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Diminishing benefits of urban living for growth and development of school-aged children and adolescents in the 21st century

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Science and Technology in childhood Obesity Policy

Title: Diminishing benefits of urban living for children and adolescents' health

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Optimal growth and development in childhood and adolescence is critical for lifelong health and wellbeing. We used 2,325 population-based studies, with measurement of height and weight in 71 million participants, to report height and body-mass index (BMI) of children and adolescents aged 5-19 years by rural and urban place of residence in 200 countries from 1990 to 2020. In 1990, children and adolescents in cities were taller than their rural counterparts in all but a few countries. By 2020, the urban height advantage became smaller in most countries, and in many high-income western countries reversed into a small urban disadvantage. The exception was for boys in most countries in sub-Saharan Africa, and in some countries in Oceania, south Asia, and the region of central Asia, Middle East and north Africa. In these countries, successive cohorts of rural boys either did not gain height or possibly even became shorter. The difference between age-standardised mean BMI of children in urban and rural areas was <1.1kg/m^2 in the vast majority of countries. Within this small range, BMI increased slightly more in cities than in rural areas, except in south Asia, sub-Saharan Africa, and some countries in central and eastern Europe. Our results show that in much of the world, the growth and developmental advantages of living in cities have diminished in the 21st century, whereas in much of sub-Saharan Africa they have amplified.

Throughout school ages (i.e., ages 5-19 years), children and adolescents' growth and development are influenced by their nutrition and environment at home, in the community and at school. Healthy growth and development at these ages helps consolidate gains and mitigate inadequacies from early childhood, and vice versa,[1] with lifelong implications for health and wellbeing[2-6]. Until recently, growth and development of older children and adolescents received substantially less attention than in early childhood and adulthood[7]. Increasing policy attention to health and nutrition during school years has been accompanied by a presumption that differences in nutrition and environment lead to distinct, and generally less healthy, patterns of growth and development in these ages in cities compared to their rural counterparts[8-17], even though some empirical studies have found that food quality and nutrition are better in cities[18,19].

Data on growth and developmental outcomes in school ages are needed, alongside data on efficacy of specific interventions and policies, to select and prioritise health- and health equity-promoting policies and programmes, both for the increasing urban population and for children who continue to grow up in rural areas. Consistent and comparable global data also help benchmark across countries and draw lessons on good practice. Yet, globally there are far fewer data on growth trajectories in rural and urban areas in these formative ages than for under-five children[20] or for adults[21]. The available studies have been in one country, at one point in time and/or in one sex and narrow age groups; the few studies that covered more than one country[22-24] mostly focused on older girls, and used at most a few dozen data sources and hence could not systematically measure long-term trends. Consequently, many policies and programmes that aim to enhance healthy growth and development in school ages focus narrowly, and somewhat generically, on specific features of nutrition or the environment in either cities or rural areas[10,13,25-28], with little attention to similarities and differences between relevant outcomes in these settings, nor to the heterogeneity of the urban-rural differences across countries.

Here, we report on mean height and body-mass index (BMI) of school-aged children and adolescents in rural and urban areas of 200 countries and territories from 1990 to 2020. Height and BMI are anthropometric measures of growth and development that are influenced by the quality of nutrition and healthiness of the living environment, and are highly predictive of health and wellbeing throughout life in observational and Mendelian randomization studies[2-6]. These studies have shown that having low height and excessively low BMI increases the risk of morbidity and mortality, and low height impairs cognitive development, and reduces educational performance and work productivity in later life[2-4]. Having high BMI in these ages increases the lifelong risk of overweight and obesity and several non-communicable diseases, and might contribute to poor educational outcomes[5,6].

We used 2,325 population-based studies that measured height and weight in 71 million participants in 194 countries (Extended Data Fig.1, Supplementary Table 2). We used these data in a Bayesian hierarchical meta-regression model to estimate mean height and BMI of children and adolescents aged 5-19 years by rural and urban place of residence, year and age for 200 countries and territories. Details of data sources and statistical methods are provided in Methods. Our results represent height and BMI for children and adolescents of the same age over time, i.e., successive cohorts, in each country's rural and urban areas, and the difference between the two. For presentation, we summarise the 15 age-specific estimates, for single years of age from 5 through 19, through age standardisation, which puts each country-year's child and adolescent population on the same age distribution, and allows comparisons to be made over time and across countries. We also show results, graphically and numerically, for index ages of 5, 10, 15 and 19 years in Extended Data and Supplementary Materials.

In 1990, school-aged boys and girls who lived in cities had a height advantage (i.e., were taller) compared to their rural counterparts, except in high-income countries where the urban height advantage was either negligible (<1 cm for age-standardised mean height; posterior probability (PP) for urban children being taller ranging from 0.51 to >0.99) or there was even a small rural advantage (e.g., Belgium, Netherlands, and the UK) (PP for rural children being taller ranging from 0.53 to >0.99 where there was a rural height advantage) (Fig. 1 and Extended Data Fig. 2). The largest height differences between cities and rural areas in 1990 occurred in some countries in Latin America (e.g., Mexico, Guatemala, Panama and Peru), east and southeast Asia (China, Indonesia and Vietnam), central and eastern Europe (Bulgaria, Hungary and Romania), and sub-Saharan Africa (DR Congo and Rwanda). The urban height advantage in boys and girls in the named countries ranged from 2.5-5.0 cm and the PP of urban children being taller than rural children was >0.99 (see Supplementary Table 3 for country-specific numerical values of height in rural and urban areas, their difference, and the corresponding credible intervals).

The urban-rural height gap in the late 20th century differed among low- and middle-income countries based on how much children and adolescents in cities and rural areas had approached versus fallen behind their peers in high-income countries, where there was little difference in rural and urban height. In countries such as Bulgaria, Hungary and Romania, urban children and adolescents' height approached that of high-income countries, whereas rural children and adolescents still lagged behind, leading to a relatively large gap. In much of sub-Saharan Africa and south Asia, the height of both urban and rural children and adolescents lagged behind their peers in high-income countries, such that the urban-rural gap was relatively small. In a third group of low- or middle-income countries that included Indonesia, Vietnam, Panama, Peru, DR Congo and Rwanda, urban children were still shorter than in high-income countries, while rural children lagged so far behind that the urban-rural gap became large.

By 2020, the urban height advantage in school ages became smaller in much of the world, and, in many high-income western countries and some central European countries it disappeared or reversed into a small (typically <1 cm) urban disadvantage (Fig. 1, Extended Data Fig. 2 and Extended Data Fig. 8). Countries with substantial convergence over these three decades were in central and eastern Europe (e.g., Croatia), Latin America and the Caribbean (e.g., Argentina, Brazil, Chile and Paraguay), east and southeast Asia (e.g., Taiwan), and for girls in central Asia (e.g., Kazakhstan and Uzbekistan). The urban height advantage in the named countries declined by ~1-2 cm from 1990 to 2020; the PP of urban-rural height difference having declined ≥0.90 for named countries). In many other middle-income countries (e.g., China, Romania and Vietnam), the urban-rural height gaps declined, but children and adolescents living in cities remained taller than their rural counterparts (by 1.7-2.5 cm in the named countries for boys and girls; PP of urban children being taller than rural children >0.99). The exception to this convergence was for boys in most countries in sub-Saharan Africa and some countries in Oceania, south Asia, and the region of central Asia, Middle East and north Africa, where the urban height advantage slightly increased over these three decades. The largest increase in the urban height advantage occurred in countries in east Africa such as Ethiopia (0.9 cm larger height gap in 2020 than 1990; 95% credible interval (CrI) -0.9 to 2.9 and PP of increase = 0.93), Rwanda (1.0, -0.7 to 3.0 and PP = 0.88), and Uganda (1.1, -0.6 to 3.1 and PP = 0.89). For girls, the urban-rural gap remained largely unchanged in many countries in sub-Saharan Africa and south Asia.

In middle-income and emerging economies (i.e., newly high-income and industrialised countries) where rural children and adolescents' height converged to those in cities, successive cohorts of rural children and adolescents outpaced their urban counterparts in becoming taller and attained what urban children in the same countries had done decades earlier: growing to heights closer to those seen in high-income countries (Fig. 2 and Fig. 3). Successive cohorts of rural children and adolescents in sub-Saharan Africa did not experience the accelerated height gain seen in rural areas of middle-income countries; and, in the case of boys, there was no gain, or possibly even a decrease, in height, which in turn led to a persistence or even widening of the urban-rural gap. As a result of these global trends, by 2020, the largest urban-rural height gaps were seen in Andean and central Latin America (e.g., Bolivia, Panama and Peru), by up to 4.7 (4.0-5.5) cm for boys and 3.81 (3.3-4.3) cm for girls, and, especially for boys, in sub-Saharan Africa (e.g., DR Congo, Ethiopia, Mozambique and Rwanda) by up to 4.2 (2.7-5.7) cm.

The urban-rural BMI difference was relatively small throughout these three decades: <1.4 kg/m^2 in all countries and years, and <1.1 kg/m^2 in all but nine countries, for age-standardised mean BMI (Fig. 4, Extended Data Fig. 3 and Extended Data Fig. 9). In 1990, the urban-rural BMI gap was largest in sub-Saharan Africa (e.g., Ethiopia, Kenya and Malawi, South Africa and Zimbabwe) and south Asia (e.g., Bangladesh and India), followed by parts of Latin America (e.g., Mexico and Peru); the urban-rural BMI gap in the two sexes in the named countries ranged from 0.4-1.2 kg/m^2 and the PP of urban children having higher BMI than rural children ≥0.89. At that time, girls and/or boys in rural areas of some of these countries had mean BMI levels that were close to, and in some ages even below, the thresholds of being underweight (i.e., >1SD below the median of the WHO reference population).

From 1990 to 2020, the BMI of successive cohorts of both urban and rural children and adolescents increased in all but a few high-income countries (e.g., Denmark, Italy and Spain) (Fig. 5 and Fig. 6). There was heterogeneity in low- and middle-income countries in how much BMI increased in cities versus rural areas. In the great majority of countries in sub-Saharan Africa and south Asia, BMI of successive cohorts of children and adolescents increased more in rural areas than in cities leading to a closing of the urban-rural difference; the reductions in the urban-rural BMI gap ranged from 0.1 to 0.65 kg/m^2 for both girls and boys, and the PP of urban-rural BMI difference declining from 1990 to 2020 ranged from 0.52 to 0.95. In both sub-Saharan Africa and south Asia, these changes shifted the mean BMI of rural boys and girls out of the range for being underweight; in many countries in sub-Saharan Africa this shift continued beyond the median of the WHO reference population, and in some cases approached the threshold for being overweight (i.e., >1SD above the median of the WHO reference population). The opposite, i.e., a larger rise in urban BMI happened in most other low-and middle-income countries, leading to a slightly larger urban BMI excess in 2020 than in 1990. High-income countries and those in central and eastern Europe experienced a mix of increasing and decreasing urban BMI excess but remained within a relatively small range (-0.3 to 0.6 kg/m^2 for almost all countries) over the entire period of analysis; at the regional level the urban-rural BMI difference changed by <0.25 kg/m^2 in these regions.

The urban height advantage was larger in boys than girls in most countries (Supplementary Figure 3). Urban excess BMI was higher in boys in only about one half of countries; in the other half, mostly in high-income western countries and those in sub-Saharan Africa, urban excess BMI was higher in girls. The urban height advantage was slightly larger at five years of age than at 19 years of age in most low- and middle-income countries, especially for girls, but there was little difference across ages in high-income regions and in central and eastern Europe (Supplementary Figure 4).

Since the introduction of modern sanitation in the 19th century, cities provided substantial nutritional and health advantages in high-income and subsequently low- and middle-income countries[19]. Our results show that, in the 21st century, during school ages these advantages have disappeared in high-income countries and diminished in middle-income countries and emerging economies in Asia, Latin America and the Caribbean, and parts of Middle East and north Africa. Specifically, in countries of these regions, successive cohorts of school-aged children and adolescents living in cities were outpaced by those in rural areas in terms of height gain but gained slightly more weight, typically in the unhealthy range (Fig. 7). This contrasted with the world's poorest region, sub-Saharan Africa, where the urban height advantage persisted or even expanded while rural mean BMI went beyond remedying underweight and surpassed the median of the WHO reference population in 2020, hence consolidating the urban advantage. South Asia had a mixed pattern of urban versus rural trends from 1990 to 2020, with children and adolescents in rural areas gaining both more height and more weight for their height than those in cities. Importantly, our results also show that differences in height and BMI between urban and rural populations within most countries are smaller than the differences across countries, even those in the same region.

We also found that the urban-rural BMI gap, although dynamic, changed much less than the BMI of either subgroup of the population, and less than commonly assumed when discussing the role of cities in the obesity epidemic[8,10,12,13,15,16]. Urban-rural BMI differences were especially small in high-income countries, consistent with the evidence from a few countries that diets and behaviours are affected more by household socioeconomic status than whether children and adolescents live in cities or rural areas[29,30]. Urban BMI excess increased slightly more in middle-income countries in east and southeast Asia, Latin America and the Caribbean, and Middle East and north Africa, a trend that was the opposite of the convergence in BMI of adults in these same regions[21]. Additional analysis of NCD-RisC data for young adults (20-29 and 30-39 years) showed that the shift from a small divergent trend to convergence of BMI between urban and rural areas happens in young adulthood (Extended Data Fig. 6 and Extended Data Fig. 7), a period during which there is substantial, but variable, weight gain among population subgroups[31]. These shifts in trends from adolescence to young adulthood might be a result of changes in diet and energy expenditure that accompany changes in household structure, social and economic roles and the living environment[32-34].

Long-term follow up studies have shown that children and adolescents do not achieve their height potential if they do not consume sufficient and diverse nutritious foods, or if they are exposed to repeated or persistent infections which result in loss of nutrients[2]. Studies with data on household socioeconomic and environmental variables have indicated that these physiological determinants of height are themselves affected by income, quality of the living environment, and access to healthcare in rural as well as urban areas[35]. This evidence indicates that the relatively small urban-rural height differentials in high-income countries may be because of a greater abundance of nutritious foods, including some fortified foods, better healthcare, and greater ability to finance programmes that promote healthy growth in countries with greater per-capita income and better infrastructure. Variations across these countries in the urban-rural height gap within this small range may be due to extent of socioeconomic inequalities and poverty, differences in the availability and cost of nutritious foods between cities and rural areas, and whether there are specific programmes (e.g., food assistance or school food programmes) that improve nutrition of disadvantaged groups[30,36,37]. The more striking changes in height in urban versus rural areas took place in middle-income countries and emerging economies. Case studies in some countries where the heights of rural and urban children and adolescents converged show that the convergence was partly due to using the growth in national income towards programmes and services that helped close gaps in nutrition, sanitation and healthcare between different areas and social groups[38-40]. In countries in central and eastern Europe, transition to a market economy and increases in trade may have reduced disparity in access to, and seasonality of, healthy foods between urban and rural areas[41], and partly underlie the convergence of height seen in our results. In contrast, country case studies show that where economic growth was accompanied by large inequalities in income, nutrition and/or services, the urban advantage persisted[42-44].

