Gadiformes</i>)	1.307	valine
Soy (tempeh)	1.136	lysine	Zebu-cattle meat	1.284	valine
Cheese (average)	1.096	tryptophan	Rabbit meat	1.271	valine
Fish (<i>Beloniformes</i>)	1.092	phenylalanine/tyrosine	Molluscs	1.267	leucine
Tofu	1.065	methionine/cysteine	Sterilized milk	1.267	methionine/cysteine
Soymilk	1.051	lysine	Mutton & lamb meat	1.264	leucine
Fish (<i>Scombroidei</i>)	1.030	leucine	Fish (all types)	1.260	leucine
Fish (all types)	1.020	tryptophan	Beef and veal meat	1.251	valine
Sharks	1.018	tryptophan	Pork meat	1.236	leucine
Beef and veal meat	1.017	tryptophan	Soymilk	1.232	lysine
Fish (<i>Gadiformes</i>)	1.016	tryptophan	Chicken meat	1.207	leucine
Skates	1.011	histidine	Fish (<i>Beloniformes</i>)	1.206	leucine
Fish (<i>Salmonidae</i>)	1.005	tryptophan	Skates	1.200	histidine
Brewer's yeast	0.999	methionine/cysteine	Reindeer meat	1.174	valine
Crustaceans	0.987	histidine	Crustaceans	1.172	histidine
Fish (<i>Clupeiformes</i>)	0.973	tryptophan	Tofu	1.157	methionine/cysteine
Chicken meat	0.932	tryptophan	Fish (<i>Salmonidae</i>)	1.147	leucine
Fish (<i>Cypriniformes</i>)	0.929	tryptophan	Fish (<i>Scombroidei</i>)	1.115	leucine
Fish (Eels)	0.918	tryptophan	Brewer's yeast	1.086	methionine/cysteine
Quinoa	0.909	leucine	Quinoa	0.984	leucine
Cowpea	0.903	methionine/cysteine	Cowpea	0.981	methionine/cysteine
Champignons	0.882	methionine/cysteine	Chick-pea	0.967	methionine/cysteine
Pea	0.812	methionine/cysteine	Champignons	0.959	methionine/cysteine
Chick-pea	0.787	tryptophan	Pea	0.883	methionine/cysteine
Beans	0.764	methionine/cysteine	Beans	0.830	methionine/cysteine
Potatoes	0.760	methionine/cysteine	Oatmeal	0.829	lysine
Lentils	0.686	methionine/cysteine	Potatoes	0.826	methionine/cysteine
Oatmeal	0.686	lysine	Buckwheat flour	0.792	lysine
Buckwheat flour	0.656	lysine	Barley (dehulled)	0.769	lysine
Barley (dehulled)	0.636	lysine	Parboiled rice	0.766	lysine
Parboiled rice	0.634	lysine	Lentils	0.746	methionine/cysteine
Cassava root meal	0.606	leucine	Sweet potatoes	0.721	lysine
Sweet potatoes	0.597	lysine	Sesame seeds	0.673	lysine
Hazelnuts	0.581	methionine/cysteine	Cassava root meal	0.656	leucine
Sesame seeds	0.557	lysine	Hazelnuts	0.631	methionine/cysteine
Walnuts	0.480	lysine	Walnuts	0.580	lysine
Wheat flour	0.480	lysine	Wheat flour	0.580	lysine
Almonds	0.466	lysine	Almonds	0.563	lysine
Maize	0.461	lysine	Maize	0.557	lysine
Sorghum	0.348	lysine	Sorghum	0.421	lysine

Sources: All data of amino acid composition are based on the FAO.org database (<http://www.fao.org/docrep/005/AC854T/AC854T03.htm#ch1.I>), except for rabbit meat, reindeer meat, tofu and walnuts, which were taken from the USDA.gov database. Notes: *Clupeiformes* = pilchard, sardines, anchovy, herring etc.; *Cypriniformes* = carps, minnows, loaches etc., including catfish; *Salmonidae* = trout, salmon, whitefish, etc.; including smelt; *Gadiformes* = cods, hakes, haddocks etc.; *Scombroidei* = tuna, mackerel, sword-fish etc.

High women's fertility rates are the most significant socio-economic indicator in the present study, although they come to the foreground only in developing countries, and show a somewhat weaker relationship to height, when directly compared with child mortality. Because resources available in families have limitations, a large number of children must inevitably lead to the decrease of resources expended per child, including the length of breastfeeding. Indeed, studies from developing countries show that closely-spaced births lead to competition among siblings for food and maternal attention (Lindstrom & Berhanu, 2000). Understandably, high fertility rates also have other negative consequences leading to overpopulation, high unemployment rates among the young generation, and social unrest (Korotayev & Zinkina, 2011). Therefore, social policies should seriously target excessive fertility as a problem having a fundamental impact on the quality of life. Suboptimal living conditions in large families can be counterbalanced by greater age spacing between siblings, and by a more rational distribution of work between fathers, mothers, and older children (Quanjer & Kok, 2019).

