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NCD Risk Factor Collaboration (NCD-RisC)

Anu Mishra

Bin Zhou

Andrea Rodriguez-Martinez

Shina Avi

See next page for additional authors

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Authors

NCD Risk Factor Collaboration (NCD-RisC), Anu Mishra, Bin Zhou, Andrea Rodriguez-Martinez, Shina Avi, Moran Blychfeld Magnazu, Ronit Endevelt, Jeremy M. Jacobs, Jochanan Stessman, and Gladys E. Maestre

Diminishing benefits of urban living for children and adolescents' growth and development

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NCD Risk Factor Collaboration (NCD-RisC)*

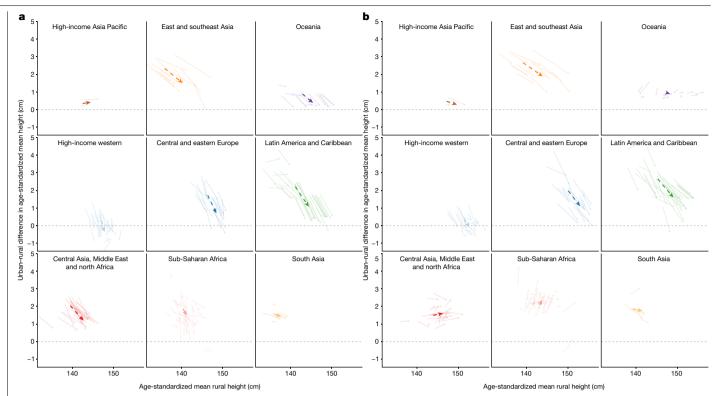
Optimal growth and development in childhood and adolescence is crucial for lifelong health and well-being¹⁻⁶. Here we used data from 2,325 population-based studies, with measurements of height and weight from 71 million participants, to report the height and body-mass index (BMI) of children and adolescents aged 5-19 years on the basis of rural and urban place of residence in 200 countries and territories from 1990 to 2020. In 1990, children and adolescents residing in cities were taller than their rural counterparts in all but a few high-income countries. By 2020, the urban height advantage became smaller in most countries, and in many high-income western countries it reversed into a small urban-based 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 boys from rural places either did not gain height or possibly became shorter, and hence fell further behind their urban peers. The difference between the age-standardized mean BMI of children in urban and rural areas was <1.1 kg 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 twenty-first century, whereas in much of sub-Saharan Africa they have amplified.

The growth and development of school-aged children and adolescents (ages 5–19 years) are influenced by their nutrition and environment at home, in the community and at school. Healthy growth and development at these ages help consolidate gains and mitigate inadequacies from early childhood and vice versa¹, with lifelong implications for health and well-being^{2–6}. Until recently, the growth and development of older children and adolescents received substantially less attention than in early childhood and adulthood⁷. Increasing attention on the importance of health and nutrition during school years has been accompanied by a presumption that differences in nutrition and the environment lead to distinct, and generally less healthy, patterns of growth and development at these ages in cities compared to rural areas⁸⁻¹⁷. This presumption is despite some empirical studies showing that food quality and nutrition are better in cities^{18,19}.

Data on growth and developmental outcomes during school ages are needed, alongside data on the efficacy of specific interventions and policies, to select and prioritize policies and programmes that promote health and health equity, 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 territories and draw lessons on good practice. Yet, globally, there are fewer data on growth trajectories in rural and urban areas in these formative ages than for children under 5 years of age²⁰ or for adults²¹. 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 country²²⁻²⁴ 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 generically on specific features of nutrition or the environment in either cities or rural areas^{10,13,25-28}. Little attention has been paid to the similarities and differences between relevant outcomes in these settings or to the heterogeneity of the urban-rural differences across countries.

Here we report on the mean height and BMI of school-aged children and adolescents residing in rural and urban areas of 200 countries and territories (referred to as countries hereafter) 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 well-being 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}. A high BMI in these

^{*}A list of authors and their affiliations appears online.



(Tokelau).