The notable exception in the global trends was sub-Saharan Africa, where a stagnation or reversal of height gain in rural areas led to persistence or widening of urban-rural height differences, while the opposite happened for BMI (Fig. 7). Case studies of specific countries have indicated that unfavourable trends in nutrition in rural Africa, where the majority of the world's poorest people live, started from macroeconomic shocks in the late 20th century, and the subsequent agriculture, trade and development policies that limited improvements in income and services in rural Africa, which increased urban-rural income inequality, and emphasised agricultural exports over local food security and diversity[45]. These macroeconomic factors in turn led to less diverse diets, with higher caloric intake rather than shifting to protein- and nutrient-rich foods (e.g., animal products, seafood, fruits and vegetables)[46-48], while the slow expansion of infrastructure and services in rural areas restricted improvements in other determinants of healthy growth such as clean water and sanitation and health care[49].

A number of other factors may also have had a secondary role in the observed trends in height and BMI and their difference in rural and urban areas: First, weight gain during childhood may reduce the age of puberty onset, which in turn may limit height gain during adolescence[50,51]. No comparable global data currently exist on age at menarche and timing of pubertal growth, even at the national level. Second, rural-to-urban migration and reclassification of previously rural areas to urban as they grow and industrialise may account for some the observed population-level trends, although migration tends to be less common in childhood and adolescence in most countries. Finally, improvements in under-five survival among rural children, particularly low birthweight children, may have influenced the height and weight of those who survive beyond five years of age in line with observed trends, noting however that current data on changes in child survival in rural and urban areas in sub-Saharan Africa are limited and inconclusive in terms of whether mortality declined faster in rural or urban areas[52,53].

As attention in global health turns to children and adolescents, there is a need to consider and evaluate how growth and development in these formative ages may be affected both by social and economic policies that influence household income and poverty and by programmes that affect nutrition, health services, and urban and rural infrastructure and living environments in rural and urban areas. The need to identify, implement and evaluate policies and programmes that improve growth and development outcomes is particularly relevant as the rise in poverty and the cost of food, especially of nutrient-rich foods, as a result of the COVID-19 pandemic and the war in Ukraine, may hinder futher gains or even set back in children and adolesxcents' healthy growth and development.

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Methods

We estimated trends in mean height and BMI for children aged 5-19 years from 1990 to 2020 by rural and urban place of residence for 200 countries and territories listed in Supplementary Table 1. We pooled, in a Bayesian meta-regression, repeated cross-sectional population-based data on height and BMI. Our results represent estimates of height and BMI for children and adolescents of the same age over time, i.e., for successive cohorts, in each country's rural and urban settings.

Data sources

We used a database on cardiometabolic risk factors collated by the Non-Communicable Disease Risk Factor Collaboration (NCD-RisC). Data were obtained from publicly available multi-country and national measurement surveys (e.g., Demographic and Health Surveys (DHS), WHO-STEPwise approach to Surveillance (STEPS) surveys, and those identified via the Inter-University Consortium for Political and Social Research, UK Data Service, and European Health Interview & Health Examination Surveys Database). With the help of World Health Organization (WHO) and its regional and country offices as well as World Heart Federation, we identified and accessed population-based survey data from national health and statistical agencies. We searched and reviewed published studies as detailed previously[54] and invited eligible studies to join NCD-RisC, as did we with data holders from earlier pooled analyses of cardiometabolic risk factors[55-58]. The NCD-RisC database is continuously updated through all the above routes and periodic requests to NCD-RisC members to suggest additional sources in their countries.

We carefully checked that each data source met our inclusion criteria, as listed below. Potential duplicate data sources were first identified by comparing studies from the same country and year, followed by checking with NCD-RisC members that had provided data about whether the sources from the same country and year were the same or distinct. If two sources were confirmed as duplicates, one was discarded. All NCD-RisC members were also periodically asked to review the list of sources from their country, to verify that the included data meet the inclusion criteria and are not duplicates.

For each data source, we recorded the study population, sampling approach, years of measurement, and measurement methods. Only data that were representative of the population were included. All data sources were assessed in terms of whether they covered the whole country, multiple subnational regions (i.e., one or more subnational regions/provinces/states, more than three cities or more than five rural communities), or one or a small number of communities (limited geographical scope not meeting above national or subnational criteria), and whether participants in rural, urban or both areas were included. As stated in the sections on statistical model, these study-level attributes were used in the Bayesian hierarchical model to estimate mean height and BMI by country, year, sex, age and place of residence using all available data while taking into account differences in the populations from which different studies had sampled. All submitted data were checked by at least two independent persons. Questions and clarifications were discussed with NCD-RisC members and resolved before data were incorporated in the database.

Anonymised individual data from the studies in the NCD-RisC database were reanalysed according to a common protocol. We calculated mean height and mean BMI, and the associated standard errors, by sex, single year of age from five to 19 years, and rural or urban place of residence. Additionally, for analysis of height, participants aged 20-30 years were included, assigned to their corresponding birth cohort, because mean height in these ages would be at least that when they were aged 19 years, given that the decline of height with age begins in the third and fourth decades of life[59]. All analyses incorporated sample weights and complex survey design, when applicable, in calculating summary statistics. For studies that had used simple random sampling, we calculated mean as average of all individuals within the group and their associated standard errors (standard deviation divided by the square root of sample size); for studies that had used multistage (stratified) sampling, we accounted for survey design features including clusters, strata and sample weights, to weight each observation by the inverse sampling probability and estimate standard error via Taylor series linearisation, as implemented in the R 'survey' package[60]. Computer code was provided to NCD-RisC members who requested assistance. For surveys without information on place of residence, we calculated age- and sex-stratified summary statistics for the entire sample, which represented the population-weighted sum of rural and urban means; data on the share of population in urban versus rural areas were from the United Nations Population Division[61].

Additionally, summary statistics for nationally representative data from sources that were identified but not accessed via the above routes were extracted from published reports. Data were also extracted for two STEPS surveys that were not publicly available. We also included data from a previous global-data pooling study[58], when not accessed through the above routes.

Data inclusion and exclusion

Data sources were included in the NCD-RisC height and weight database if:

- measured data on height and weight were available;
- study participants were five years of age and older;
- data were collected using a probabilistic sampling method with a defined sampling frame;
- data were from population samples at the national, subnational, or community level as defined above; and
- data were from the countries and territories listed in Supplementary Table 1.

We excluded all data sources that were solely based on self-reported weight and height without a measurement component because these data are subject to biases that vary by geography, time, age, sex and socioeconomic characteristics[62-64]. Due to these variations, approaches to correcting self-reported data may leave residual bias. We also excluded data sources on population subgroups whose anthropometric status may differ systematically from the general population, including:

- studies that had included or excluded people based on their health status or cardiovascular risk;
- studies whose participants were only ethnic minorities;
- specific educational, occupational, or socioeconomic subgroups, with the exception noted below;
- those recruited through health facilities, with the exception noted below; and
- females aged 15-19 years in surveys which sampled only ever-married women or measured height and weight only among mothers.

We used school-based data in countries and age-sex groups with school enrolment of 70% or higher. We used data whose sampling frame was health insurance schemes in countries where at least 80% of the population were insured. Finally, we used data collected through general practice and primary care systems in high-income and central European countries with universal insurance, because contact with the primary care systems tends to be as good as or better than response rates for population-based surveys.

We excluded <0.01% of all participants whose age was <18 years and whose data were not reported by single year of age because height and weight may have non-linear age associations in these ages, especially during growth spurts. We excluded BMI data for females who were pregnant at the time of measurement (<0.01% of all participants). We excluded <0.2% of all participants who had recorded height outside the range <60 cm or >180 cm for ages <10 years; <80 cm or >200 cm for ages 10-14 years; <100 cm or >250 cm for ages ≥15 years, recorded weight outside the range <5 kg or >90 kg for age <10 years; <8 kg or >150 kg for ages 10-14 years; <12 kg or >300 kg for ages ≥15 years, or recorded BMI outside the range <6 kg/m^2 or >40 kg/m^2 for ages < 10 years; <8 kg/m^2 or >60 kg/m^2 for ages 10-14 years; <10 kg/m^2 or >80 kg/m^2 for ages ≥15 years.

Conversion of BMI prevalence metrics to mean BMI

In 0.5% of our data points mostly extracted from published reports or from a previous pooling analysis[58], mean BMI was not reported, but data were available for the prevalence of one or more BMI categories, for example, BMI ≥30 kg/m^2. In order to use these data, we used previously validated conversion regressions[65] to estimate the missing primary outcome from the available BMI prevalence metric(s). Additional details on regression model specifications along with the regression coefficients are reported on https://github.com/NCD-RisC/ncdrisc-methods/.

Statistical model overview

We used a Bayesian hierarchical meta-regression model to estimate mean height and BMI by country, year, sex, age and place of residence using the aforementioned data. For presentation, we summarised the 15 age-specific estimates, for single years of age from 5 through 19, through age standardisation which puts each country-year's child and adolescent population on the same age distribution, and hence allows comparisons to be made over time and across countries. We generated age-standardised estimates by taking weighted means of age-specific estimates, using age weights from the WHO standard population[66]. We also show results, graphically and numerically, for index ages of 5, 10, 15 and 19 years in Extended Data and Supplementary Materials.

The statistical model is described in detail in statistical papers[67,68], related substantive papers[7,20,21,55-58,65,69] and in the section below on model specification. In summary, the model had a hierarchical structure in which estimates for each country and year were informed by its own data, if available, and by data from other years in the same country and from other countries, especially those in the same region and super-region, with data for similar time periods. The extent to which estimates for each country-year were influenced by data from other years and other countries depended on whether the country had data, the sample size of the data, whether they were national, and the within-country and within-region variability of the available data. For the purpose of hierarchical analysis, countries were organised into 21 regions, mostly based on geography and national income (Supplementary Table 1). Regions were in turn organised into nine super-regions.

We used observation year, i.e., the year in which data were collected, as the time-scale for the analysis of BMI and birth year as the time scale for the analysis of height, consistent with previous analyses[7,65,70]. Time trends were modelled through a combination of a linear term, to capture gradual long-term change, and a second-order random walk, which allows for non-linear trends[71], both modelled hierarchically The age associations of height and BMI were modelled, using cubic splines, to allow non-linear changes over age, including periods of rapid as well as slow rise. Periods of rapid rise represent adolescent growth spurts, which occur earlier in girls than boys[72-74], was reflected in placement of spline knots for boys and girls, respectively, as detailed in the section on model specification. Spline coefficients were allowed to vary across countries, based on their own data as well as in a hierarchical structure, as previously described[69].

The model also accounted for the possibility that height or BMI in subnational and community samples might differ systematically from nationally representative samples and have larger variation than in national studies. These features were accounted for through the inclusion of fixed-effect and random-effect terms for subnational and community data as detailed in the model specification section below. The fixed effects accounted for systematic differences between subnational or community studies and national studies. The inclusion of random effects allowed national data to have greater influence on the estimates than subnational or community data with similar sample sizes, because the subnational and community data have additional variance from the random effect terms. Both were estimated empirically as a part of model fitting.

Following the approach of previous papers[20,21,67], the model included parameters representing the urban-rural height or BMI difference, which is empirically estimated and allowed to vary by country, year, and age. We further expanded the model to allow urban-rural difference in height or BMI to vary by age, as height or weight with age may vary between rural versus urban children. If data for a country-year-age group contained mixed urban and rural children, but were not stratified by place of residence (21% of all data sources), the estimated BMI difference was informed by stratified data from other age groups, years and countries, especially those in the same region with data from similar time periods and/or ages.

Statistical model specification

As stated earlier, for each data source, we calculated mean height and BMI, together with corresponding standard errors, stratified by sex, age and rural or urban place of residence. For sources that did not stratify the sample on the place of residence, we obtained age-and-sex-stratified data. Each study contributed up to 30 mean BMI data points or 32 mean height data points for each sex with the exact number depending how many age groups were represented in the study, and whether or not the study provided data stratified on urban and rural place of residence. The likelihood for an observation at urbanicity level *s* (urban-only, rural-only or mixed;

referred to as stratum hereinafter) and age group h, with age *z*, from study *i*, carried out in country *j* at time *t* is:

$$y_{s,h,i} \sim N\left(a_{j[i]} + b_{j[i]}t_i + u_{j[i],t_i} + \gamma_i(z_h) + \boldsymbol{X_i\beta} + e_i + I_{s,i}\left[p_{j[i]} + q_{j[i]}t_i + r_{j[i]}z_h + d_i\right], SD^2_{s,h,i}/n_{s,h,i} + \tau_i^2\right)$$

where the country-specific intercept and linear time slope from the *j*th country (*j* = 1 … *J*, where *J* = 200 which is the total number of countries in our analysis) are denoted a_j and b_j, respectively. We describe the hierarchical model used for the a's and b's in *Linear components of country time trends* section. Letting *T* = 31 be the total number of years from 1990 to 2020, the *T*-vector u_j captures smooth non-linear change over time in country *j*, as described in *Non-linear change* section. The age effects of the *h*th age group (with age z) in study i are denoted by γ_i; we describe the age model in *Age model* section. The matrix $\boldsymbol{X}$ contains terms describing whether studies were representative at the national, sub-national or community level. In addition, a random effect, e_i, is estimated for each study, described in *Study-level term and study-specific random effects* section.

Linear components of country time trends

The model had a hierarchical structure: studies were nested in countries, which were nested in regions (indexed by *k*), which were nested in super-regions (indexed by *l*), which were, of course, all nested in the globe (see Supplementary Table 1 for list of countries in each region, and regions in each super-region). This structure allowed the model to share information across units to a greater degree when data were non-existent or weakly informative (e.g., have a small sample size or were not nationally representative), and to a lesser extent in data-rich countries and regions[75].

The a and b terms are country-specific linear intercepts and time slopes with terms at each level of the hierarchy, denoted by the superscripts $c, r, s,$ and g, respectively:

$$a_j = a_j^c + a_{k[j]}^r + a_{l[k]}^s + a^g$$

$$b_j = b_j^c + b_{k[j]}^r + b_{l[k]}^s + b^g$$

$$a_j^x \sim N(0, \kappa_a^x)$$

$$b_j^x \sim N(0, \kappa_b^x) \text{ (where } x = \{c, r, s\}\text{)}$$

The κ terms are each assigned a flat prior on the standard deviation scale[76]. We also assigned flat priors to a^g and b^g.