The situation in the newly added sample of 40 American countries/territories does not fundamentally differ from that in North Africa, Asia and Oceania, with nutrition (rice & maize proteins) and total fertility being the most important factors in the regression analysis. The diet in America markedly differs from other continents only by the higher consumption of maize. American countries also reach the highest values of social inequality (the Gini index) in our global sample and these large social differences undoubtedly go along the racial lines. However, these data are still available for a limited number of countries and it is very likely that Gini indices of Muslim oil superpowers are similar. Besides that, differences in stature across American populations appear to have an interesting aspect related to genetic factors.

The fact that height in America correlates negatively with Native American ancestry is in accordance with the extremely short statures (around ~160 cm) that we find in men from virtually all aboriginal populations of Mesoamerica and South America, especially from the rainforest of Amazonia (Sinson, 1990). The tallest populations live in the south, in areas with the highest temperature difference between the hottest and coldest month. This extreme can be demonstrated by the example of the Ona from Tierra del Fuego (175.4 cm in men, 159.2 cm in women).

The conspicuous shortness of rainforest groups is usually explained as a result of genetic adaptations to the humid tropical climate (Bergmann's rule) or inadequate diet. According to Dufour (1992), the diet of these tribes consists mainly of cassava roots and bananas, and has an extremely high carbohydrate content, with high volume and a very low nutrient density. Similar factors must have played a fundamental role in the case of agricultural civilizations of Mexico and the Andes. In fact, the estimated stature of men in tropical America decreased from ~165 cm to ~160 cm rather quickly after the adoption of agriculture (Mummert et al., 2011).

Paradoxically, the Plains Indians from North America were officially the tallest people in the world in the mid-19th century, with 176.7 cm in men from the Cheyenne tribe, 174.3 cm in the Arapaho and 173.6 cm in the Crow (Steckel & Price, 2001). These impressive values can be explained by a high-quality diet relying on buffalo and low population density, and raise questions of whether there are differences in the maximum genetic potential between various Native American groups. Although Berg et al. (2017) recently tested the presence of height-associated genetic loci in 187 world populations, including Native Americans, their results have certain limitations because these loci are specific for Europeans. According to this analysis (which included only two samples from the Western Balkans, and none from Remote Oceania) the tallest ‘genetic height’ was predicted in people from northern, central and eastern regions of Europe, and correlated positively with the proportion of European Paleolithic ancestry. The relationship of Neolithic (Near Eastern) ancestry to height in Europe was negative. Populations from the Mediterranean, Near East and India had moderate values of predicted height; Sub-Saharan Africans, Papuomelanesians, Siberians and Native Americans were rather below the global average; the lowest genetic height could be seen in Southeast and East Asians. Therefore, Sub-Saharan Africans and Native Americans would have roughly the same genetic height, and there should be little differences among Native Americans, except for two eccentric outliers (Tlingit Indians from northwestern Canada and the Aleut), whose genetic predispositions would match those of South Europeans. However, this study did not include any other aboriginal populations from North America, and as the authors emphasized, their results predict similar height in the (moderately tall) Maasai and (dwarfish) Mbuti Pygmies, which illustrates their unreliability outside Europe.

Conclusion

Our study used an ecological methodology to trace the relationships among external factors and physical growth in children in 152 world populations. Although the ecological approach alone cannot establish causal relationships, the results are generally meaningful, consistent in both sexes, and some of them are very convincing, especially with regard to the nutritional predictors of stature. Because our previous experience with the FAOSTAT database of food supply was very positive, and most of the anthropometric data come from large nationwide studies (a median of 334 male and 442 female participants), the observed correlations between height and dietary variables should not be far from the ‘real-world’ relationships between nutrition and child growth.

Given the admitted imperfection of the current protein recommendations, particular attention should be paid to discrepancies between our results and the current views on child nutrition. As already mentioned in footnotes, practical observations from our own anthropometric surveys speak in favour of the ecological methodology. If anything, contemporary recommendations regarding

daily protein intake in children are very hard to defend. Also worth noting is the disagreement between the observed ranking of protein sources and their biological quality according to the new FAO/WHO amino acid standard 2007. Our study definitely accords better with the older FAO/WHO standard 1985. On the other hand, it is true that the observed patterns between height and protein sources are not always consistent at the level of regions, which indicates that they are also influenced by mean consumption rates, collinearity among certain foodstuffs, and perhaps even other important factors such as genetics.

Our future aim is to collect data even from sub-Saharan Africa, where average values of height are higher than the extremely high levels of poverty predict (Deaton, 2007; Hirvonen & Moradi, 2011). Although many WHO-sponsored STEPS surveys measured body height in young African adults, the data are often omitted in final reports and will be very difficult to access. Our preliminary results based on a limited number of countries indicate that sub-Saharan African populations are not outliers in graphic comparisons but their height is indeed often higher than predicted which points to the role of genetic factors.

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