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Identifying the limits to socioeconomic influences on human growth

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ABSTRACT

Contemporary humans occupy the widest range of socioeconomic environments in their evolutionary history, and this has revealed unprecedented environmentally-induced plasticity in physical growth. This plasticity also has limits, and identifying those limits can help researchers: (1) parse when population differences arise from environmental inputs or not and (2) determine when it is possible to infer socioeconomic disparities from disparities in body form. To illustrate potential limits to environmental plasticity, we analyze body mass index (BMI) and height data from 1,768,962 women and 207,341 men (20–49 y) living in households exhibiting 1000-fold variation in household wealth (51 countries, 1985–2017, 164 surveys) across four world regions—sub-Saharan Africa, South Asia, Latin America, and North Africa and the Middle East. We find that relationships of environmental inputs with both mean height and BMI bottom out at roughly 100–700 USD per capita household wealth (2011 international units, PPP), but at different basal BMIs and basal heights for different regions. The relationship with resources tops out for BMI at around 20 K–35 K USD for women, with growth potential due to environmental inputs in the range of 6.2–8.4 kg/m^2. By contrast, mean BMI for men and mean height for both sexes remains sensitive to environmental inputs even at levels far above the low- and middle-income samples studied here. This suggest that further work integrating comparable data from low- and high-income samples should provide a better picture of the full range of environmental inputs on human height and BMI. We conclude by discussing how neglecting such population-specific limits to human growth can lead to erroneous inferences about population differences.

1. Introduction

Due to dramatic economic and technological changes over recent centuries, much of contemporary humanity has witnessed unprecedented declines in infectious disease burden alongside increases in life expectancy, stature, and body mass (Baten and Blum, 2012; Deaton, 2007; Floud et al., 2011; Fogel, 2004; Komlos and Baur, 2004; Van Zanden et al., 2014). Given lags in access to such improvements, contemporary humans as a whole also occupy the widest array of socioeconomic environments in their evolutionary history. This includes over thousand-fold variation in the income and wealth enjoyed by individuals and households (Davies et al., 2011; Hruschka et al., 2015) with associated inequalities in access to adequate diets, clean water, hygienic sanitation, immunizations, and healthcare (Preston, 2015).

This unprecedented environmental variation has revealed a substantial influence of environmental inputs on human growth, including height (Collaboration, 2016; Floud et al., 2011; Komlos, 1998, 2014) and weight-for-height (Hruschka and Brewis, 2013). Decades of study have identified the specific environmental factors shaping human body form, including nutritional intake and the energetic costs of physical activity, disease, and daily survival (Baten and Blum, 2014; Bogin, 2013; Cole, 2000; Eveleth et al., 1976; Grasgruber et al., 2016; Haeffner et al., 2002; Hruschka and Hadley, 2018; Prince and Steckel, 2003; Scrimshaw et al., 1968; Victora et al., 2008). Depending on the specific body dimension, these environmental inputs may have their greatest influence at different life stages from fetus to adulthood (Eveleth et al., 1976). For example, human height is most sensitive to environmental inputs before growth plates fuse in late adolescence, while body mass index can increase over a person's lifetime. In turn, these inputs also depend on individual-, household-, and community- level socioeconomic factors which constrain the ability to achieve an adequate diet, to prevent infectious disease, and to offload physical activity (Hruschka and Brewis, 2013; Subramanian et al., 2011).

The vast majority of research on human growth has examined such environmental plasticity. However, there are also a number of mechanisms that may create lower and upper bounds on the effects of environmental inputs (Henry, 2005; Lui and Baron, 2011).

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First, individuals at the extremes of body form may experience greater mortality. For example, in situations of extreme scarcity, extremely low weight-for-height can indicate low energy reserves, which can in turn put individuals at increased mortality from infectious diseases and other insults (De Onis, 2017). Similarly, individuals enjoying extreme abundance may also experience selective mortality due to biomechanical limits on functioning and histories of excess energy consumption (Smith et al., 2000). Second, physiological control mechanisms may shift energetic investment away from physical growth at extremes of body form, prioritizing other tasks, such as immune function, brain growth, and reproduction (Lui and Baron, 2011; Said-Mohamed et al., 2018). Finally, there are also developmental limits on growth rate and growth timing that may place upper bounds on expected population body form (Eveleth et al., 1976). These different processes may impose a lower bound on a population's mean body form in situations of extreme deprivation (i.e., *a basal* level) and an upper bound in situations of extreme abundance. We refer to the difference between the upper bound and lower bound as a population's environmentally-induced *growth potential* over and above any *basal* level.

The degree to which individual-level and population-level genetic differences contribute to variation in these limits has been hotly contested. A number of authors have presented data suggesting that population differences in body form are almost entirely the product of environmental factors (Collaboration, 2016; De Onis et al., 2006; Habicht et al., 1974; Martorell and Habicht, 1986; Prince and Steckel, 2003). However, at the population-level, there are substantial differences in both height and BMI that cannot be accounted for by a wide range of environmental inputs (Baten and Blum, 2014; Hackman and Hruschka, 2018; Hruschka and Hadley, 2016; Hruschka et al., 2014; Natale and Rajagopalan, 2014). As an example, both Japan and the Netherlands have experienced impressive gains to adult height as the economic well-being of their populations have improved (14–16 cm). However, in recent decades, both countries have seen those gains plateau at potential upper limits, and the difference between these plateaus is also quite substantial (˜10 cm) (Collaboration, 2016; Tanner et al., 1982). Indeed, increasing evidence suggests that genetic variation may also account for substantial variation in body forms between populations (A'Hearn, 2016; Baten and Blum, 2014; Grasgruber et al., 2014; Stulp and Barrett, 2016; Turchin et al., 2012). This is important because such genetic differences might mean that different populations have different *basal* levels of body proportions as well as different *growth potentials*. This, in turn, is fundamentally important to take into account when comparing populations, and particularly, when using body form as a measure of the biological standard of living (Komlos, 1993).

Identifying and characterizing both the plasticity and limits of growth can help researchers: (1) parse when population differences arise from environmental inputs or not and (2) determine when it is appropriate to infer socioeconomic disparities from disparities in body form (Hackman and Hruschka, 2018; Hruschka and Hadley, 2016). Historical studies in Europe, USA, and Japan have traditionally focused on relationships between body form and macro-level economic indicators examined across regions or decades. However, barring a few exceptions (Harris, 1994; Horrell et al., 2009), these have largely been limited to conscripted, imprisoned, or enslaved men (Baten and Blum, 2014; Cole, 2000; Floud et al., 2011; Hatton and Bray, 2010; Komlos, 1987, 1998, 2014; Komlos and A'Hearn, 2017; Schmidt et al., 1995; Tanner et al., 1982). To complement this historical data, contemporary cross-sectional, population-based health surveys in low-income countries worldwide have provided valuable microdata on environmental inputs to human growth, including individual socioeconomic status, household resources and access to clean water and sanitation, and local disease burden (Grasgruber et al., 2014; Hackman and Hruschka, 2018; Hruschka and Hadley, 2016; Hruschka and Brewis, 2013; Hruschka et al., 2014; Mamidi et al., 2011; Subramanian et al., 2011). However, until recently, these studies have largely focused on women and children. Fortunately, a new wave of worldwide demographic surveys that include anthropometrics for both men and women and a range of microdata on environmental inputs now permits examining: (1) how the fullest range of these inputs are associated with growth in both sexes and (2) what limits might exist to the influence of these environmental inputs.