Non-linear change

Mean BMI or height may change non-linearly over time[7,54,58,65,70]. We captured smooth non-linear change in time in urban and rural strata of country *j* using the vector u_j. Just as a_j and b_j are each defined as the sum of country, region, super-region, and global components, we defined:

$$u_j = u_j^c + u_{k[j]}^r + u_{l[k]}^s + u^g$$

In order to allow the model to differentiate between the degrees of non-linearity that exist at the country, region, super-region, and global levels, we assigned each of the u's four components a Gaussian autoregressive prior as in Breslow and Clayton[77] and Rue and Held[71]. In particular, the T-vectors u_j^c (*j* = 1 … *J*), u_k^r (*k* = 1 … *K*), u_l^s (*l* = 1 … *L*), and u^g each have a normal prior with mean zero and precision $\lambda_c P$, $\lambda_r P$, $\lambda_s P$, and $\lambda_g P$ respectively, where the scaled precision matrix P in the Gaussian autoregressive prior penalizes first and second differences:

$$
\begin{aligned}
P &= \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ -2 & 1 & 0 & \cdots & 0 \\ 1 & -2 & 1 & \cdots & 0 \\ 0 & 1 & -2 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix}
\begin{bmatrix} 1 & -2 & 1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & -2 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & -2 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \\
&= \begin{bmatrix} 1 & -2 & 1 & 0 & 0 & \cdots & 0 \\ -2 & 5 & -4 & 1 & 0 & \cdots & 0 \\ 1 & -4 & 6 & -4 & 1 & \cdots & 0 \\ 0 & 1 & -4 & 6 & -4 & \cdots & 0 \\ 0 & 0 & 1 & -4 & 6 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & \cdots & 1 \end{bmatrix}.
\end{aligned}
$$

P is multiplied by the estimated precision parameters λ_c, λ_r, λ_s, and λ_g, thus up-weighting or down-weighting the strength of its penalties and ultimately determining the degree of smoothing at each level. For each of the four precision parameters, we used a truncated flat prior on the standard deviation scale $(1/\sqrt{\lambda})$ as recommended by Gelman[76]. We truncated these priors such that $\log \lambda \leq 20$ for each of the four λ's. This upper bound is enforced as a computational convenience: models with $\log\lambda > 20$ are treated as equivalent to a model with $\log\lambda = 20$ as they essentially have no extra-linear variability in time. In practice, this upper bound had little effect on the parameter estimates. Furthermore, we order the λ's a priori: $\lambda_c < \lambda_r < \lambda_s < \lambda_g$. This prior constraint conveys the natural expectation that, for example, the global BMI trend has less extra-linear variability than the trend of any given region.

The matrix P has rank $T - 2$, corresponding to a flat, improper prior on the mean and the slope of the u_j^c's, the u_k^r's, the u_l^s's and of u^g, and is not invertible[78] Thus, we have a proper prior in a reduced-dimension space as discussed in Rue and Held[71], with the prior expressed as:

$$P\left(u_j^c \middle| \lambda_c\right) \propto \lambda_c^{\frac{T-2}{2}} \exp\left\{-\frac{\lambda_c}{2} u_j^{c\prime} P u_j^c\right\}$$

Note that if u_j^c had a non-zero mean, this would introduce non-identifiability with respect to a_j^c. By the same token, b_j^c would not be identified if u_j had a non-zero time slope, and similarly for the other means and slopes. Thus, in order to achieve identifiability of the a's, b's, and u's, we constrained the mean and slope of u^g and of each u^s, u^r, and u^c to be zero. Enforcing orthogonality between the linear and non-linear portions of the time trends means that each can be interpreted independently.

In cases where we have observations for at least two different time points, this improper prior will not lead to an improper posterior since the data will provide information about the mean and slope. However, to enforce the desired orthogonality between the linear and non-linear portions of the model, we constrained the mean and slope of the u_j^c's, u_k^r's, u_l^s's, and of u^g to be zero, using the approach described by Rue and Held[71].

For the six countries with no height data, and seven countries with no BMI data, we took the Moore-Penrose pseudoinverse of P[79], setting to infinity those eigenvalues that correspond to the non-identifiability. This effectively constrains the non-identified portions of the model to zero, as the corresponding variances are set to zero[77]; in this case the Rue and Held correction[71] is not needed. An intermediate case occurs when data are observed for only one time point in a country. In this case, the full conditional precision has rank $T-1$ because the mean but not the linear trend of u_j^c is identified by the data. We thus constrained the linear trend of u_j^c to zero by taking the generalised inverse of the full conditional precision. We then constrained the mean of u_j^c to zero using the one-dimensional version of the correction described in Rue and Held[71].

Age model

To capture sex-specific patterns of growth, especially adolescent growth spurts, we modelled age using cubic splines. The number and position of splines' knots were selected based on a combination of physiological and statistical considerations, as described in a national level analysis[7]. For age group *h* with age *z,* in study *i*, the age effect for height and BMI is given, respectively, by:

$$\gamma_i(z_h) = \gamma_{1i} z_h + \gamma_{2i} z_h^2 + \gamma_{3i} z_h^3 + \gamma_{4i}(z_h - k_1)_+^3 + \gamma_{5i}(z_h - k_2)_+^3 + \gamma_{6i}(z_h - k_3)_+^3 + \gamma_{7i}(z_h - k_4)_+^3 \qquad \text{(height)}$$

$$\gamma_i(z_h) = \gamma_{1i} z_h + \gamma_{2i} z_h^2 + \gamma_{3i} z_h^3 + \gamma_{4i}(z_h - k_1)_+^3 + \gamma_{5i}(z_h - k_2)_+^3 \qquad \text{(BMI)}$$

For height, four spline knots were placed at ages $\{k_1, k_2, k_3, k_4\} = \{8, 10, 12, 14\}$ for girls and at ages $\{k_1, k_2, k_3, k_4\} = \{10, 12, 14, 16\}$ for boys. For BMI, we used two spline knots (at ages 10 and 15 years) because, at the population level, changes in BMI with age are smoother than those in height[7,72,73]. Each of the spline coefficients was allowed to vary across countries, with a hierarchical structure as described in a previous paper[69], using the equation below, where ψ is the global intercent and c, r, s are the country, region and super-region random intercepts, respectively, The age effect coefficients ($\gamma_{k,i}$) for each age group *h*, with age *z*, are given by:

$$\gamma_{k,i} = \psi_k + c_{k,j[i]} + r_{k,l[i]} + s_{k,m[i]}$$

$$c_{k,j} \sim N(0, \sigma_{k,c}^2)$$

$$r_{k,l} \sim N(0, \sigma_{k,r}^2)$$

$$s_{k,l} \sim N(0, \sigma_{k,s}^2)$$

A flat improper prior was placed of each of the σ_k's.

Study-level term and study-specific random effects

Mean height or BMI from individual studies may deviate from the true country-year mean due to factors associated with sampling, response or measurement. We used a study-level term to help account for potential systematic differences associated with data sources that are representative of sub-national and community populations. Our model thus included time-varying offsets (referred to as fixed effects above) for sub-national and community data in the term $\boldsymbol{X_i\beta}$:

$$\boldsymbol{X_i\beta} = \beta_1 I\left\{X_{j[i],t[i]}^{cvrg} = \text{subnational}\right\} + \beta_2 I\left\{X_{j[i],t[i]}^{cvrg} = \text{subnational}\right\} t_i +$$

$$\beta_3 I\left\{X_{j[i],t[i]}^{cvrg} = \text{community}\right\} + \beta_4 I\left\{X_{j[i],t[i]}^{cvrg} = \text{community}\right\} t_i$$

where $X_{j[i],t[i]}^{cvrg}$ is the indicator for whether the coverage of study *i*, in country *j* and year *t*, is sub-national or community.

Even after accounting for sampling variability, national studies may still not reflect the country's true mean BMI level with perfect accuracy, and sub-national and community studies have even larger variability. In study *i*, the study-specific random effect e_i allows all age groups from the same study to have an unusually high or an unusually low mean after conditioning on the other terms in the model. Each e_i is assigned a normal prior with variance depending on whether study *i* is representative at the national, sub-national or community level. Random effects from national studies were constrained to have smaller variance (v_n) than random effects of sub-national studies (v_s), which were in turn constrained to have smaller variance than community studies (v_c). To make country-level predictions, we set e_i = 0, thus not including random effects due to imperfections in study design and to within-country variability of BMI means.

Urban and rural strata

To model mean height and BMI by urban and rural places of residence, the model included offsets for the two strata. The offsets were captured by country-specific intercept, linear time and age effects, using a centred indicator term ($I_{s,i}$):

$$I_{s,i}[p_{j[i]} + q_{j[i]}t_i + r_{j[i]}z_h + d_i] \quad \text{(where, } I_{s,i} = -1 + 2X_{s,i}^{urb}\text{)}$$

with

$$X_{s,i}^{urb} = \begin{cases} 1, & \text{if stratum } s \text{ contains only urban individuals} \\ 0, & \text{if stratum } s \text{ contains only rural individuals} \\ X_{j[i],t[i]}^{urb} & \text{if stratum s contains a mixture of urban and rural individuals} \end{cases}$$

In other words, for data not stratified by place of residence, the model treats the unstratified mean height or BMI as equivalent to the weighted sum of the (unobserved) urban sample mean BMI and rural sample mean BMI, with the weights based on the proportion of the study country's population living in urban areas in the year of the survey ($X_{j[i],t[i]}^{urb}$).

The intercept (p) and slope (q) terms capture the country-to-country variation in the magnitude of the height or BMI difference between urban and rural populations and how the difference changes over time. The slope (r) captures the country-to-country variation in the BMI or height difference between urban and rural populations across age groups. These were specified with the same geographical hierarchy as the country-specific intercepts (a) and slopes (b):

$$p_j = p_j^c + p_{k[j]}^r + p_{l[k]}^s + p^g,$$

$$q_j = q_j^c + q_{k[j]}^r + q_{l[k]}^s + q^g,$$

$$r = r_j^c + r_{k[j]}^r + r_{l[k]}^s + r^g,$$

$$p_j^x \sim N(0, \kappa_p^x),$$

$$q_j^x \sim N(0, \kappa_q^x),$$

$$r_j^x \sim N(0, \kappa_r^x) \qquad (\text{where}, x = \{c, r, s\})$$

The study random effect term d_i incorporates deviations from the country-level urban-rural difference in each study and is analogous to e_i.

Residual age-by-study variability

The age patterns across communities within a given country may differ from their country's overall age pattern. This within-study variability cannot be captured by the e's, which are equal across age-specific observations in each study, so we include an additional variance component for each study, τ_i^2. We again assume that there is less residual variability in national studies than in sub-national and community-level studies, with $\tau_n^2 < \tau_s^2 < \tau_c^2$.

Model implementation

All analyses were done separately by sex because age, geographical and temporal patterns of height and BMI differ between girls and boys[7,65]. We fitted the statistical model using Markov chain Monte Carlo (MCMC). We started 35 parallel MCMC from randomly-generated over-dispersed starting values. For computational efficiency, each chain was run for a total of 75,000 iterations. All chains converged to the same target distribution within this number, but with the over-dispersed initial values, the length of burn-in required to converge to the target distribution varied. After the runs were completed, we used trace plots to monitor convergence and select chains that had completed burn-in within 35,000 iterations. This resulted in 16 chains for boys and 17 for girls for BMI, and 14 chains for boys and 16 for girls for height. Within each chain, post-burn-in iterations were thinned by keeping every 10th iteration, which were then combined for all chains and further thinned to a final set of 5,000 draws of the model parameter estimates. We used the posterior distribution of the model parameters to obtain the posterior distributions of our outcomes: mean urban and rural height and BMI, and the urban-rural difference in mean height and BMI. Posterior estimates were made for by one-year age groups from five to 19 years, as well as for age-standardised outcomes, by year. The reported credible intervals represent the 2.5th and the 97.5th percentiles of the posterior distributions. We also report the posterior standard deviation of estimates, and posterior probability that the estimated change in height or BMI in rural or urban areas, and in the estimated urban-rural height or BMI difference over time, represents a true increase or decrease.

Convergence was confirmed for the country-sex specific posterior outcomes – namely mean urban height and BMI, mean rural height and BMI and the urban-rural difference in mean height and BMI – for reporting ages (5, 10, 15, 19 years and age-standardised) and years (1990 and 2020) using the R-hat diagnostic[80,81]. For height, the 2.5th to 97.5th percentiles of the R-hats for the reporting ages and years were 0.999-1.010 for girls and 0.999-1.004 for boys. For BMI, the 2.5th to 97.5th percentiles of the R-hats were 0.999-1.004 for girls and 0.999-1.005 for boys.

We applied the pool-adjacent-violators algorithm, a monotonic regression that uses an iterative algorithm based on least squares to fit a free-form line to a sequence of observations such that the fitted line is non-decreasing[82,83], on the posterior height estimates to ensure that each birth cohort's height increased monotonically with age. In practice, this had little effect on the results, with height at age 19 years adjusted by an average 0.26 cm or less for both boys and girls. All analyses were conducting using the statistical software R (version 4.1.2)[84].

Strengths and limitations

An important strength of our study is its novel scope of presenting consistent and comparable estimates of urban and rural height and BMI among school-aged children and adolescents, which is essential to formulate and evaluate policies that aim to improve health in these formative ages. We used an unprecedented amount of population-based data from 194 countries and territories covering ~99% of the world's population. We maintained a high level of data quality and representativeness through repeated checks of study characteristics against our inclusion and exclusion criteria, and did not use any self-reported data to avoid bias in height and weight. Data were analysed according to a consistent protocol, and the characteristics and quality of data from each country were rigorously verified through repeated checks by NCD-RisC members. We used a statistical model that used all available data and took into account the epidemiological features of height and BMI by using non-linear time trends and age associations. The model used the available information on the urban-rural difference in height and BMI and estimated the age- and time-varying urban-rural difference for all countries hierarchically.

Despite our extensive efforts to identify and access data, some countries and regions had fewer data, especially those in the Caribbean and Polynesia, Micronesia, and sub-Saharan Africa. Of the studies used, fewer than half had data for children aged 5-9 years compared with nearly 90% with data for children and adolescents aged 10-19 years, which increases the uncertainty of findings. The scarcity of data is reflected in the larger uncertainty of our estimates for these countries and regions, and younger age groups. This reflects the need to systematically include school-aged children in both health and nutrition surveys, and especially in countries where school enrolment is high, to use schools as a platform for monitoring growth and developmental outcomes for entire national populations and key subgroups such as those in rural and urban areas. Though urban and rural classifications are commonly based on national statistical offices definitions, classification of cities and rural areas may, appropriately, vary by country due to their demographic characteristics (e.g., population size or density), economic activity, administrative structures, infrastructure and environment. Similarly, urbanisation takes place through a variety of mechanisms such as changes in fertility in rural and urban areas, migration, and reclassification of previously rural areas to urban as they grow and industrialise. Each of these mechanisms may have different implications for nutrition and physical activity, and hence height and/or BMI, and should be a subject of studies that follow individual participants and changes in their place of residence. Finally, there is variation in growth and development of children within rural or urban areas, based on household socioeconomic status and community characteristics that affect access to and the quality of nutrition, the living environment and healthcare[35,85,86]. Among these, in some cities, a large number of families live in slums[19,87]. School-aged children and adolescents living in slums have nutrition, environment and healthcare access that is typically worse than other residents of the city, although often better than those in rural areas[19,87-90].

Data availability

Estimates of mean BMI and height by country, year, sex, single year of age as well as age-standardised, and place of residence (urban and rural) will be available from www.ncdrisc.org in machine-readable numerical format and as visualisations upon publication of the paper. Input data from publicly available sources can also be downloaded from www.ncdrisc.org and Zenodo (https://doi.org/10.5281/zenodo.7355602) upon publication of the paper. For other data sources, contact information for data providers can be obtained from www.ncdrisc.org and Zenodo (https://doi.org/10.5281/zenodo.7355602).