Fig. 1 | **Change in the urban-rural height difference from 1990 to 2020. a,b**, Change in the urban-rural difference in age-standardized mean height in relation to the change in age-standardized mean rural height in girls (**a**) and boys (**b**). 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 the urban-rural difference, a positive number shows a higher urban mean height and a

negative number shows higher rural mean height. See Extended Data Fig. 2 for urban-rural differences in age-standardized mean height and their change over time shown as maps, together with uncertainties in the estimates. See Supplementary Fig. 4a for results at ages 5, 10, 15 and 19 years. We did not estimate the difference between rural and urban height for countries classified

as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or entirely rural

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 and 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. Details of data sources and statistical methods are provided in the Methods. Our results represent the height and BMI for children and adolescents of the same age over time (that is, successive cohorts) in rural and urban areas of each country, and the difference between the two. For presentation, we summarize the 15 age-specific estimates, for single years of age from 5 to 19, through age standardization, which puts each country-year's child and adolescent population on the same age distribution and enables 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 the Supplementary Information.

In 1990, school-aged boys and girls who lived in cities had a height advantage (that is, were taller) compared with their rural counterparts. The exception was in high-income countries, where the urban height advantage was either negligible (<1.2 cm for age-standardized mean height; posterior probability (PP) for children living in urban areas being taller ranging from 0.51 to >0.99) or there was a small rural advantage (for example, Belgium, the Netherlands and the United Kingdom) (PP for children in rural areas being taller ranging from 0.53 to >0.95 where there was a rural height advantage) (Fig. 1 and Extended Data Fig. 2). The largest height differences between children and adolescents in cities and rural areas in 1990 occurred in some countries in Latin America (for example, 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 (Democratic Republic of Congo (DR Congo) and Rwanda). The urban height advantage in boys and girls in the named countries ranged from 2.4 to 5.0 cm, and the PP of children living in urban areas being taller than children living in rural areas was >0.99 (see Supplementary Table 3 for country-specific numerical values of height in children living in rural versus urban areas, their difference and the corresponding credible intervals (CrIs)).

The urban-rural height gap in the late twentieth century among low-income and middle-income countries was determined by how much children and adolescents in cities and rural areas had approached as opposed to fallen behind their peers in high-income countries, where there was little difference between urban and rural height. In countries such as Bulgaria, Hungary and Romania, the height of children and adolescents living in urban areas approached that of high-income countries, whereas children and adolescents in rural areas lagged behind, leading to a relatively large gap. In much of sub-Saharan Africa and south Asia, the height of children and adolescents lagged behind their peers in high-income countries regardless of where they lived, such that the urban-rural gap was relatively small. In a third group of low-income or middle-income countries that included Indonesia, Vietnam, Panama, Peru, DR Congo and Rwanda, children living in urban areas remained shorter than in high-income countries, but children from rural areas lagged even further behind, such that the urban-rural gap became large.

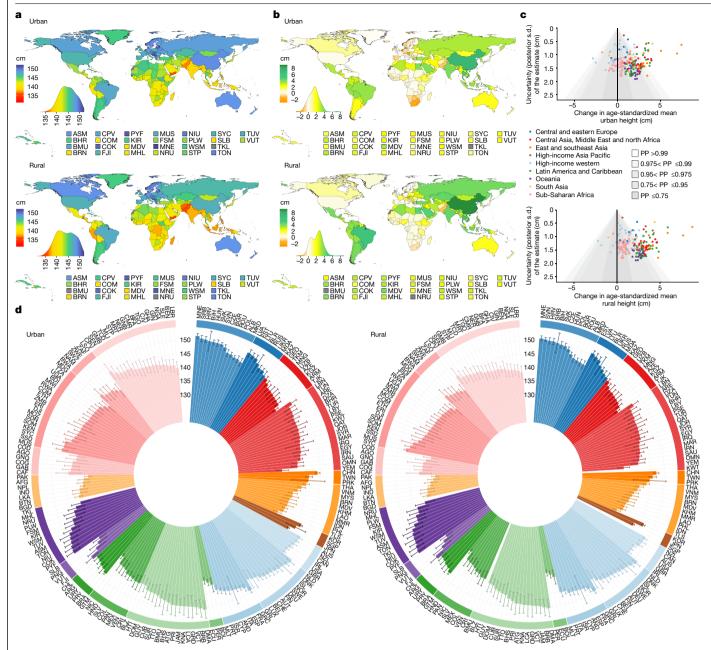


Fig. 2|See next page for caption.