In this paper, we bring together three decades of population-based data from four major world regions—sub-Saharan Africa, South Asia, North Africa and the Middle East, and Latin America—to provide population-level estimates of: (1) lower bounds on the sensitivity of body forms to environmental inputs (i.e. *basal height and basal BMI)*, (2) population-level variation in *basal levels* independent of (known) environmental factors, and (3) population-level variation in environmentally-induced *growth potential*. First, we illustrate how population mean height and BMI is associated with increased household wealth by age and gender. Second, we model the influence of a broader range of environmental inputs on height and BMI, including household wealth and socioeconomic status, improved sanitation, reduced disease burden, common sources of food energy, and urban residence. These models show that the relationship between these environmental inputs and body form is better described by a sigmoid function with lower and upper bounds than a linear relationship. Using these sigmoid models, we estimate lower and upper bounds, the potential growth between them, and resource levels at which the association with resources begin to bottom out (the point at which a population reaches 5% of its growth potential above basal level) and top out (the point at which it reaches 95% of potential above basal level). We then use this same modeling approach to estimate regional and country-level variation in upper and lower bounds and the population growth potential that lies between these upper and lower bounds. We conclude by describing how neglecting such bounds can lead to a number of analytic and interpretive problems when attempting to examine the relationship between body form and environmental inputs.

The current analyses use observational data to estimate associations between environmental inputs and human growth. An inherent limit of observational data is that observed associations may arise from a number of processes that must be considered when interpreting the findings. As outlined earlier, environmental resources may influence physical growth, thus creating the observed associations. However, researchers have also documented other processes that may give rise to correlations between body form and one's environment. For example, preferences for and discrimination against certain body forms (e.g., taller, thinner, more muscular) in labor and marriage markets can lead to correlations between household economic resources and an individual's body form (Baten and Murray, 1998; Hruschka, 2017). Correlations between body form (e.g., height) and other attributes (e.g., intelligence) that make individuals more competitive at school and work can also lead to such associations between resources and body form (Guven and Lee, 2015; Spears, 2012). Thus, it is important to interpret observed associations as potentially arising from any of these influence or selection processes. That said, by estimating bounds on the shape and magnitude of these associations across a wide range of social and ecological settings, these analyses provide a firmer empirical foundation for future studies of these different processes and the expected magnitudes of effect they should have in different social ecologies (Hruschka, 2017).

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2. Methods

2.1. Data

We use data from Demographic and Health Surveys, nationally representative household surveys that collect information on a range of health and socioeconomic indicators. Importantly, these surveys use measured height which does not suffer from systematic biases and missing data in semi-literate settings introduced by self-reported height and weight (Engstrom et al., 2003; Maupin and Hruschka, 2014). Given potential macro-regional differences in key parameters of growth—basal levels and environmentally-induced growth potential—we stratify analyses by WorldBank regions and focus on four regions that have the largest quantity of data in the Demographic and Health Surveys—sub-Saharan Africa (32 countries), South Asia (5), North Africa and Middle East (4), and Latin America and the Caribbean (10). Haiti has a very different genetic background from the other Latin American countries considered here due to its near complete genetic affinity with African populations (Salzano and Sans, 2014). For that reason, we include it with sub-Saharan Africa for most analyses except to illustrate the problems that arise when including it in the Latin America and Caribbean region. Two available countries were also excluded because FAOSTAT data on macronutrient composition was not available (Burundi and Democratic Republic of Congo).

We used data from 164 surveys from 1985 to 2017 from 51 countries, which have necessary data on adult height, BMI, and household resources. Due to the small number of men's samples from most regions, we focus men's analyses on sub-Saharan Africa (12 countries) and South Asia (3) (Table 1).

Table 1
Sample sizes by country and body dimension. SSA = Sub-saharan Africa, SA = South Asia, MENA = Middle East and North Africa, LA + C = Latin America and the Caribbean. *Haiti analyzed with sub-Saharan Africa except to illustrate problems introduced by analyzing with Latin America and Caribbean.

		Women			Men		
	Region	20-49 Sample	BMI Sample	Height Sample	20-49 Sample	BMI Sample	Height Sample
BD	SA	55151	12635	22195	1353	0	1154
BF	SSA	20846	4428	8284	0	0	0
BJ	SSA	30651	6593	12833	0	0	0
BO	LA + C	18768	3891	7589	0	0	0
BR	LA + C	2884	186	1564	0	0	0
CF	SSA	1760	116	872	0	0	0
CG	SSA	8907	1878	3502	0	0	0
CI	SSA	8089	1310	3474	0	0	0
CM	SSA	10304	2044	4076	0	0	0
CO	LA + C	65858	18259	24037	0	0	0
DR	LA + C	15880	3829	6065	0	0	0
EG	MENA	82412	23412	32634	0	0	0
ET	SSA	36966	7894	14628	17869	4002	7073
GA	SSA	5939	1214	2293	0	0	0
GH	SSA	14574	3229	5820	2900	777	1049
GM	SSA	3169	594	1293	0	0	0
GN	SSA	9050	1892	3661	0	0	0
GU	LA + C	25507	5392	9999	0	0	0
GY	LA + C	3587	1112	1164	0	0	0
HN	LA + C	30217	7183	11417	0	0	0
HT	*	18945	4566	7001	0	0	0
IA	SA	698227	185513	258994	134305	35752	48991
JO	MENA	18649	5281	7728	0	0	0
KE	SSA	22973	4330	9744	0	0	0
LB	SSA	8352	2040	3093	3225	831	1228
LS	SSA	7724	1852	2814	3947	762	1515
MA	MENA	15518	3897	5841	0	0	0
MD	SSA	13952	3155	5567	0	0	0
ML	SSA	25798	5482	10421	0	0	0
MV	SA	5139	1357	1952	0	0	0
MW	SSA	29959	5993	11799	0	0	0
MZ	SSA	20645	4268	8213	0	0	0
NC	LA + C	18351	4211	6923	0	0	0
NG	SSA	54884	13631	21036	0	0	0
NI	SSA	12731	2048	5716	0	0	0
NM	SSA	12189	2632	4773	2735	613	1014
NP	SA	27582	6277	10760	3070	887	1045
PE	LA + C	126883	33863	47061	0	0	0
PK	SA	3968	1199	1462	0	0	0
RW	SSA	20348	4772	7652	8510	1684	3640
SL	SSA	8294	1821	3254	4803	1269	1670
SN	SSA	9731	1912	3911	2826	627	1023
ST	SSA	1723	455	675	1468	360	580
SZ	SSA	3414	798	1238	2727	505	1024
TD	SSA	13441	2373	5898	0	0	0
TG	SSA	6643	1202	2971	0	0	0
TZ	SSA	31002	6499	12276	0	0	0
UG	SSA	15181	2751	6240	6975	1520	2776
YE	MENA	13287	3101	5440	0	0	0
ZM	SSA	27713	5036	11431	0	0	0
ZW	SSA	25197	5005	10100	10628	2199	4190
Total		1768962	434411	679384	207341	51788	77972

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We include only adults between the ages of 20 and 49 y with heights within the range of 100 cm to 200 cm, weight between 20 kg and 200 kg, and BMI in the range of 10 to 90 kg/m^2, since such extreme measures may indicate misreporting. This excluded 0.9% of cases. We also exclude pregnant women from analyses (7.4% of women) due to the substantial effect of pregnancy on BMI (Hruschka and Hagaman, 2015). This resulted in the inclusion of 1,768,962 women and 207,341 men ages between the ages of 20–49 y. For age-specific analyses, there were 434,411 40–49 y women and 51,788 40–49 y men for the BMI analyses and 679,384 25–34 y women and 77,972 25–34 y men for the height analyses.

2.2. Variables

The key variables considered here are height and BMI as outcomes of growth, and resource variables that represent sources of influence on growth, ranging from resource access to hygiene and infectious disease exposure (Headey et al., 2016). Below, we indicate whether these resource variables are measured at the individual-, household-, sampling cluster-, or country-level. The sampling cluster usually represents about 20 households that are in relatively close proximity to each other, but can vary between 1 and 1000 households depending on the survey.