Code availability

The computer code for the Bayesian hierarchical model as well as code to generate tables and figures used in this work will be available at www.ncdrisc.org and Zenodo (https://doi.org/10.5281/zenodo.7355602) upon publication of the paper.

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Supplementary information

This file contains Supplementary Tables 1-4, Supplementary Figures 1-8 and Supplementary References.

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Author contributions

AM, BZ, ARM, HB and RS led the data collection and management. AM, BZ, ARM, HB, CJP, JEB and ME developed the statistical method. AM, BZ, ARM and HB coded the statistical method. AM conducted analyses and prepared results. Pooled Analysis and Writing Group contributed to study design, collated data and checked data sources in consultation with the Country and Regional Data Group. Country and Regional Data Group collected and reanalysed data and checked pooled data. ME, AM, BZ, ARM and HB wrote the first draft of the report. Other authors commented on the draft report.

Declaration of interests

ME reports a charitable grant from the AstraZeneca Young Health Programme. The authors alone are responsible for the views expressed in this Article and they do not necessarily represent the views, decisions, or policies of the institutions with which they are affiliated.

Additional Information

Supplementary Information is available for this paper.

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NCD Risk Factor Collaboration (NCD-RisC)

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Fig. 1. Change in the urban-rural height difference from 1990 to 2020.

Change in urban-rural difference in age-standardised mean height in relation to change in age-standardised mean rural height.

Each solid arrow in lighter shade shows one country, beginning in 1990 and ending in 2020. The dashed arrows in darker shade show the regional averages, calculated as the unweighted arithmetic mean of the values for all countries in each region along the horizontal and vertical axes. For urban-rural difference, a positive number shows higher urban mean height and a negative number shows higher rural mean height.

See Extended Data Fig. 2 for urban-rural differences in age-standardised mean height, and their change over time shown as maps, together with uncertainties in the estimates. See Supplementary Figure 4A for results at ages 5, 10, 15 and 19 years.

We did not estimate the difference between rural and urban height for areas classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or entirely rural (Tokelau)

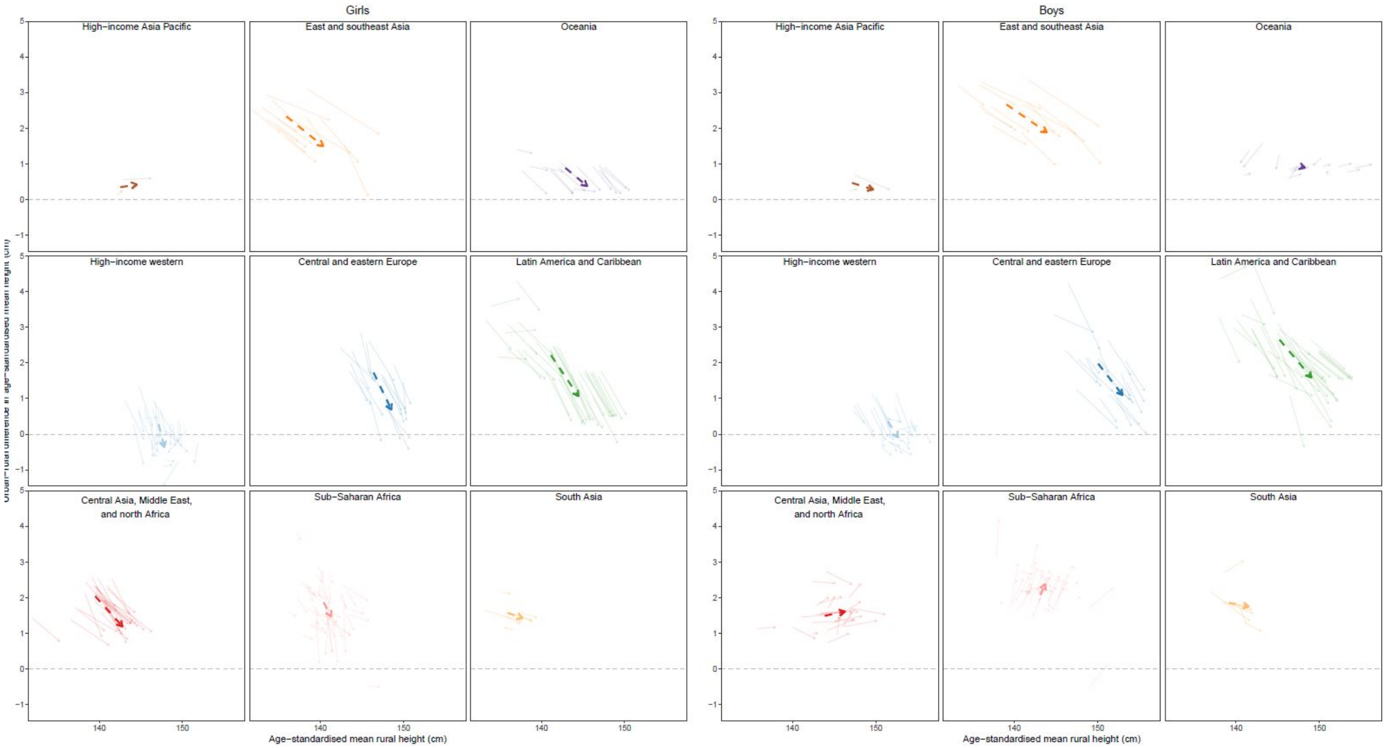


Fig. 2. Urban and rural height in 2020 and change from 1990 to 2020 for girls.

(A) The maps show age-standardised mean height in 2020 by urban and rural place of residence for girls. The density plots show the distribution of estimates across countries. (B) The maps show age-standardised change in mean height from 1990 to 2020, by urban and rural place of residence for girls. The density plots show the distribution of estimates across countries. (C) The scatter plots show the change from 1990 to 2020 in mean height in relation to the uncertainty of the change measured by posterior standard deviation. Each point in the scatter plots shows one country. Shaded areas show the posterior probability (PP) of an estimated change being a true increase or decrease. The PP of a decrease is one minus that of an increase. If an increase in mean height is statistically indistinguishable from a decrease, the PP of an increase and a decrease is 0.50. PPs closer to 0.50 indicate more uncertainty, those towards 1 indicate more certainty of change. (D) The circular plots show the age-standardised mean height in 2020 for all countries. The height of each column is the posterior mean estimate shown together with its 95% credible interval. Countries are ordered by region and super-region.

See Extended Data Fig. 4 for a map of PPs of the estimated change. See Supplementary Figure 5 for results at ages 5, 10, 15 and 19 years. See Supplementary Table 3 for numerical results, including credible intervals, as age-standardised and at ages 5, 10, 15 and 19 years.

We did not estimate mean rural height in areas classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore), mean urban height in areas classified as entirely rural (Tokelau), or their change over time in these areas, as indicated by grey colour.

Countries are labelled using their International Organization for Standardization (ISO) codes. Afghanistan, AFG; Albania, ALB; Algeria, DZA; American Samoa, ASM; Andorra, AND; Angola, AGO; Antigua and Barbuda, ATG; Argentina, ARG; Armenia, ARM; Australia, AUS; Austria, AUT; Azerbaijan, AZE; Bahamas, BHS; Bahrain, BHR; Bangladesh, BGD; Barbados, BRB; Belarus, BLR; Belgium, BEL; Belize, BLZ; Benin, BEN; Bermuda, BMU; Bhutan, BTN; Bolivia, BOL; Bosnia and Herzegovina, BIH; Botswana, BWA; Brazil, BRA; Brunei Darussalam, BRN; Bulgaria, BGR; Burkina Faso, BFA; Burundi, BDI; Cabo Verde, CPV; Cambodia, KHM; Cameroon, CMR; Canada, CAN; Central African Republic, CAF; Chad, TCD; Chile, CHL; China, CHN; Colombia, COL; Comoros, COM; Congo, COG; Cook Islands, COK; Costa Rica, CRI; Cote d'Ivoire, CIV; Croatia, HRV; Cuba, CUB; Cyprus, CYP; Czechia, CZE; Denmark, DNK; Djibouti, DJI; Dominica, DMA; Dominican Republic, DOM; DR Congo, COD; Ecuador, ECU; Egypt, EGY; El Salvador, SLV; Equatorial Guinea, GNQ; Eritrea, ERI; Estonia, EST; Eswatini, SWZ; Ethiopia, ETH; Fiji, FJI; Finland, FIN; France, FRA; French Polynesia, PYF; Gabon, GAB; Gambia, GMB; Georgia, GEO; Germany, DEU; Ghana, GHA; Greece, GRC; Greenland, GRL; Grenada, GRD; Guatemala, GTM; Guinea Bissau, GNB; Guinea, GIN; Guyana, GUY; Haiti, HTI; Honduras, HND; Hungary, HUN; Iceland, ISL; India, IND; Indonesia, IDN; Iran, IRN; Iraq, IRQ; Ireland, IRL; Israel, ISR; Italy, ITA; Jamaica, JAM; Japan, JPN; Jordan, JOR; Kazakhstan, KAZ; Kenya, KEN; Kiribati, KIR; Kuwait, KWT; Kyrgyzstan, KGZ; Lao PDR, LAO; Latvia, LVA; Lebanon, LBN; Lesotho, LSO; Liberia, LBR; Libya, LBY; Lithuania, LTU; Luxembourg, LUX; Madagascar, MDG; Malawi, MWI; Malaysia, MYS; Maldives, MDV; Mali, MLI; Malta, MLT; Marshall Islands, MHL; Mauritania, MRT; Mauritius, MUS; Mexico, MEX; Micronesia (Federated States of), FSM; Moldova, MDA; Mongolia, MNG; Montenegro, MNE; Morocco, MAR; Mozambique, MOZ; Myanmar, MMR; Namibia, NAM; Nauru, NRU; Nepal, NPL; Netherlands, NLD; New Zealand, NZL; Nicaragua, NIC; Niger, NER; Nigeria, NGA; Niue, NIU; North Korea, PRK; North Macedonia, MKD; Norway, NOR; Occupied Palestinian Territory, PSE; Oman, OMN; Pakistan, PAK; Palau, PLW; Panama, PAN; Papua New Guinea, PNG; Paraguay, PRY; Peru, PER; Philippines, PHL; Poland, POL; Portugal, PRT; Puerto Rico, PRI; Qatar, QAT; Romania, ROU; Russian Federation, RUS; Rwanda, RWA; Saint Kitts and Nevis, KNA; Saint Lucia, LCA; Samoa, WSM; Sao Tome and Principe, STP; Saudi Arabia, SAU; Senegal, SEN; Serbia, SRB; Seychelles, SYC; Sierra Leone, SLE; Singapore, SGP; Slovakia, SVK; Slovenia, SVN; Solomon Islands, SLB; Somalia, SOM; South Africa, ZAF; South Korea, KOR; South Sudan, SSD; Spain, ESP; Sri Lanka, LKA; Saint Vincent and the Grenadines, VCT; Sudan, SDN; Suriname, SUR; Sweden, SWE; Switzerland, CHE; Syrian Arab Republic, SYR; Taiwan, TWN; Tajikistan, TJK; Tanzania, TZA; Thailand, THA; Timor-Leste, TLS; Togo, TGO; Tokelau, TKL; Tonga, TON; Trinidad and Tobago, TTO; Tunisia, TUN; Turkey, TUR; Turkmenistan, TKM; Tuvalu, TUV; Uganda, UGA; Ukraine, UKR; United Arab Emirates, ARE; United Kingdom, GBR; United States of America, USA; Uruguay, URY; Uzbekistan, UZB; Vanuatu, VUT; Venezuela, VEN; Viet Nam, VNM; Yemen, YEM; Zambia, ZMB.

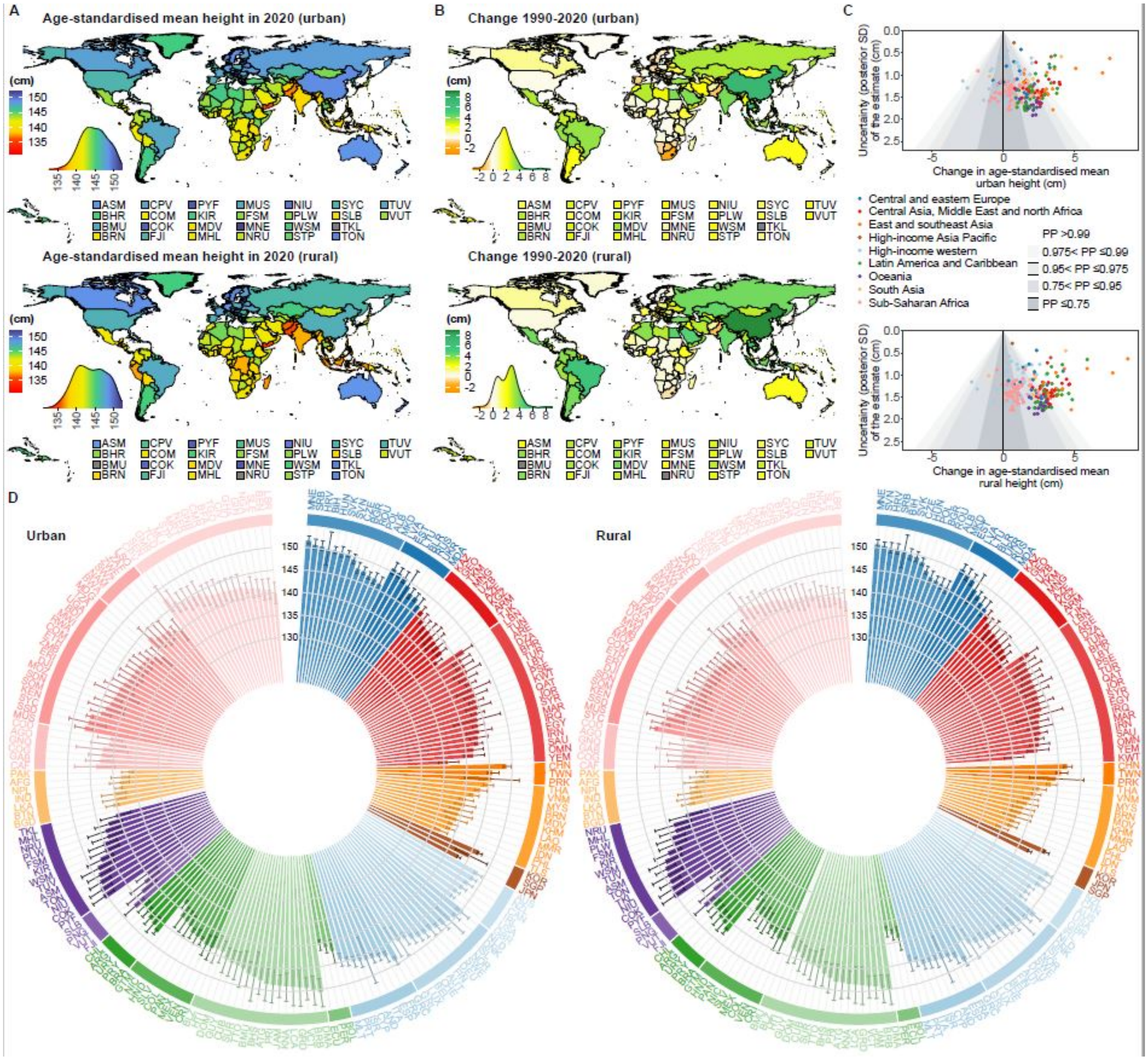


Fig. 3. Urban and rural height in 2020 and change from 1990 to 2020 for boys.

See Fig. 2 caption for descriptions of the contents of the figure and for definitions.

We did not estimate mean rural height in areas classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore), mean urban height in areas classified as entirely rural (Tokelau), or their change over time in these areas, as indicated by grey colour.

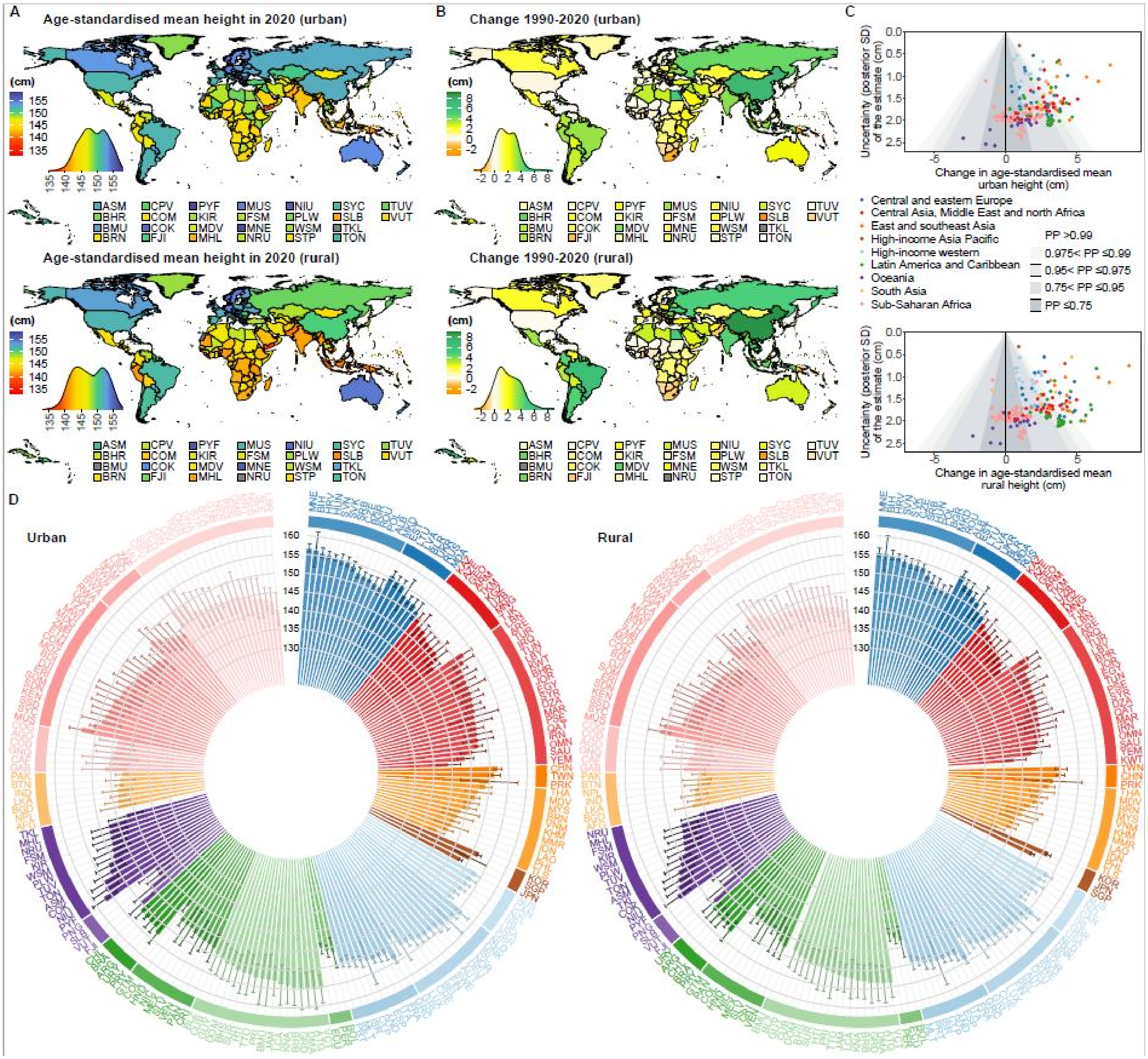


Fig. 4. Change in the urban-rural body-mass-index (BMI) difference from 1990 to 2020.

Change in urban-rural difference in age-standardised mean BMI in relation to change in age-standardised mean rural BMI. See Fig. 1 caption for description of figure contents.

See Extended Data Fig. 3 for urban-rural differences in age-standardised mean BMI, and their change over time shown as maps, together with uncertainties in the estimates. See Supplementary Figure 4B for results at ages 5, 10, 15 and 19 years.

We did not estimate the difference between rural and urban BMI for areas classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or entirely rural (Tokelau).

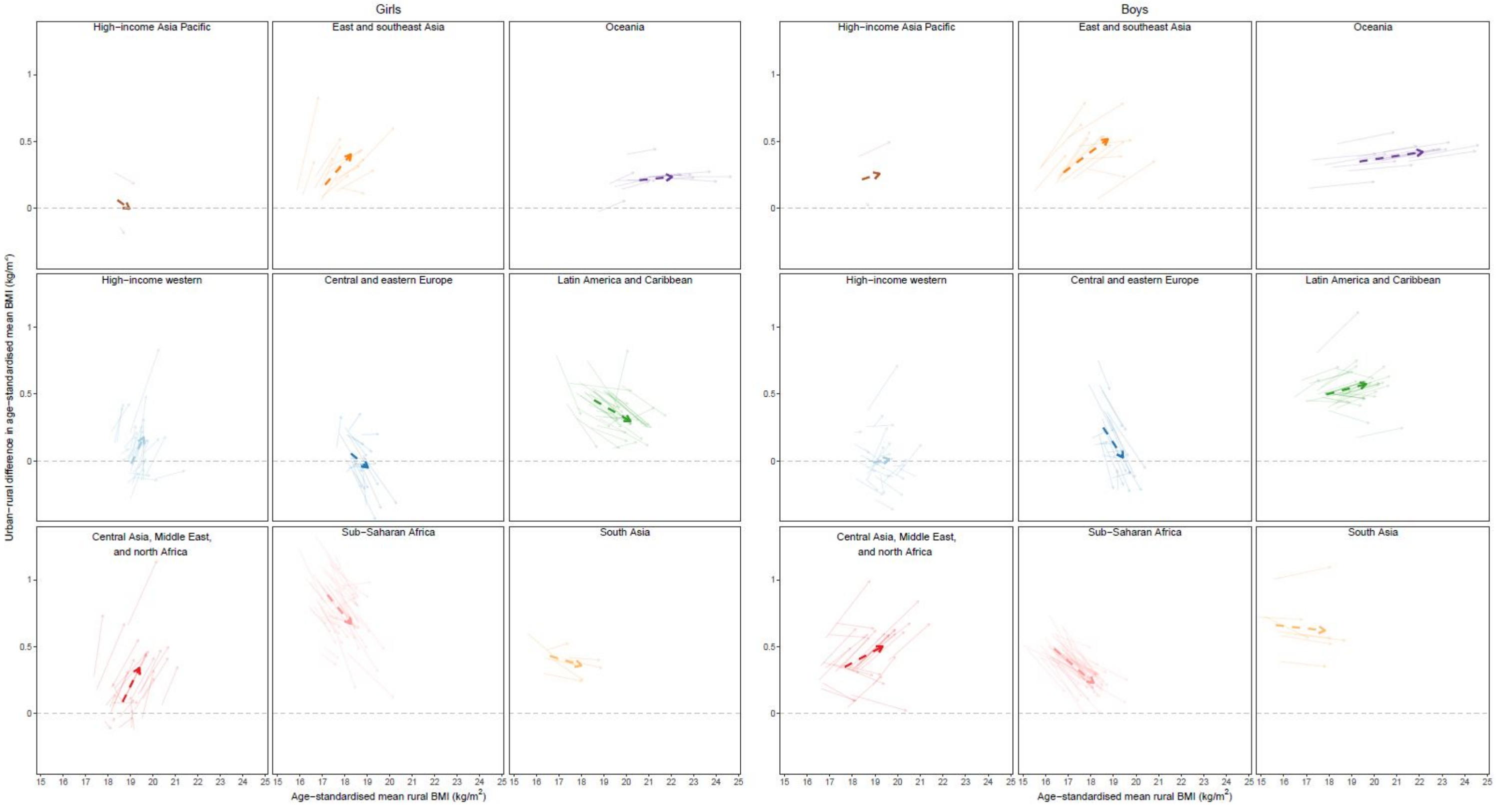


Fig. 5. Urban and rural body-mass index (BMI) in 2020 and change from 1990 to 2020 for girls.

See Fig. 2 caption for descriptions of the contents of the figure and for definitions.

See Extended Data Fig. 5 for a map of posterior probabilities of the estimated change. See Supplementary Figure 6 for results at ages 5, 10, 15 and 19 years. See Supplementary Table 4 for numerical results, including credible intervals, as age-standardised and at ages 5, 10, 15 and 19 years.

We did not estimate mean rural BMI in areas classified as entirely urban (Singapore, Bermuda and Nauru), mean urban BMI in areas classified as entirely rural (Tokelau), or their change over time, as indicated by grey colour.

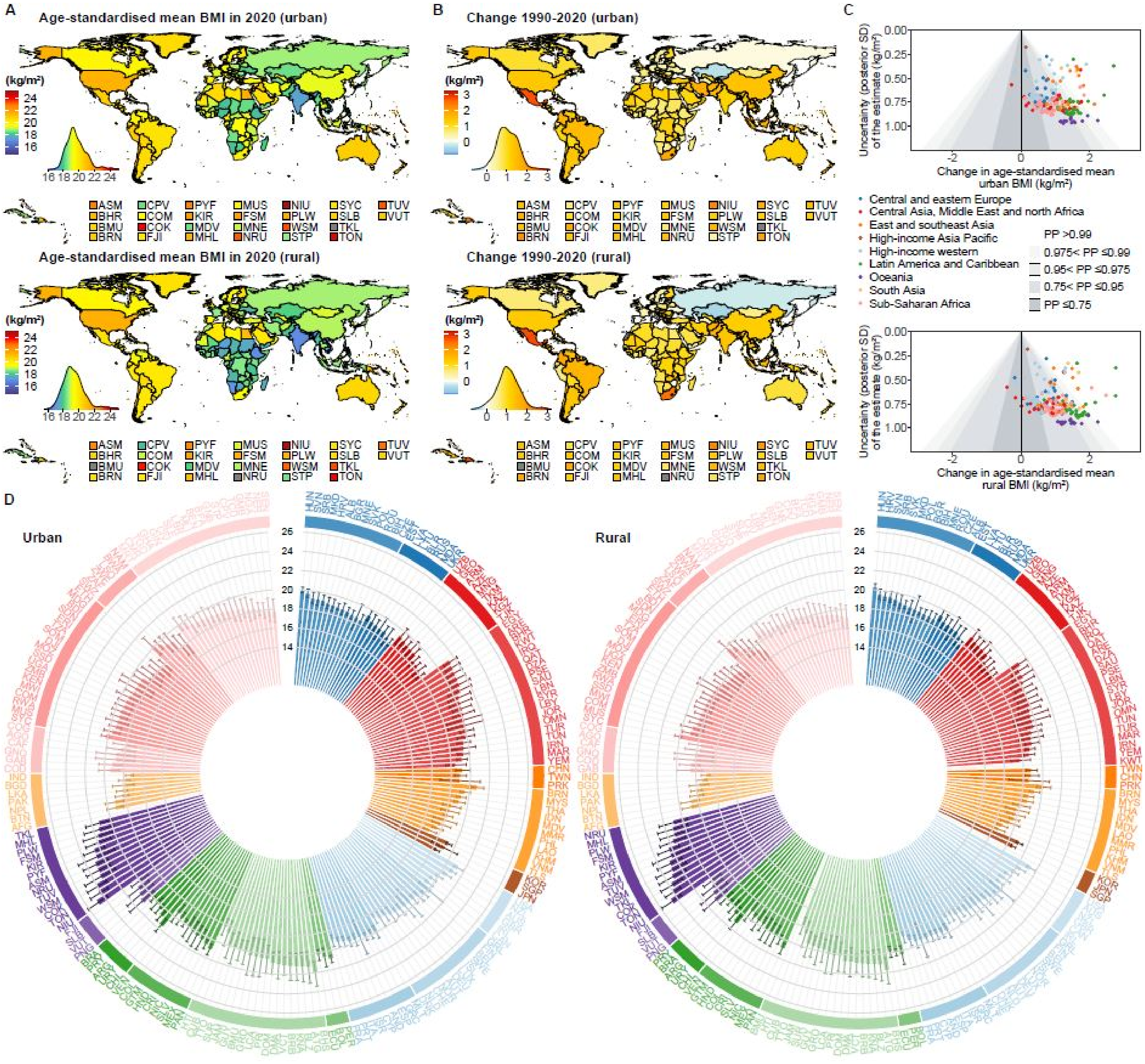

A
Age-standardised mean BMI in 2020 (urban)
(kg/m²)
24
22
20
18
16
16 18 20 22 24
ASM BHR BMU BRN CPV COM COK FJI PYF KIR MDV MHL MUS FSM MNE NRU NIU PLW WSM STP SYC SLB TKL TON TUV VUT
Age-standardised mean BMI in 2020 (rural)
B
Change 1990-2020 (urban)
(kg/m²)
3
2
1
0
0 1 2 3
Change 1990-2020 (rural)
C
Uncertainty (posterior SD) of the estimate (kg/m²)
0.00
0.25
0.50
0.75
1.00
-2
0
2
Change in age-standardised mean urban BMI (kg/m²)
Change in age-standardised mean rural BMI (kg/m²)
Central and eastern Europe
Central Asia, Middle East and north Africa
East and southeast Asia
High-income Asia Pacific
High-income western
Latin America and Caribbean
Oceania
South Asia
Sub-Saharan Africa
PP >0.99
0.975< PP ≤0.99
0.95< PP ≤0.975
0.75< PP ≤0.95
PP ≤0.75
D
Urban
Rural
26
24
22
20
18
16
14

Fig. 6. Urban and rural body-mass index (BMI) in 2020 and change from 1990 to 2020 for boys.

See Fig. 2 caption for descriptions of the contents of the figure and for definitions.

We did not estimate mean rural BMI in areas classified as entirely urban (Singapore, Bermuda and Nauru), mean urban BMI in areas classified as entirely rural (Tokelau), or their change over time, as indicated by grey colour.