Variables for dietary energy from different foods are country- and year-level averages (kcal/capita/day), and thus can be matched to the decade when they should be most directly related to height (30 years prior for height among 25–34 y olds) and BMI (5 years prior for BMI among 40–49 y olds). While these survey-level averages provide important information about large-scale population differences in nutritional intake, they cannot account for individual-level differences in body form which constitute the vast majority of global variation (Baten and Blum, 2014; De Onis et al., 2006; Grasgruber et al., 2016). Other explanatory variables take advantage of the individual- and household-level microdata from demographic and health surveys that also include the anthropometric data. This permits fine-grained linkage of environmental variables with individual outcomes. For BMI, these individual- and household-level variables directly reflect the environmental conditions that would be relevant for recent fat deposition. For height, however, these variables represent a 25–34 y old individual's environment nearly 15–35 years after their first 10 years of life when environmental variables are expected to exert strong effects. Thus, a key assumption underlying the interpretation of many variables in the height analyses is that between-individual differences in socio-economic conditions in this sample are relatively large compared to any within-individual changes in socio-economic between the first decade of birth and the third decade of life. There are advantages and disadvantages to this approach relative to focusing only on country-level and year-level averages that are matched by decade of birth. The microdata approach preserves important information about between-individual differences but introduces unknown error caused by temporal changes (e.g. if household wealth in early adulthood is very different from household wealth in early childhood). The other approach more closely matches explanatory variables with decade of birth but ignores potentially important individual differences. Notably, the between-country differences in many of the dietary values are highly consistent over a 25 year period (all $r > 0.80$, except for overall kcal which was $r = 0.47$).

2.2.1. Height, weight & BMI

In each of the Demographic and Health Survey samples, height (cm) and weight (kg) measures were taken by trained technicians. BMI was calculated as weight(kg)/height(m)^2.

2.2.2. Absolute wealth estimates (AWE)—household-level

We used an asset-based approach that calculates comparable household wealth estimates in absolute units—2011-constant international dollars with purchasing power parity (Hruschka et al., 2015). This facilitates comparisons of the wealth of households both within a country across different survey years, as well as across populations from different countries. We used a continuous log-transformed value of AWE for analyses and a categorical variable binned into nineteen categories for visualization. The categorical variable had breakpoints representing a roughly 50% increase over the prior breakpoint starting at 90 USD–Roughly 90, 140, 200, 300, 450, 700, 1 K, 1.5 K, 2.3 K, 3.5 K, 5 K, 8 K, 12 K, 18 K, 26 K, 40 K, 60 K, and 90 K.

2.2.3. Education—Individual-level

As another measure of socioeconomic status, we include individual-level education, as a four-level ordinal variable indicating none, some primary, some secondary or some higher education.

2.2.4. Hygiene and sanitation—cluster-level

Due to the importance of local sanitation for disease ecology and child growth (Headey et al., 2016), we control for the impact of sanitation on height and BMI using a cluster level variable of the proportion of households in the cluster who engage in open defecation.

2.2.5. Exposure to infectious disease—cluster-level

To account for infectious disease exposure, we calculated the proportion of children in a sampling cluster who experienced diarrhea in the previous two weeks. We use data on child diarrhea because comparable data is not available for adults assuming that disease burden among children is a good proxy for disease burden among adults.

2.2.6. Dietary sources of energy – country- and year-level

Compromised growth is a result of both chronic lack of calories and specific macronutrient intake. Thus, we include variables reflecting total energy supply (kcal/capita/day) as well as energy supply from key food sources that have been shown to be correlated with growth in other studies. These include energy from animal sources (i.e., red meat, fish, poultry, dairy) as well as energy from rice and wheat (Baten and Blum, 2014; Grasgruber et al., 2016). These data come from the FAOstat database (http://www.fao.org/faostat), which uses household food balance sheets to estimate average, per-capita dietary energy intake from different sources. These three-year country-average estimates were available for all survey years before 2014. We assign the value for each country from the 30 years prior to the survey for height and 5 years prior to the survey for BMI. These variables combined account for most of the variance in energy from animal proteins ($R^2 > 0.95$), and so we do not include animal protein as an independent predictor.

2.2.7. Study year

We include a year variable indicating year since 1990 to capture any environmentally-induced secular changes in height or body mass index over time that are not captured by our other explanatory variables.

2.3. Analysis

We initially present the relationship between household wealth and height and body mass index by world region. Given potentially differing sensitivities to environmental inputs by age, we stratify by age (20–29 y, 30–39 y, 40–49 y) (Hruschka and Brewis, 2013).

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To model the relationship between height and BMI and the full suite of resources, we fit two kinds of models—a linear model that does not assume any bottoming or topping out of the effects of resources and a sigmoid model that does permit such non-linear relationships (Hackman and Hruschka, 2018). We model BMI for adults aged 40–49 y—the age category showing the largest association with socioeconomic resources. We limit the height models to ages 25–34 y—the age group which has experienced complete growth in height and yet is closest to the life stage when environmental inputs would have had their effect. Height was similarly modeled as described for BMI below.

The sigmoid version of the model of the relationship between BMI and the full set of environmental input variables X_k takes the following basic form:

$$BMI = \frac{a}{1 + e^{\left(c - \sum \beta_k X_k\right)}} + d_i + \varepsilon_{ij}$$

where $\sum \beta_k X_k$ is a linear combination of the individual-, household-, cluster-, and country-level variables representing the full suite of variables for environmental inputs described above (e.g. nutrition, infectious disease, sanitation). Parameter d_i is a random effect that represents the lower bound (e.g. basal level) for population i. This is the expected BMI in a given population when environmental variables are at the most extreme level of deprivation and represents our best estimate of the population's basal BMI. Importantly, the random effects model allows this d parameter to vary across countries, so that we can assign each country its own basal level and characterize the variation in those basal levels.

Parameter a_i is the distance between the lower bound and the upper bound of the sigmoid curve relating resources and BMI. This represents *growth potential*—the total potential increase in BMI above the baseline across the full spectrum of resources. Finally, the c parameter represents the point in the sigmoid curve where 50% of a population's environmentally-induced growth potential has been achieved. The mixed effect model was estimated using the nlme function in R (Pinheiro et al., 2017). In those cases where the model did not converge, we identified starting values for each parameter in the full model by running a simpler model that did converge.

To estimate country-specific and region-specific basal levels (i.e., the d parameter) and growth potential (i.e., the a parameter), we use the conditional modes of the random effects for each country (using restricted maximum likelihood REML), which are similar to the Empirical Best Unbiased Linear Predictions (EBLUPs) from linear mixed effects models (Pinheiro et al., 2017; Faraway, 2016; Züur, Ieno, Walker, Saveliev, & Smith, 2009).

To test for regional variation in the lower bound (d), growth potential (a), and inflection points (c), we also include dummy variables for region-specific fixed effects for each of these three model parameters. These dummy variables permit estimates of how far these three parameters in different regions (e.g. South Asia, Latin America and the Caribbean, Middle East and North Africa) deviate from the sub-Saharan Africa estimates. They also permit tests of whether these regional deviations from the sub-Saharan Africa estimates are statistically significant. Given the relatively limited range of environmental inputs in any given country, it was not possible to get robust country-specific estimates of growth potential (a) and inflection points (c), so we relied instead on estimates of growth potential and inflection points pooled by world region.

The linear version of the model of the relationship between BMI and the full set of environmental inputs takes a similar form where the linear combination of environmental inputs is simply included as follows.

$$BMI = \sum \beta_k X_k + d_i + \varepsilon_{ij}$$

We use Akaike information criteria applied to maximum likelihood estimates of the models to compare the fit of the linear and sigmoid models to the data, and to determine if the sigmoid model with bottoming and topping out of the relationship with resources provides a better fit.