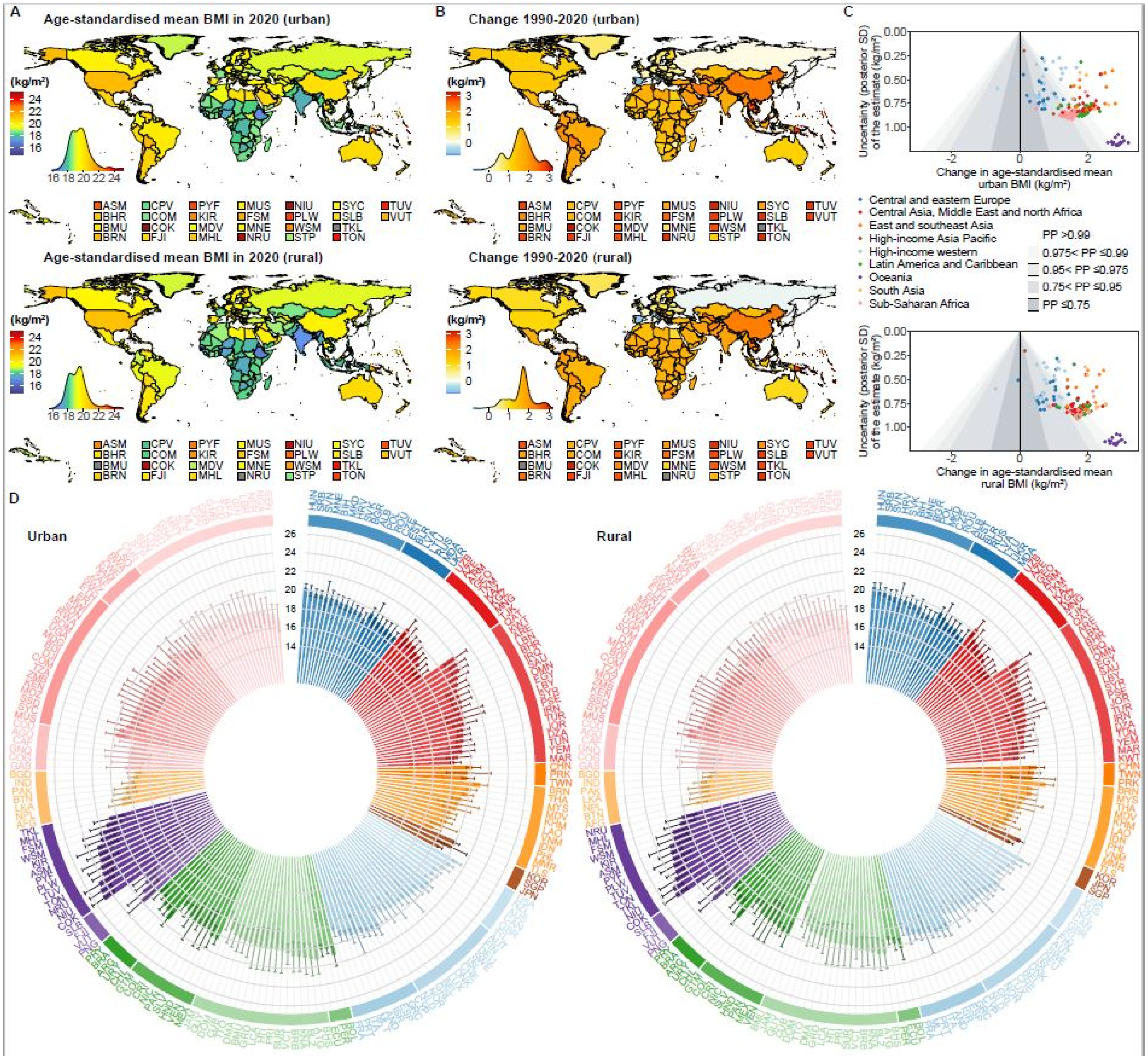
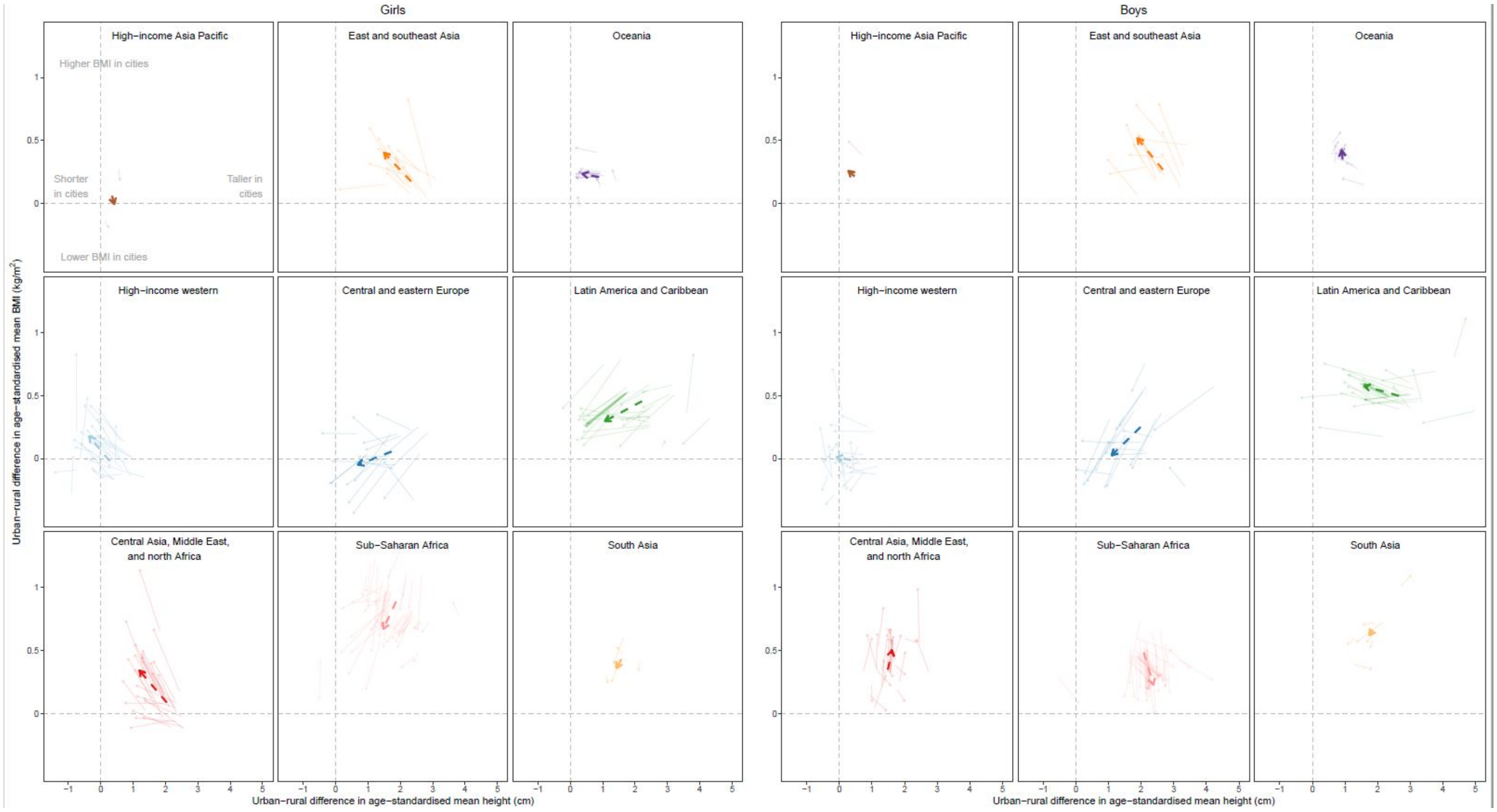


Fig. 7. Change in the urban-rural height and body-mass-index (BMI) difference from 1990 to 2020.

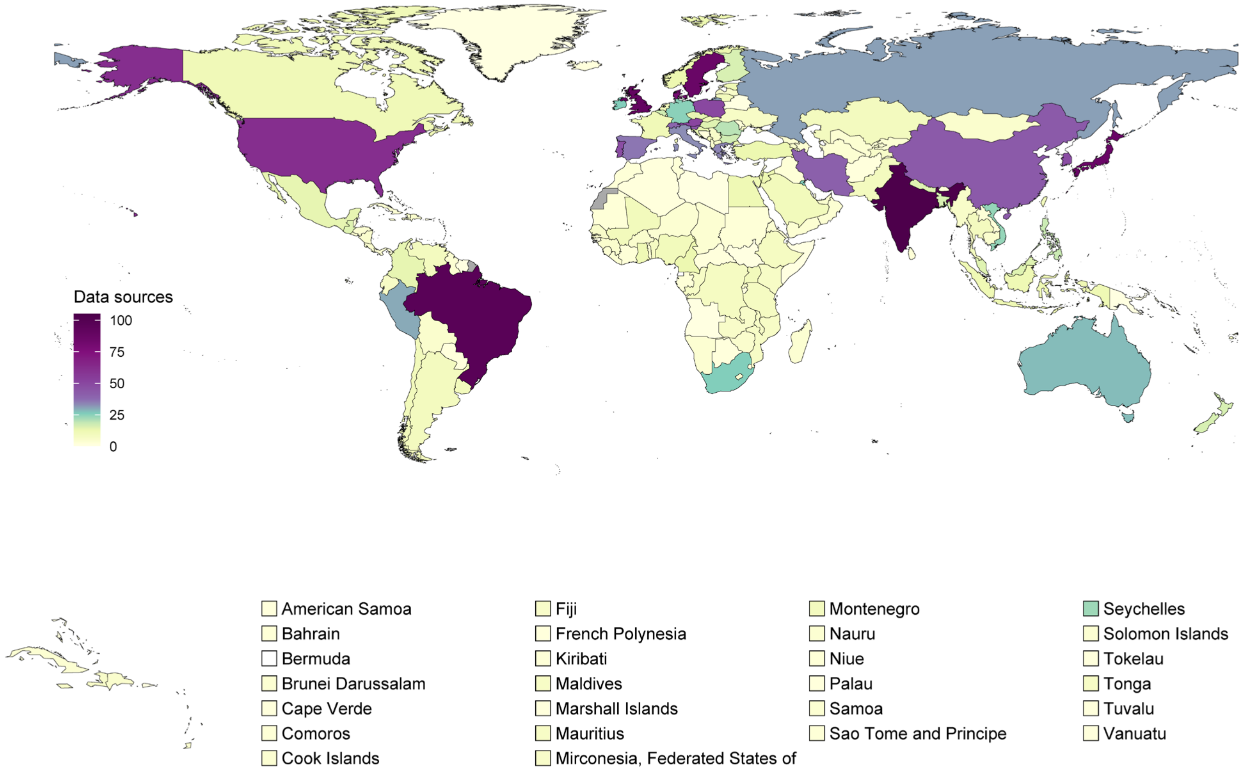
Change in urban-rural difference in age-standardised mean height and urban-rural difference in age-standardised mean BMI. See Fig. 1 caption for description figure contents.

See Supplementary Figure 4C for results at ages 5, 10, 15 and 19 years.

We did not estimate the difference between rural and urban height and BMI for areas classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or entirely rural (Tokelau).



Extended Data Fig. 1. Number of data sources used in the analysis, by country.



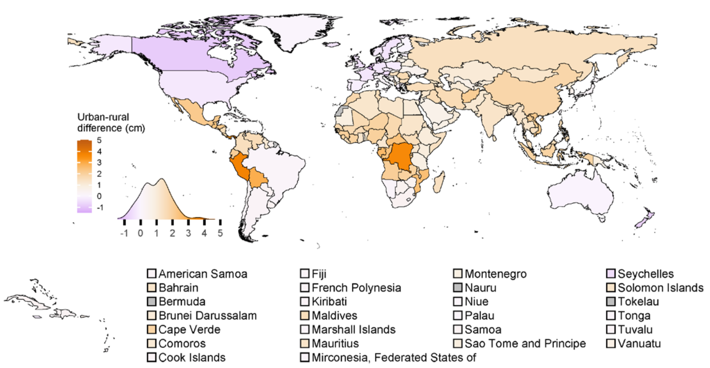
Extended Data Fig. 2. Urban-rural height difference in 2020 and change from 1990 to 2020.

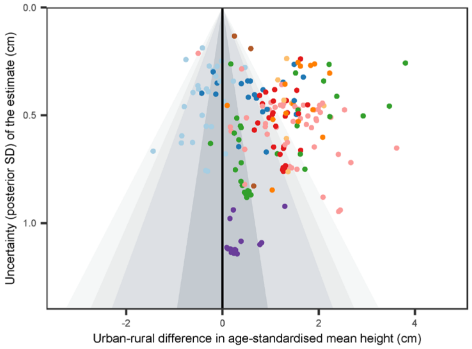
The top two maps show the urban-rural difference in age-standardised mean height in 2020 for girls and boys resepectively. A positive number shows higher urban mean height and a negative number shows higher rural mean height. The bottom two maps show the change from 1990 to 2020. The density plot below each map shows the distribution of estimates across countries. The top two scatter plots show the urban-rural difference in age-standardised mean height in relation to the uncertainty of the change measured by posterior standard deviation. The bottom two scatter plots in each panel show the change from 1990 to 2020 in urban-rural difference in mean height in relation to the uncertainty of the change measured by posterior standard deviation. Each point in the scatter plots shows one country. Shaded areas show the posterior probability (PP) of a true difference (top two scatter plots) and of a true increase or decrease in difference (bottom two scatter plots).

See Extended Data Fig. 8 for PPs of the urban-rural difference in age-standardised mean height and its change. See Supplementary Figure 7 for results at ages 5, 10, 15 and 19 years.

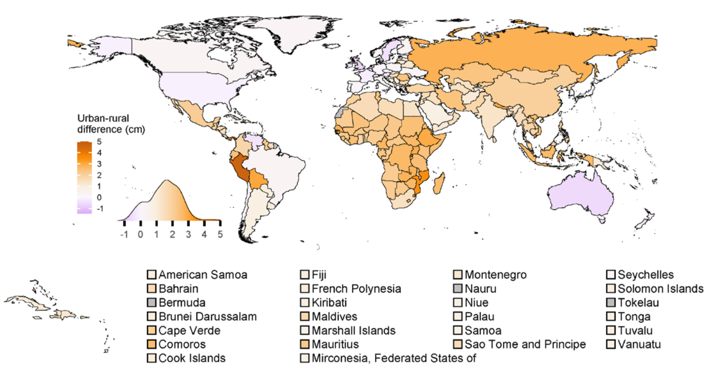
We did not estimate the difference between rural and urban height for areas classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or entirely rural (Tokelau), as indicated by grey colour.

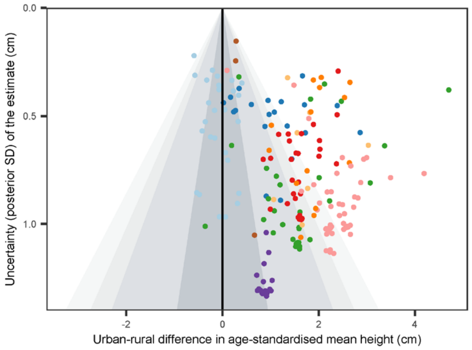
Urban-rural difference in 2020 (girls)



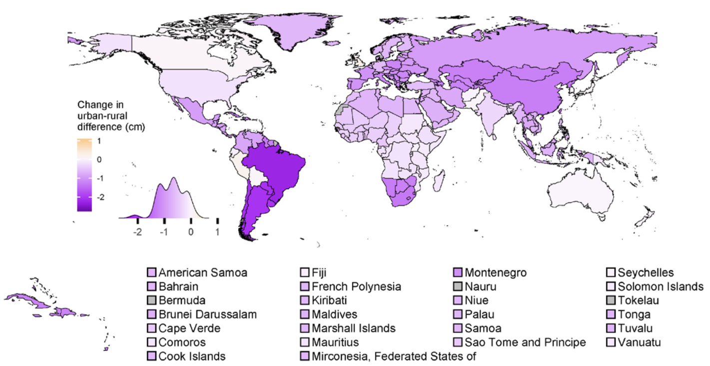


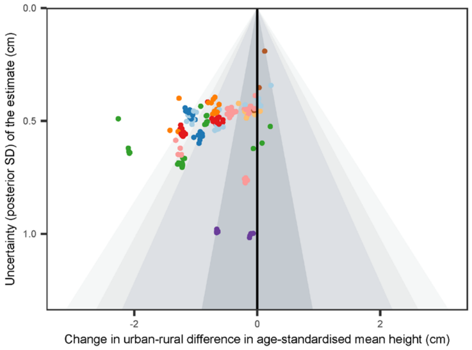
Urban-rural difference in 2020 (boys)



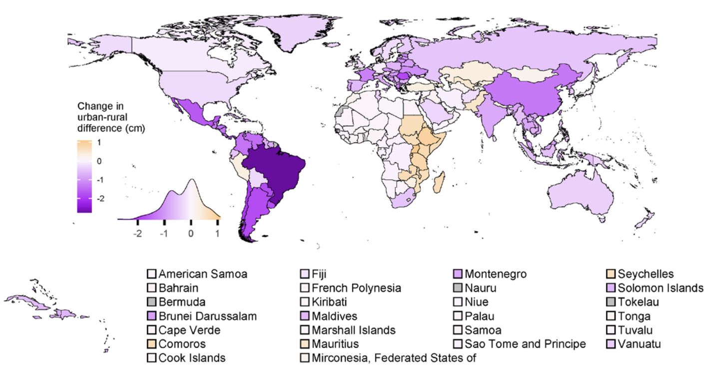


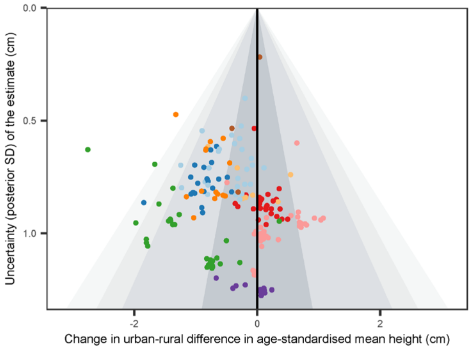
Change 1990-2020 (girls)





Change 1990-2020 (boys)





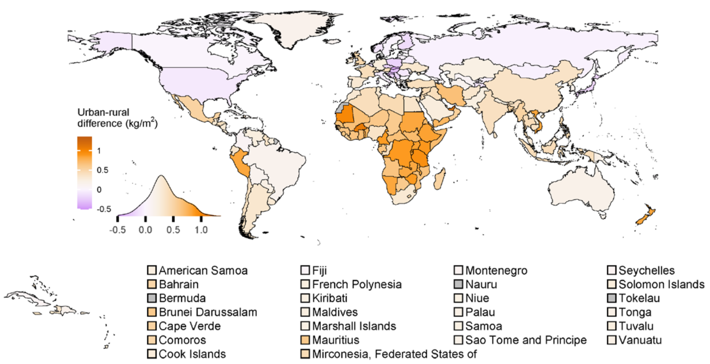
Extended Data Fig. 3. Urban-rural body-mass index (BMI) difference in 2020 and change from 1990 to 2020.

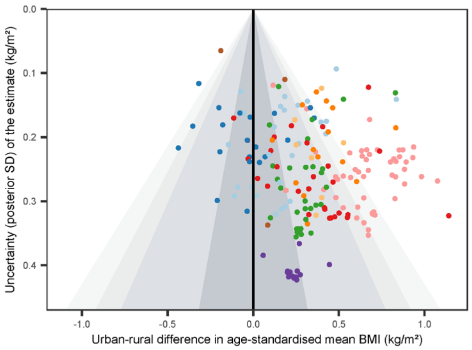
See Extended Data Fig. 2 caption for descriptions of the contents of the figure and for definitions.

See Extended Data Fig. 9 for posterior probabilities of the urban-rural difference in age-standardised mean BMI and its change. See Supplementary Figure 8 for results at ages 5, 10, 15 and 19 years.

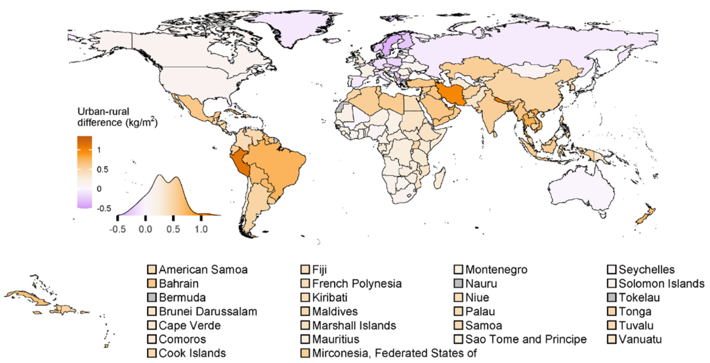
We did not estimate the difference between rural and urban BMI for areas classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or entirely rural (Tokelau), as indicated by grey colour.

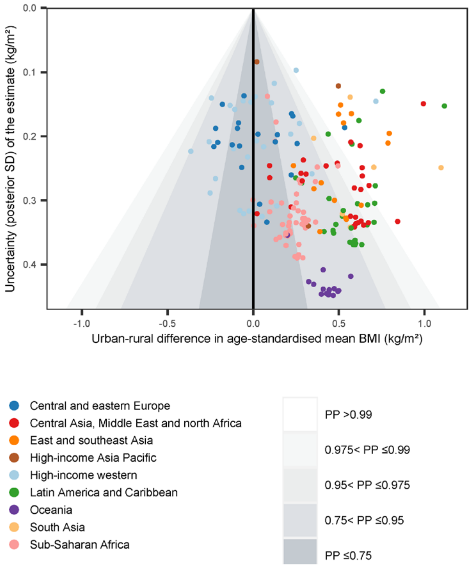
Urban-rural difference in 2020 (girls)



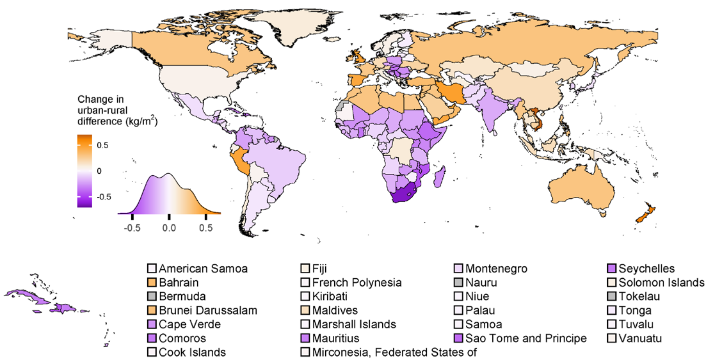


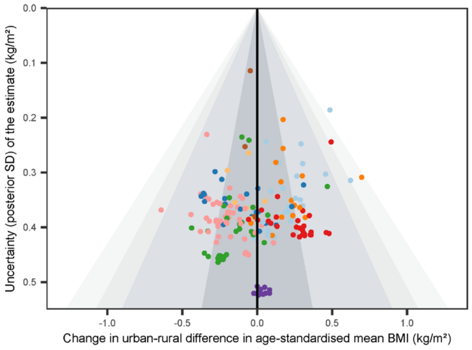
Urban-rural difference in 2020 (boys)



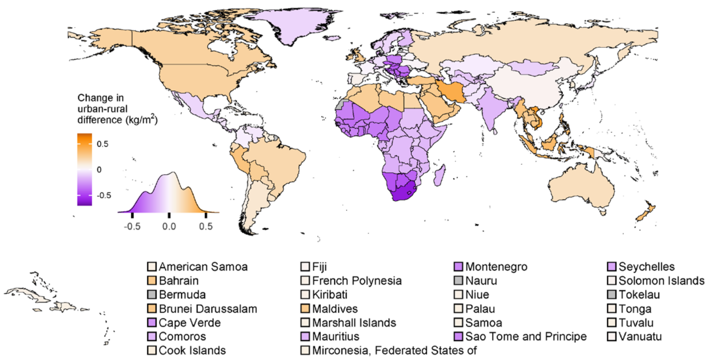


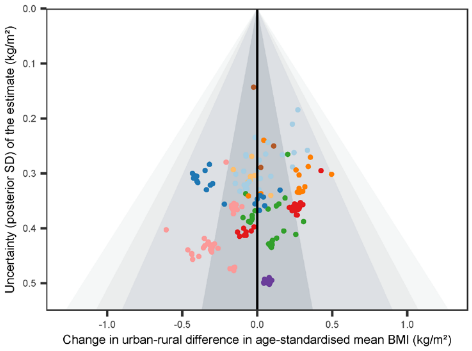
Change 1990-2020 (girls)





Change 1990-2020 (boys)



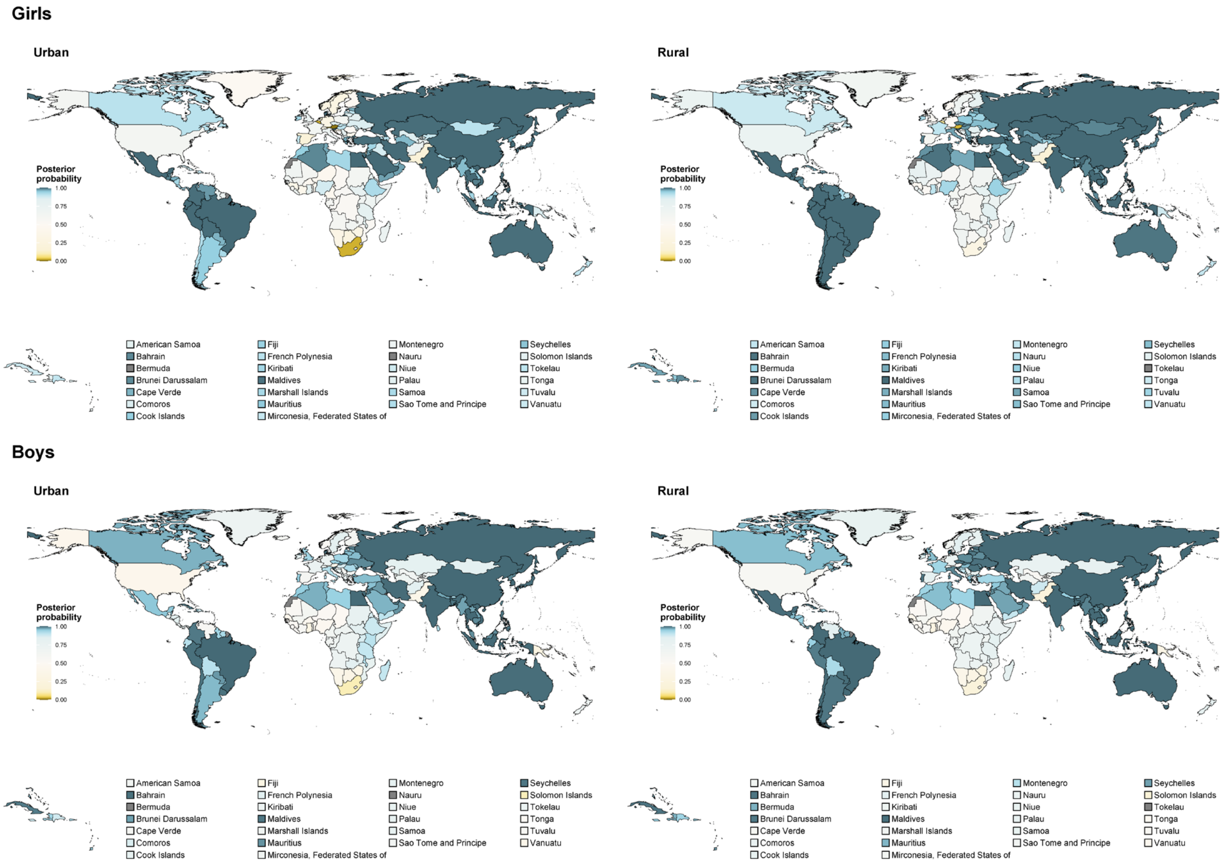


1950

Extended Data Fig. 4. Posterior probability of increase in mean height in urban and rural areas from 1990 to 2020.

The maps show the posterior probability (PP) that the age-standardised mean height increased from 1990 to 2020. The PP of a decrease is one minus that of an increase. If an increase in mean height is statistically indistinguishable from a decrease, the PP is 0.50. PPs closer to 0.50 indicate more uncertainty, those towards 1 indicate more certainty of an increase, and those towards 0 indicate more certainty of a decrease.

We did not estimate PP for change in mean rural height for areas classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or change in mean urban height for areas classified as entirely rural (Tokelau).

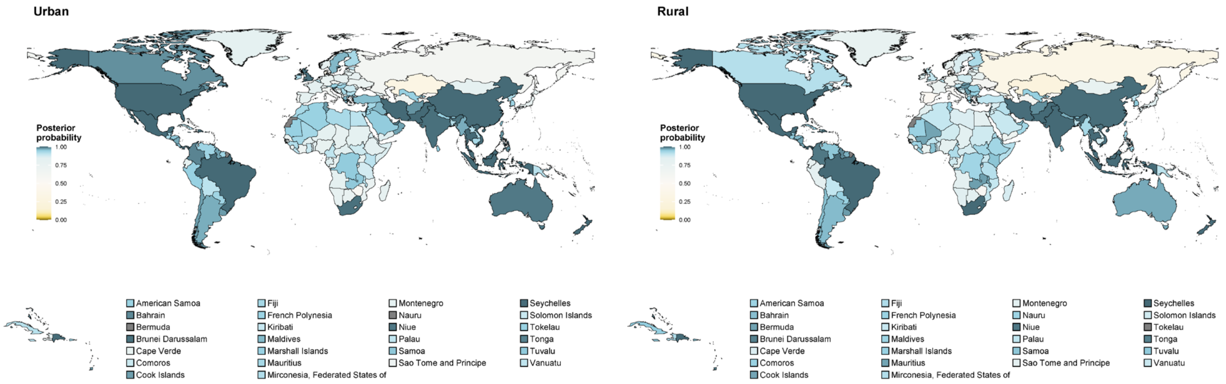


Extended Data Fig. 5. Posterior probability of increase in mean body-mass index (BMI) in urban and rural areas from 1990 to 2020.