After establishing that the sigmoid model provides better fit, we describe the estimated sigmoid curves by major world region, and report estimated lower bounds (d) and growth potential (a). To illustrate the relationship of the full suite of environmental inputs with height and BMI in a common metric, we translate the estimated linear combination of environmental inputs $\sum \beta_k X_k$ for any given individual into an equivalent level of absolute household wealth (Absolute Wealth Estimates). To do this, we use an OLS regression predicting an individual's value on the linear combination of environmental inputs by their household's AWE value. The linear combination of environmental inputs estimated for each of the models showed a strong to moderate positive relationship with the household wealth variable (male BMI = 0.89 and height = 0.54, female BMI r = 0.85 and height r = 0.75). This indicates that household wealth provides a good approximation for representing the relationship with increasing resources. Using this translation permits plotting height and BMI by environmental inputs in terms of the expected wealth of a household with a specific suite of environmental inputs.

We also estimate the point at which bottoming out begins as the resource level at which a population would achieve 5% of potential growth above the basal level. Similarly, we estimate the point at which topping out begins as the resource level at which a population would achieve 95% of potential growth.

3. Results

3.1. Relationship between household wealth and body form

Figs. 1 illustrates how both body mass index and height are associated with changing household wealth. There is a clear positive relationship at middle levels of wealth for both BMI and height. The relationship between BMI and wealth increases substantially with age, with an environmentally-induced growth potential among 40–49 y adults of roughly 5 to 8 kg/m^2 from the lowest to highest wealth categories (Fig. 1a, right panels), but only 2 to 4 kg/m^2 among 20–29 y adults (Fig. 1a, left panels). This sensitivity to wealth is particularly pronounced in women. By contrast, the relationship between height and wealth is roughly comparable across ages with an increase of 5–7 cm from the lowest to highest wealth categories.

Across genders and regions, there appears to be a bottoming out of the relationship between both BMI and height and household wealth at low levels of wealth (between 100 and 1500 USD).

There also appears to be a topping out for BMI somewhere between 10 K and 50 K USD that is particularly pronounced in women. This topping out occurs at lower levels of wealth for two regions—Latin America and the Caribbean and Middle East and North Africa—and even appears to reverse for women (but not men) at the highest levels of wealth, which is consistent with previous work (Hruschka, 2017; Hruschka and Han, 2017; Sobal and Stunkard, 1989). By contrast, we find little evidence of a topping out for height in the wealth ranges examined here.

3.2. Height and BMI as a function of wealth and other resources

The sigmoid models fitted to the two growth outcomes—height and BMI—showed much better fit than did the linear models for both women and men (Table 2). Fig. 2 illustrates the model estimates by world region for men and women, and Tables 1 shows

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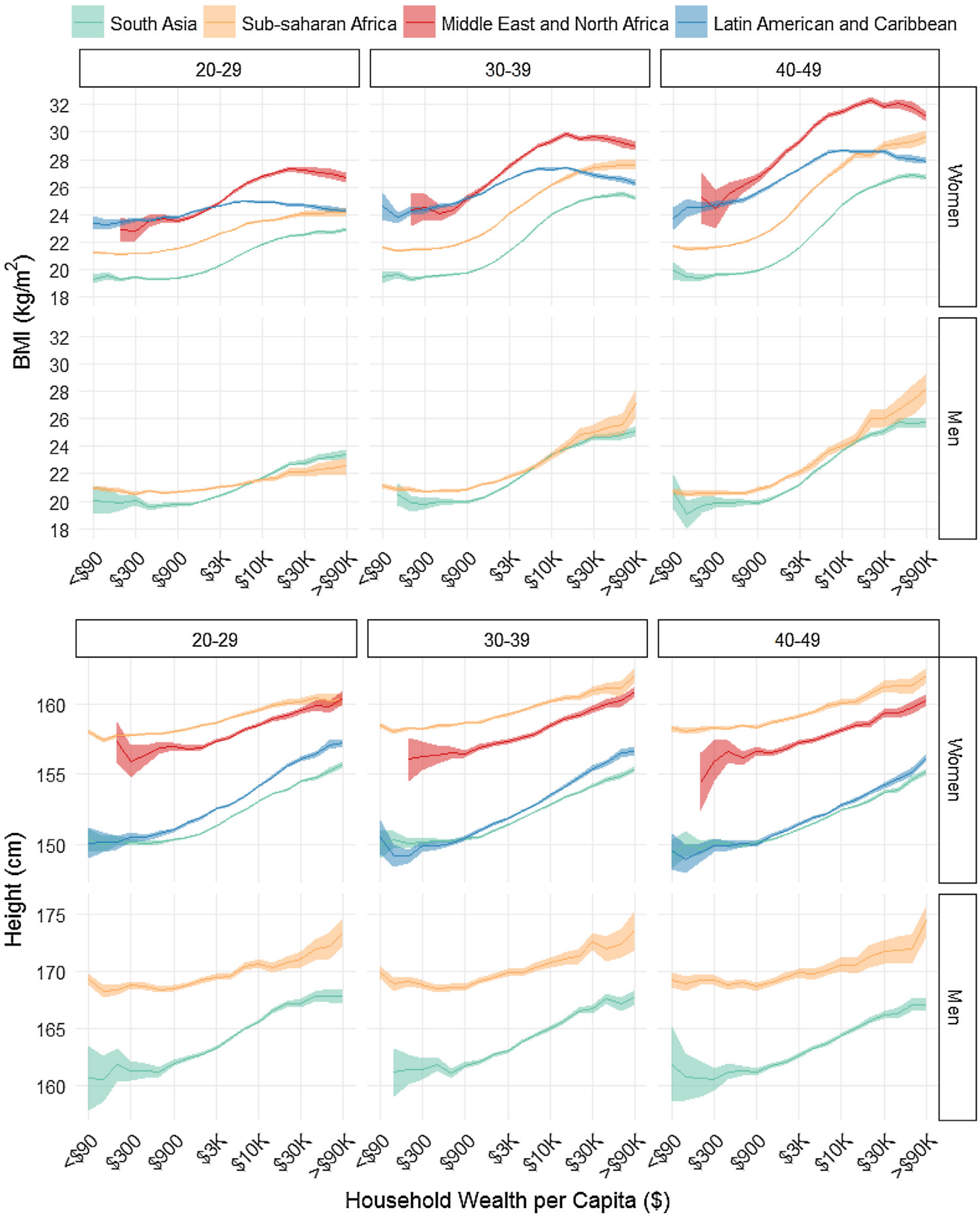

Fig. 1. Body mass index (A) and height (B) by gender, age category, world region, and wealth. Household wealth per capita is in 2011-constant international dollars with purchasing power parity. The line represents the mean per wealth bin, and the bands represent the 95% confidence intervals. Means and confidence intervals were not reported when the sample size was less than ten. The scale for height (B) on the y-axis is different for men and women.

the model estimates for men and women. There were also some differences in estimated basal levels, growth potential, and inflection points across regions (Table 2). For example, for women, Latin America & Caribbean had a much higher basal BMI compared to sub-Saharan Africa, while it had a much lower growth potential in BMI. South Asia had a much lower basal BMI for both men and women. The inflection points at which populations reach 50% of their estimated growth potential vary somewhat between body dimension and world region, with: (1) men having inflection points at lower levels of wealth than women for height and at higher levels of wealth for BMI and (2) height measures having inflection points at higher levels than BMI. Specifically, inflection points vary between 2000 and 3000 USD for female BMI, 4000–15000 USD for male BMI, 15,000 and 25,000 USD for female height, and 7000 and 20,000 USD for male height.

As expected, household wealth and education showed consistently significant and positive associations with BMI and height for both men and women (Table 2). Higher levels of community open

Table 2
Models relating BMI and Height with resources. 95% CI in parentheses, * $p < 0.005$, † $p < 0.05$. Estimates for basal level, growth potential, and inflection point are for sub-Saharan Africa.

	BMI (kg/m2)		Height (cm)	
	Women	Men	Women	Men
countries	51	14	51	15
surveys	164	21	164	22
n	434411	51788	679384	77972
Basal level (d)	21.4* (20.9,21.9)	20.9* (20.3,21.5)	157.7* (157.0,158.5)	168.5* (166.9,170.2)
Growth Potential (a)	8.4* (8.2,8.6)	7.4* (6.8,7.9)	6.8* (6.1,7.5)	10.3* (6.9, 13.6)
Inflection Point (c)	11.3* (10.9,11.6)	11.1* (9.9,12.4)	5.5* (5.1,5.9)	5.5 * (3.6,7.5)
ln(wealth)	1.03* (0.99,1.06)	0.96* (0.88,1.03)	0.46* (0.42,0.49)	0.55* (0.43,0.67)
Education				
Primary	0.27* (0.24,0.30)	0.14* (0.06,0.21)	0.14* (0.10,0.18)	0.03 (-0.05,0.11)
Secondary	0.40* (0.37,0.43)	0.35* (0.28,0.42)	0.61* (0.55,0.67)	0.42* (0.31,0.54)
Higher	0.47* (0.40,0.54)	0.73* (0.62,0.84)	0.93* (0.85,1.01)	0.72* (0.54,0.89)
Open defecation	−0.39* (-0.42,-0.35)	−0.18* (-0.26,-0.09)	−0.18* (-0.23,-0.14)	0.24* (0.15,0.33)
Child Diarrhea	−0.05 (-0.13,0.03)	−0.56* (-0.76,-0.36)	−0.20* (-0.27,-0.13)	0.26† (0.07,0.44)
Calories—All (100 kcal)	0.06* (0.05,0.07)	0.03 (-0.02,0.09)	0.06* (0.04,0.07)	0.0 (-0.0.0.0)
—Meat	0.94*(0.81,1.07)	0.76† (0.1,1.4)	−0.5* (-0.6,-0.3)	−0.2 (-1.0,0.6)
—Fish	0.11 (-0.04,0.27)	−0.92† (-1.73,-0.11)	−0.4* (-0.7,-0.2)	−6.6* (-8.6, -4.5)
—Poultry	1.46* (1.23,1.69)	−0.92 (-2.20,0.35)	0.7* (0.5,1.0)	−5.4 (-13.3, 2.4)
—Dairy	0.11* (0.04,0.18)	−0.24 (-0.81,0.33)	−0.6* (-0.7,-0.5)	−2.0* (-3.2, -0.9)
—Wheat	0.001 (-0.027,0.028)	−0.04 (-0.15,0.07)	0.07* (0.05,0.09)	−0.07 (-0.19,0.05)
—Rice	0.004 (-0.008,0.017)	−0.03 (−0.10,0.03)	−0.04* (-0.06,-0.03)	0.22* (0.13,0.31)
Urban residence	0.31* (0.29,0.34)	−0.03 (-0.09,0.03)	−0.30* (-0.34,-0.27)	−0.30* (-0.38,-0.21)
Year	0.03* (0.03,0.03)	0.07* (0.05,0.09)	−0.00† (-0.00,-0.00)	0.02 (-0.02, 0.05)
Regional divergences				
Basal levels (d)				
South Asia	−1.7† (-3.1,-0.4)	−1.6† (-3.2,-0.1)	−7.8* (-9.9,-5.8)	−12.6* (-16.6,-8.6)
LA & C	1.3† (0.2,2.4)		−7.6*(-9.2,-5.9)	
MENA	0.8 (-0.7,2.4)		−3.0† (-5.3,-0.8)	
Growth Potential (a)				
South Asia	−0.4* (-0.5,-0.3)	−0.1(-0.5,0.3)	2.5*(1.9,3.1)	2.3† (0.0,4.5)
LA & C	−2.2* (-2.5,-2.0)		5.0* (4.4,5.6)	
MENA	−0.1 (-0.5,0.4)		−1.0*(-1.6,-0.5)	
Inflection Point (c)				
South Asia	0.1 (-0.1,0.3)	−1.2* (-2.0,-0.5)	0.0 (-0.02,0.3)	−0.7 (-1.9,0.6)
LA & C	−0.5* (-0.6,-0.3)		−0.2† (-0.4,-0.0)	
MENA	−0.5*(-0.6,-0.3)		0.0 (-0.3,0.3)	
$\text{AIC}_{\text{sigmoid}}$	2539993	277634	4368610	520489
$\text{AIC}_{\text{linear}}$ - $\text{AIC}_{\text{sigmoid}}$	9625	858	2593	608

defecation and childhood diarrhea were negatively associated with BMI and height for women and for BMI among men. However, there was an unexpected positive association of these two variables in one of the four analyses—men's height. We explore this in more detail in a later section. Finally, there was a small positive residual secular trend by year for BMI in both sexes.

The effects of overall available food energy were positive for both height and BMI among women, as was food energy coming from poultry. Consistent with prior work on male height, a greater quantity of food energy coming from rice showed a negative effect on female height while a greater quantity from wheat showed a positive effect (Grasgruber et al., 2016). Quantities of energy from other foods had opposing associations with height and BMI, with greater quantities of red meat and dairy associated with increasing BMI but lower height. These latter findings are inconsistent with recent studies, and we point out later in the resultsa number of potential reasons for these differences (Baten and Blum, 2014; Grasgruber et al., 2016).

While the estimates for women may be considered relatively robust given the larger numbers of countries (n = 51) and surveys (n = 164) included in these analyses, the estimates for men are based on seven-between country variables estimated from few countries (n = 14–15) and surveys (n = 21–22). This might account for the fewer significant associations with nutritional variables. It also suggests that any associations should be interpreted with caution. That said, most of the significant associations are consistent with findings for women. These include a positive association of red meat with BMI, a negative association of fish with height (and BMI), and a negative association of dairy with height. The only significant association among men that was not consistent with the findings from women was a positive association of rice consumption with height, which was in the opposite direction of the finding for women and from prior studies (Grasgruber et al., 2016).

3.3. Bounds on environmental inputs to BMI

The models estimated substantial regional variation in basal BMI (between-region fixed effects range of 3.0 kg/m2, between-country random effects range of 6.5 kg/m^2). Consistent with previous findings, South Asia has the lowest BMI at the bottoming out point and Latin America and the Caribbean have the highest (Hruschka and Hadley, 2016) (Fig. 2). The sigmoid curves reaches 5% of potential growth at between 200 and 700 USD household wealth per capita and reaches 95% of potential growth at between 20 K to 35 K USD for women. For men, the estimated point at which the sigmoid curve reaches 95% of potential is well above the household wealth of most households in this sample (i.e. greater than 300 K). The models also estimate that environmental inputs are associated with an average 8.4 kg/m^2 increase over the full range of inputs in sub-Saharan Africa (7.4 kg/m^2 for men), with a significantly lower growth potential among South Asian women (8.0 kg/m^2) and Latin American women (6.2 kg/m^2, a 26% decrease from sub-Saharan Africa).