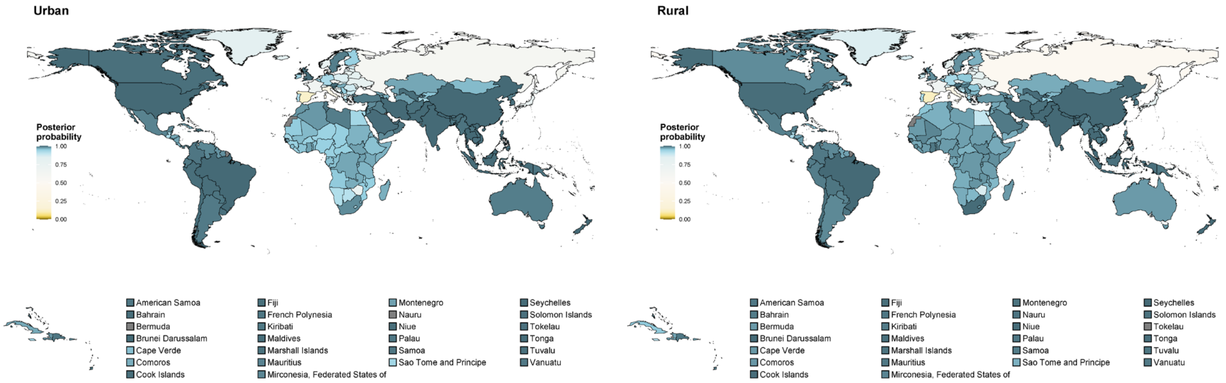
The maps show the posterior probability (PP) that the age-standardised mean BMI increased from 1990 to 2020. The PP of a decrease is one minus that of an increase.

We did not estimate PP for change in mean rural BMI in areas classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or change in mean urban BMI in areas classified as entirely rural (Tokelau).

Girls

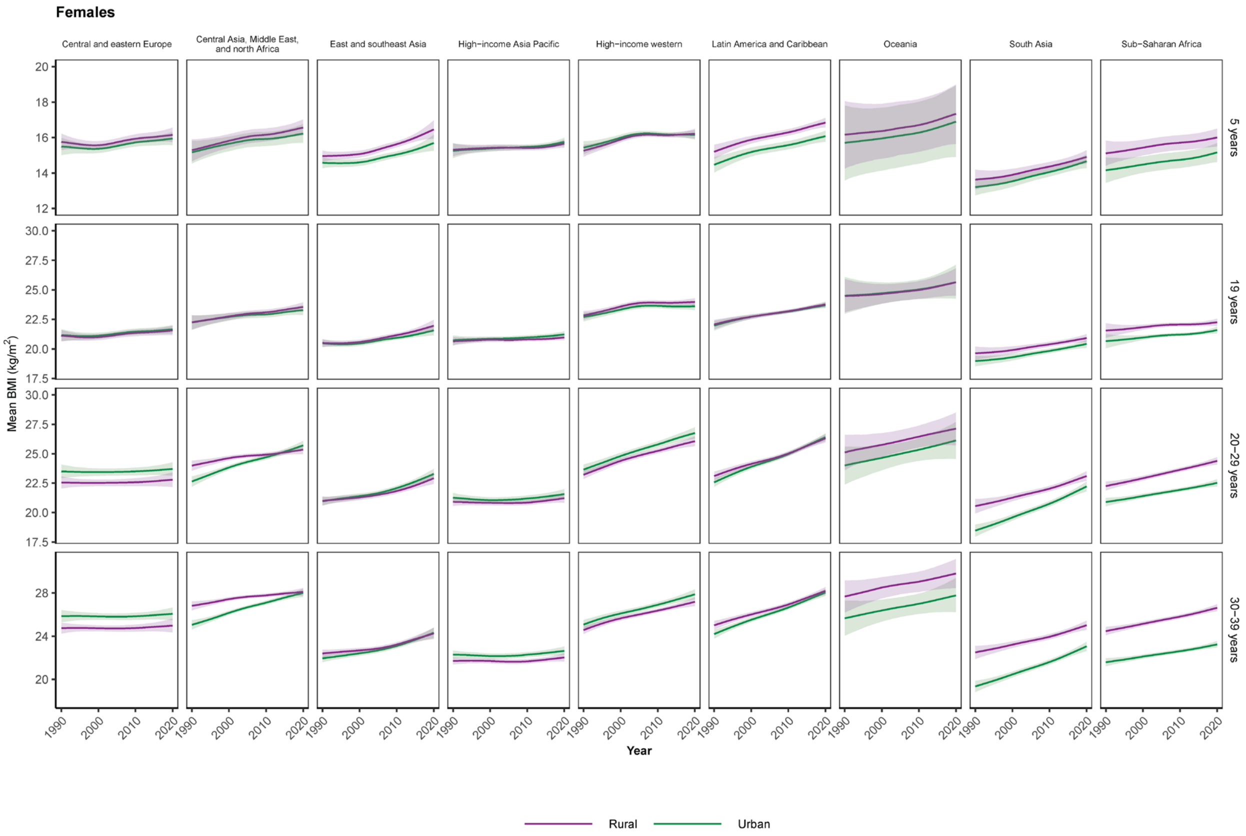


Boys



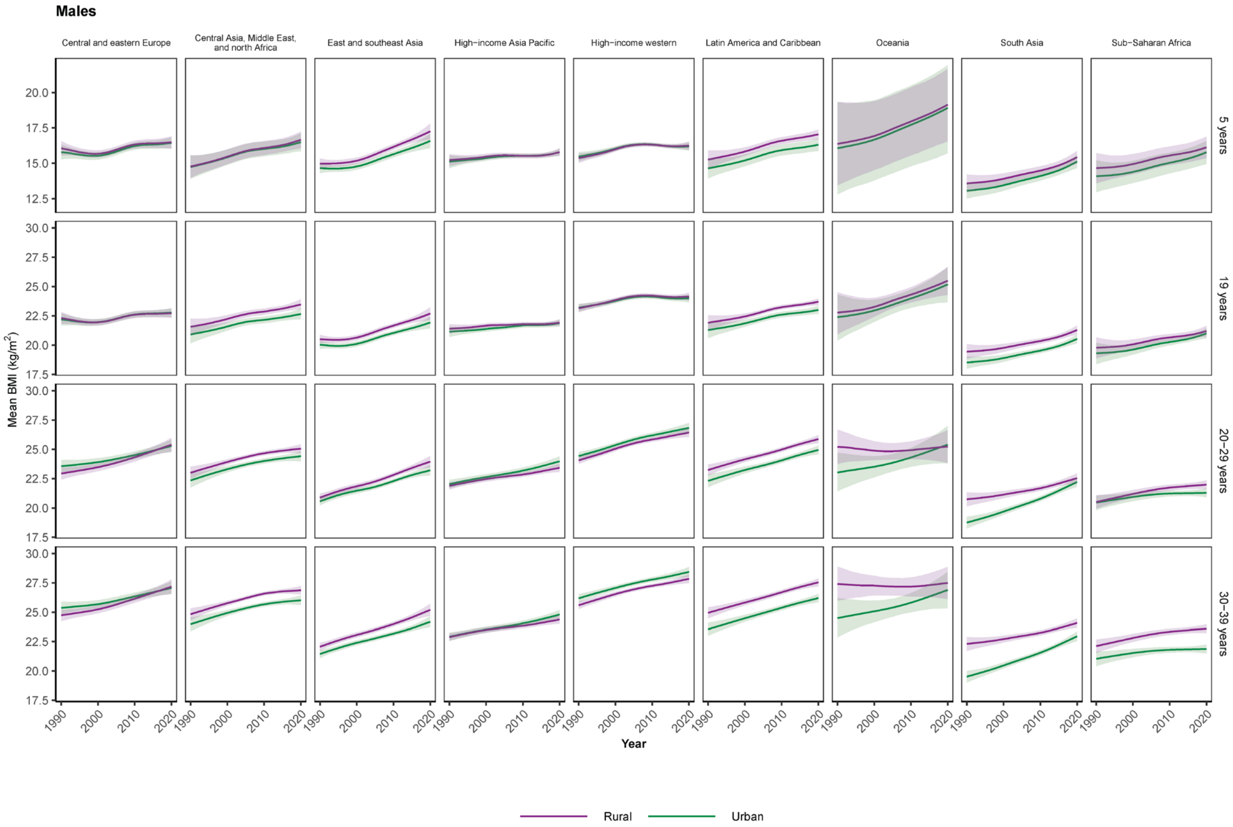
Extended Data Fig. 6. Trends in body-mass index (BMI) by place of residence for children, adolescents and young adults for females.

The figure shows trends in mean BMI at ages five and 19 years, and in age-standardised mean BMI for young adults (20-29 years and 30-39 years) for females. Shaded areas show the 95% credible intervals. Trend for young adults were estimated using a model similar to the one described in Methods, where BMI-age patterns were allowed to vary flexibly via a cubic spline function without knots.



Extended Data Fig. 7. Trends in body-mass index (BMI) by place of residence for children, adolescents and young adults for males.

The figure shows trends in mean BMI at ages five and 19 years, and in age-standardised mean BMI for young adults (20-29 years and 30-39 years) for males. See Extended Data Fig. 6 caption for description of figure contents.

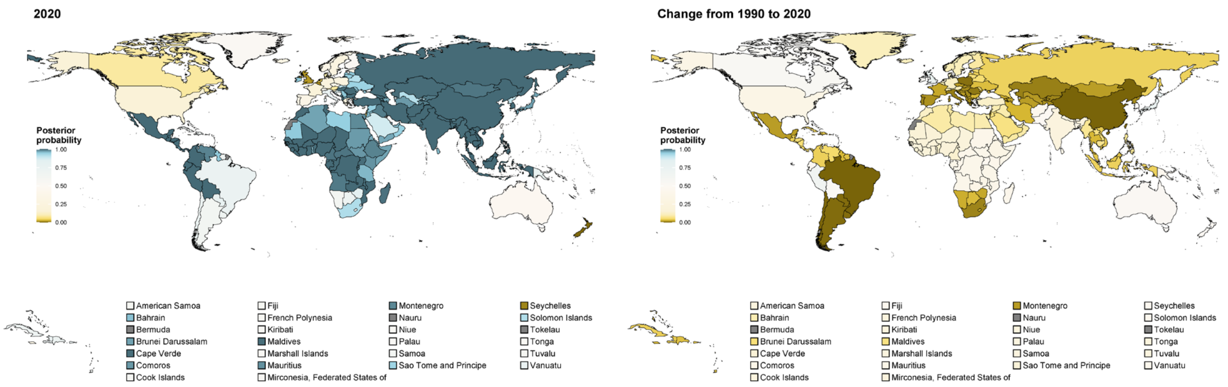


Extended Data Fig. 8. Posterior probability of urban-rural height difference in 2020 and its increase from 1990 to 2020.

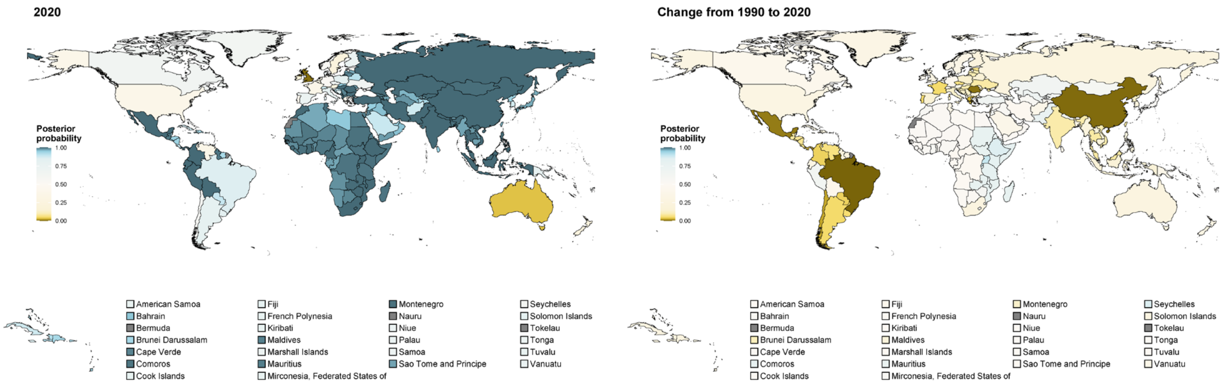
The maps show the posterior probability (PP) that age-standardised mean height in 2020 in urban areas was higher than in rural areas (left-hand panels), and the PP that the urban-rural difference in age-standardised mean height increased from 1990 to 2020 (right-hand panels). For 2020, if estimated age-standardised mean urban height is statistically indistinguishable from rural height, the PP is 0.50. PPs closer to 0.50 indicate more uncertainty, those towards 1 indicate more certainty of urban children being taller, and those towards 0 indicate more certainty of rural being taller.

We did not estimate the PP for differences between rural and urban height for areas classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or entirely rural (Tokelau), as indicated by grey colour.

Girls



Boys

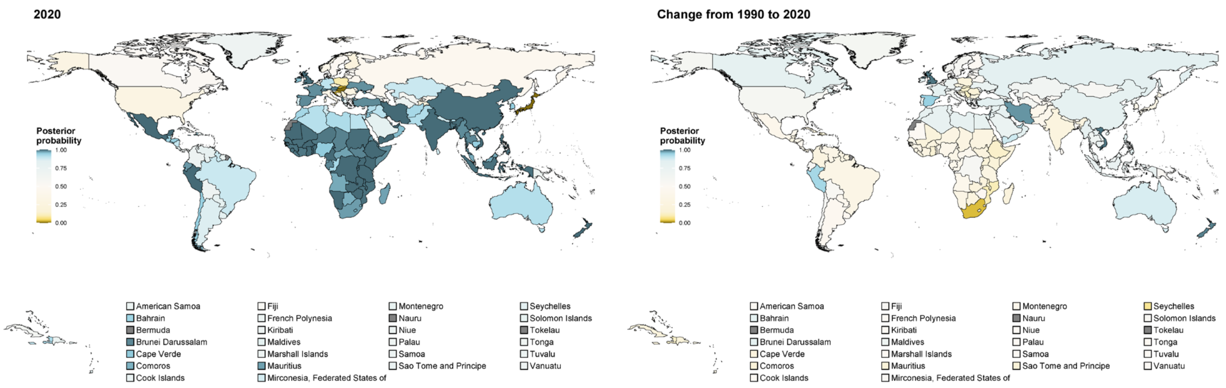


Extended Data Fig. 9. Posterior probability of urban-rural body-mass index (BMI) difference in 2020 and its increase from 1990 to 2020.

The maps show the posterior probability (PP) that age-standardised mean BMI in 2020 in urban areas was higher than in rural areas (left-hand panels), and the PP that the urban-rural difference in mean BMI increased from 1990 to 2020 (right-hand panels).

We did not estimate the PP for differences between rural and urban BMI for areas classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or entirely rural (Tokelau), as indicated by grey colour.

Girls



Boys