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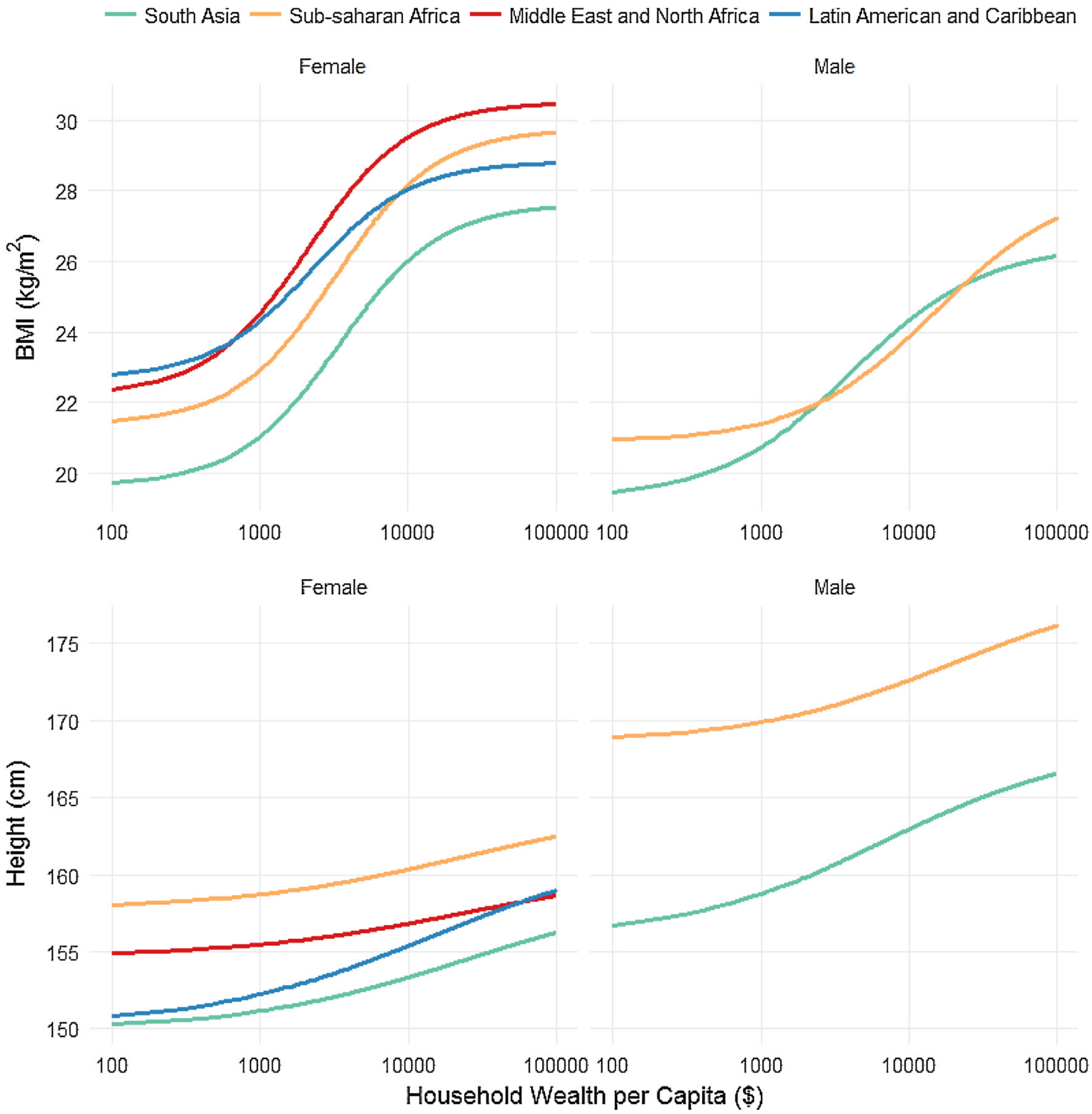

Fig. 2. Height and BMI as functions of increasing resources by gender and world region.

3.4. Bounds on environmental inputs to height

As shown in Fig. 2, the relationship of environmental inputs with height exhibits bottoming out at lower wealth than bottoming out for BMI—100-200 USD household wealth per capita. There is also substantial regional variation in the height at which populations bottom out (between-region range of 10.3 cm, between-country range of 17.6 cm), with sub-Saharan Africa and North Africa and the Middle East having the highest basal heights and South Asia and Latin America and Caribbean having the lowest (Fig. 2). In contrast to women's BMI, the relationship between environmental inputs and height does not plateau even at the highest levels of resources examined here. Without data at higher resource levels, the following estimates of growth potential or topping out for height should be interpreted with caution. Because for height there were no signs of topping out points (that might become apparent only with higher levels of resources), region-level variation in estimated growth potential for height shows much greater variation than that for BMI. Specifically, the estimated growth potential in Latin America and Caribbean women was 74% greater than the comparable estimate in sub-Saharan women (11.8 compared to 6.8 cm). However, as we mention above, the lack of data from higher-income populations necessary for robust estimates of growth potential in height means that any difference in estimates may simply be attributable to estimation errors.

There is a potential methodological explanation for the presence of a sigmoid relationship. It is possible that the sigmoid relationships observed here are due to increasing measurement error in environmental inputs at both extremes of deprivation and abundance. This is unlikely for the upper limit, since height shows increasing relationships with resources even at the highest resource levels. Moreover, if wealth was more likely to be misclassified at the lower and upper levels of wealth, then we would expect greater variation in BMI and height at these extreme levels of wealth (due to misclassification of individuals). However, BMI and height showed greatest variance at the middle wealth categories, suggesting that the sigmoid shape of the relationship cannot be accounted for by increasing measurement error at extreme levels of wealth.

There are also potential methodological explanations as to why regional variation in basal levels and growth potential exist. For example, regional variation in basal levels may be attributed to regional differences in unmeasured environmental inputs and

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other factors affecting the ability to partial out environmental inputs. However, comparing basal height and BMI across regions indicates that basal levels are not uniformly high or low for the same region across these two dimensions. For example, Latin America and Caribbean populations show much lower average basal height than sub-Saharan African populations (-7.6 cm) while showing greater basal BMI (+1.3 kg/m2). Thus, if unmeasured environmental inputs are responsible for these differences, they would need to affect height and BMI in very different ways. Finally, the presence of regional differences in potential height or BMI gain might reflect regional differences in the quality of measuring environmental inputs. If this were the case, then we should see attenuated estimates of growth potential in both height and BMI in regions with poorer measurement. However, there is no correlation between estimated growth potential in height and BMI across world regions.

3.5. Exploring the positive association of open defecation and diarrhea with men's height

As expected, community open defecation and diarrhea prevalence were negatively associated with growth in three of the four analyses. However, these two variables showed unexpected positive associations with male height. Further explorations indicate that these positive associations with male haight arise independently in regional analyses of both South Asia (open defecation = 0.30 95% CI (0.19,0.41), community diarrhea = 0.36 95% CI (0.11,0.61)) and sub-Saharan Africa (open defecation = 1.45 95% CI (0.81,2.09), community diarrhea = 0.13 95% CI (-0.40,0.66)). A between-country analysis of male height (n = 15) also indicates that at least some of the positive association at the individual level is driven by a substantial positive correlation of country-level male height with mean community diarrhea ($r = 0.54$, $p < 0.05$) and to a lesser extent open defecation ($r = 0.22$, $p = 0.22$). Despite, these puzzling relationships with male height, the model for male height excluding community-level open defecation and diarrhea provides qualitatively similar results for the main findings of interest in this paper. Specifically, the sigmoid model still provides a better fit than a linear model, and the shape parameters for the sigmoid curve as well as estimates and inferences about other model coefficients are all roughly the same. Thus, the unexpected association in no way modifies the more crucial interpretations for this paper.

3.6. Exploring the negative association of meat and dairy with height

In most cases, food energy from red meat and dairy was positively associated with adult BMI. However, the association of these two variables with adult height was negative, a finding that is inconsistent with other recent studies (Baten and Blum, 2014; Grasgruber et al., 2016). A number of factors may contribute to these differing estimates. Most notably, the sample of countries used in this and prior studies are markedly different. Our analyses focus on demographic and health surveys of low- and middle-income countries, with roughly half of countries from low-income countries (45% in women's sample, 53% in men's) and no high-income countries. By contrast, previous studies have included a much larger proportion of high-income countries (45–49% high-income compared to 4–11% low-income) (Baten and Blum, 2014; Grasgruber et al., 2016). One possible explanation for the difference in effects of meat and milk that deserves further attention is that the effect of total energy is more important in low income contexts, while specific sources of food energy may provide additional gains at higher incomes. The current sample also differs substantially from earlier samples in another way that may be important. Specifically, the current samples are almost entirely from sub-Saharan Africa and South Asia (75% of women's sample countries, 100% of men's sample), while none are from Europe, North America, Australia, or New Zealand. Meanwhile, earlier studies included substantial representation from Europe, North America, Australia, and New Zealand (40–50%) with far less representation from sub-Saharan Africa and South Asia (7–19%). These regions differ markedly in both average height and in consumption of red meat and dairy, but are ordered in different ways (Baten and Blum, 2014; Food and Agriculture Organization of the United Nations, 2016). Specifically,

Dairy consumption: Europe > Latin America & Caribbean > South Asia > sub-Saharan Africa

Red meat consumption: Europe > Latin America & Caribbean > sub-Saharan Africa > South Asia

Contemporary height: Europe > sub-Saharan Africa > Latin America & Caribbean > South Asia.

Thus, a sample that leaves out European countries may not estimate the strong positive association of milk or meat with height, and may in fact estimate a negative association depending on the regional balance of that sample. Ideally, an analytic method that uses each country as its own control through time (Baten and Blum, 2014), but also permits inclusion of micro-level data on key environmental variables (as is done here) will help determine the reasons for these varying regional differences.

Notably, most of the key results are robust to removing dairy and meat from models for male and female height. These include the better fit of a sigmoid curve than a linear function and the estimated magnitude of regional differences in basal height. That said, there are some quantitative differences. The basal height estimate for women does not change, but among men the estimate is 2 cm lower in the model without dairy and meat. Reflecting the earlier mentioned data limitations for reliably estimating growth potential in height, the estimates for growth potential did change somewhat between models (1.8 cm lower for women and 3.2 cm higher for men).

4. Discussion

To examine the limits of environmental inputs to human growth, we analyzed adult height and body mass index from households exhibiting 1000-fold variation in household wealth in 51 countries across four world regions. Our findings illustrate bottoming out of the relationship between environmental inputs and both measures of growth—body mass index and height—at the equivalent of roughly 100–700 USD per capita household wealth. Moreover, there is substantial region- and country-level variation in the basal BMI and basal height at which different populations bottom out. At the high extremes of body form, BMI topped out at roughly 20 K to 35 K USD per capita for women, permitting estimation of environmentally-induced growth potential in BMI between 6.2 to 8.4 kg/m2 depending on world region. Meanwhile, BMI among men and height for both sexes showed no clear levelling off within this range of environmental inputs, indicating that efforts to identify the full range of bounds to environmental inputs on human height will need to integrate data from high-income countries (Collaboration, 2016). Since height seems to be leveling off in the most affluent countries (Collaboration, 2016; Schönbeck et al., 2013), it is likely that with increasing resources, height will also "top out" but at much higher resource levels than the low- and middle-income populations considered in these analyses. Such an endeavor will also allow addressing how tall human populations can get.

Notwithstanding the current limitations in estimating lower and upper bounds (especially for height), the range of environmentally-induced growth potentials estimated across world regions (6.2–8.4 kg/m2 in BMI and 5.8–12.6 cm in height) are largely consistent with the magnitude of historical population

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changes that have been observed in the existing literature (Keep and Bogin, 1999; Komlos, 1987, 2014; Komlos and Baur, 2004; Ogden et al., 2004). Variation in estimated potential may be due to a number of factors that deserve further exploration. These include the potential for existence of relatively high quality diets among even the poorest in some countries or regions of the world, which in turn would lead to a higher floor and thus a lower estimated growth potential (Deaton, 2007). We have attempted to deal with this by using country- and year-level estimates of dietary quality. However, future work would ideally use finer-grained household- or community-level measures to account for within-country variation in diet. The estimated variation in growth potential across regions could also result from insufficient data at extremes of deprivation and abundance across a sufficiently diverse set of populations that makes accurate estimates of growth potential difficult.

As future work extends these analyses to higher-income countries and populations, it will also be important to examine other processes that might lead to novel relationships between increasing resources and body form. One of the most puzzling findings in the current literature is the reversal of the relationship between wealth and body mass index among women in the wealthiest rungs of contemporary humanity (Hruschka, 2012; Offer, 2006; Sobal and Stunkard, 1989). Consistent with a large body of existing cross-sectional studies, we find this same reversal occurring among women in two world regions—Latin America and the Caribbean and Middle East and North Africa. There is still considerable debate about whether this results from the influence of resources on BMI (e.g., through increased consumption of costly, thinning foods and leisure exercise) or of selection of thinner individuals into wealthier households (Hruschka, 2017; Hruschka and Han, 2017). Resolving these debates should help inform more general models of how environmental inputs lead to observed variation in human body form, and to what degree observed correlations between human body form and environmental variables are actually due to selection processes (Baten and Murray, 1998)

These findings also have implications for the interpretation of disparities in body form as an indicator of socioeconomic disparities or human development (Collaboration, 2016). A frequently held assumption in the study of anthropometrics is that genetic differences between populations are suitably small that phenotypic variation between populations is a good indicator of socioeconomic and nutritional well-being (Collaboration, 2016; De Onis et al., 2006; Prince and Steckel, 2003). However, we identified substantial population differences in both height and weight that are independent of a number of crucial environmental inputs, mirroring earlier findings (Baten and Blum, 2014; Deaton, 2007; Grasgruber et al., 2016). This is important for two reasons. First, population differences are thus likely to be a consequence of a combination of unmeasured environmental factors and genetic difference between populations (Baten and Blum, 2014; Grasgruber et al., 2014; Hruschka and Hadley, 2016; Steckel, 1983; Stulp and Barrett, 2016; Stulp et al., 2015). Second, by not taking such differences into account, scholars run the risk of misinterpreting certain phenotypic differences as representing socioeconomic and environmental disparities. To illustrate, if we had naively combined all populations into a single dataset and examined the relationship between wealth and height, we would have incorrectly discovered a puzzling result—a curvilinear relationship between wealth and height such that the poorest and richest are the tallest and the individuals in the middle are the shortest (Fig. 3). Without further critical analysis, this might lead to theorizing about the social and economic causes of such a puzzling relationship. But this is simply an artifact of combining one population that starts off taller but has far more poorer households (sub-Saharan Africa) with another population that starts off shorter and has far more wealthier households (South Asia). A less severe version of the same problem can arise at sub-regional levels. For example, Fig. 3b shows the relationship between height and wealth if we had combined Haiti—the poorest of the Latin American and Caribbean countries considered here with almost complete genetic affinity with sub-Saharan Africa—with other wealthier Latin American and Caribbean countries which also have much larger representation of indigenous and European genetic admixture. It is important to note that this same problem can also arise within countries when multiple populations simultaneously have different basal heights or BMIs and different access to resources. For example, in Uganda datasets considered here, Bantu-speaking populations have higher average economic status (n = 1357, mean household wealth per capita = 1965 USD) and smaller average stature (167.5 cm). Meanwhile, Luo-speaking populations in Uganda have lower average economic status (n = 625, mean household wealth per capita = 570 USD) and higher average stature (172.0 cm). As in the earlier examples, conflating these populations in an analysis of economic status and height would give the paradoxical (but false) impression that increased resources are associated with declining statures.

These examples illustrate the kinds of problems researchers can encounter when failing to take into account region-specific bounds on growth at multiple scales (Steckel, 1983). However, if these population differences are sufficiently systematic, it also suggests that future research might constructively identify population-sensitive adjustments that would permit meaningful comparison of anthropometrics across worldwide populations as a measure of standards of living (Hruschka and Hadley, 2016).

Many of the associations of environmental variables and adult height and BMI were consistent with prior theoretically and empirically derived expectations. Individuals with more wealth and education were on average taller and had higher BMIs, and in general individuals living in communities with higher levels of open defecation and diarrheal disease were on average shorter and had lower BMIs. However, there were a few surprising results which deserve further attention. First, among men, high community levels of open defecation and child diarrhea were associated with increased height. Exploratory analyses revealed that this is not unique to a single world region, and that the results are likely driven in part by between-country differences in both male height and these hygiene variables. The reasons for this unexpected finding are unclear. However, it may be worthwhile exploring sex-biased mortality among infants and children with shorter stature as well as differential migration of taller males to areas of reduced open defecation and diarrheal disease burden in young adulthood.

This study presents efforts to estimate a first approximation to the limits to environmentally-induced human growth across a wide range of socioeconomic environments. Future work will hopefully enrich these models with more information about other factors related to diet, subsistence, and physical activity at the individual and household level, most notably the ratio of high-quality to low-quality proteins and other variation in macronutrient and micronutrient balance (Baten and Blum, 2014; Deaton, 2007; Grasgruber et al., 2014, 2016; Moradi, 2010). Further investigation of how the relationships between these variables and growth vary by region should also refine these models. Moreover, combining multiple measures from diverse age groups would give additional opportunities to examine the points in the life course when we should see the strongest influence of environmental inputs on growth (Hackman and Hruschka, 2018). Another important focus for future research is how body dimensions change in tandem with increasing resources. For example, body mass index is a function of height, and if a population witnessed a height increase from 150 cm to 160 cm due

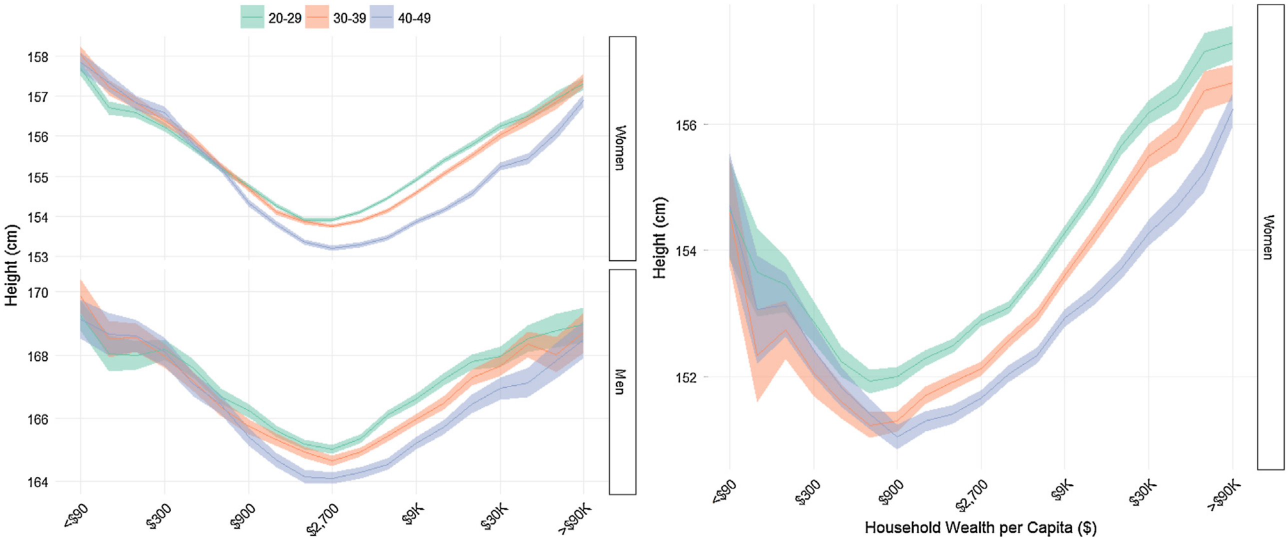

Fig. 3. Relationship between household wealth and height when: (A) combining all populations and not taking into account regional structure (women & men) and (B) combining Haiti with other Latin American and Caribbean countries (women).

to environmental changes, that would mean a roughly 12% decline in body mass index if weight remained the same. Thus, a better understanding of the pace and timing of environmentally-induced changes in different body dimensions should improve our understanding of how, for example, changes in height put constraints on changes in body mass index. Finally, we have considered the current range of environmental inputs, but as new technological innovations that can change human bodies—e.g., plastic surgery, physiology altering drugs, novel foods, genetic treatments—arise and proliferate, this may fundamentally alter the relationship between resources and the body form. Moreover, as the relationship between height and BMI and resources begins to flatten out in situations of extreme abundance, we may be able to start detecting other processes that link resources and body form, such as the influence of societal body ideals and selection of individuals with certain body forms into higher paying jobs and (Baten and Murray, 1998) wealthier households (Averett and Korenman, 1996; Hruschka, 2017).

The current analyses also necessarily rely on measurements of environmental inputs that are collected at a different time than the relevant window of sensitivity to environmental inputs. For example, the environment at age 25–34 y may not reflect the earlier environmental inputs relevant to final stature and the environment at 40–49 may not reflect the environment in earlier decades that contributed to later life BMI. Future work that examines linear growth in childhood when environmental measures are closer in time to the relevant developmental window may provide a way to triangulate these findings (Hackman and Hruschka, 2018). Similar analyses of BMI that examine in more detail the effects of current environmental conditions at BMI at different ages, should also improve our understanding of how the anthropometric effects of current and past environmental conditions accrue over time.

As noted in the introduction, the observed associations between body form and environmental variables might have arisen from a variety of both influence and selection processes. While this poses some problem for interpretation, the current estimates can in some cases place bounds on what kind of growth potential we might expect. For example, a growing literature on height premiums demonstrates that taller individuals are more likely to be selected into higher-paying jobs (Sohn, 2015a) and wealthier households through marriage (Sohn, 2015b). Such premiums will create a positive association between economic resources and height, which is in same direction as the correlation expected from the influence of economic resources on height. Thus, such premiums would generate an estimate of growth potential that is spuriously greater than the true growth potential. For this reason, the estimates for growth potential provided here would be an upper bound on the true growth potential. By contrast, documented premiums on BMI are often in the opposite direction, with thinner individuals selected into higher-paying jobs and wealthier households through marriage (Hruschka, 2017). In that case, the premiums would generate an estimate of growth potential that is spuriously lower than the true growth potential. Indeed, this may be why the sigmoid curve for female BMI reaches its upper bound at much lower levels of economic resources than curves for height or for male BMI. In such cases, it will be important to develop additional study designs that identify the expected slope relating economic resources and BMI from such selection mechanisms, and partial those slopes out.

The present analyses focus specifically on how population means in height and BMI are associated with wealth, environmental resources, and disease burden. However, in many developing countries, increases in mean BMI are also associated with increasing variance in BMI (Hruschka, 2012), which may be responsible for an increasing dual burden of disease with countries simultaneously suffering from undernutrition and overnutrition (Doak et al., 2005; Prentice, 2005; Wells, 2012). Future work that goes beyond means to analyze how entire distributions change (e.g. dispersion, skewness, kurtosis) would give additional information about how populations as a whole respond to changing resources.

More broadly, continued work on estimating and refining the limits to environmentally-induced changes in human growth should contribute to more meaningful comparisons of worldwide populations and more context-sensitive interpretations of body form as an indicator of socio-economic status. They would also permit stronger predictions of how tall or fat we expect specific populations to become at extremes of abundance. Such work should ideally consider human growth across the broadest possible range of human environments and also include a diversity of proxies for the kinds of environmental inputs that are expected to shape human growth at different points in the life course. Ideally, it will also integrate different measures of economic

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resources—e.g. asset-based wealth in low-income settings and wage income in high-income settings—to provide a seamless portrait of the effects of increasing environmental inputs across orders of magnitude in household resources (Kaiser et al., 2017). By building better models for environmental inputs on human growth, such efforts should provide a framework for interpreting variation in human body form as a window into social and economic processes in the past and present (Komlos, 1994; Komlos and Baten, 2004).

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ehb.2018.12.005.

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