By 2020, the urban height advantage in school ages became smaller in much of the world. 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 and Extended Data Figs. 2 and 8). Countries with substantial convergence over these three decades were in central and eastern Europe (for example, Croatia), Latin America and the Caribbean (for example, Argentina, Brazil, Chile and Paraguay), east and southeast Asia (for example, Taiwan) and for girls in central Asia (for example, Kazakhstan and Uzbekistan). The urban height advantage in the named countries declined by around 1-2.5 cm from 1990 to 2020 (the PP of urban-rural height difference having declined \geq 0.90 for the named countries). In many other middle-income countries (for example, China, Romania and Vietnam), the urbanrural 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; the PP of children in cities being taller than children in rural areas in 2020 > 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 for boys occurred in countries in east Africa such as Ethiopia (0.9 cm larger height gap in 2020 than 1990; 95% Crl –0.9 to 2.9, and PP of an increase of 0.86), Rwanda (1.0 cm larger gap, 95% Crl –0.7 to 3.0, and PP 0.88) and Uganda (1.1 cm larger gap, 95% Crl of -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 countries and emerging economies (newly high-income and industrialized countries) where the height of children and adolescents residing in rural areas converged to those in cities, successive cohorts of children and adolescents living in rural areas outpaced their urban counterparts in becoming taller and attained heights that urban children in the same countries had done decades earlier: growing to heights closer to those seen in high-income countries

Fig. 2 | Urban and rural height in 2020 and the change from 1990 to 2020 for girls. a, Age-standardized mean height in 2020 by urban and rural place of residence for girls. The density plots show the distribution of estimates across countries. b, Age-standardized 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, Change in mean height from 1990 to 2020 in relation to the uncertainty of the change measured by posterior standard deviation. Each point in the scatter plots shows one country. Shaded areas approximately show the 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, whereas those towards 1 indicate more certainty of change, **d**. Agestandardized mean height in 2020 for all countries. The height of each column is the posterior mean estimate shown together with its 95% Crl. Countries are ordered by region and super-region. See Extended Data Fig. 4 for a map of PP of the estimated change. See Supplementary Fig. 5 for results at ages 5, 10, 15 and 19 years. See Supplementary Table 3 for numerical results, including Crls, as age-standardized and at ages 5, 10, 15 and 19 years. We did not estimate mean rural height in countries classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore), mean urban height in countries classified as entirely rural (Tokelau) or their change over time in these countries, as indicated in grey. Countries are labelled using their International Organization for Standardization (ISO) 3166-1 alpha-3 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, GNO: 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; Vietnam, VNM; Yemen, YEM; Zambia, ZMB.

(Figs. 2 and 3). Successive cohorts of children and adolescents residing in rural areas in sub-Saharan Africa did not experience the accelerated height gain seen in cohorts in rural areas of middle-income countries. Notably, in the case of boys living in sub-Saharan Africa, there was nogain, or possibly 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 gaps in height were seen in Andean and central Latin America (for example, Bolivia, Panama and Peru, by up to 4.7 cm (95% Crl 4.0–5.5 cm) for boys and 3.8 cm (95% Crl 3.3–4.3 cm) for girls) and, especially for boys, in sub-Saharan Africa (for example, DR Congo, Ethiopia, Mozambique and Rwanda, by up to 4.2 cm (95% Crl 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-standardized mean BMI (Fig. 4 and Extended Data Figs. 3 and 9). In 1990, the urban–rural BMI gap was largest in sub-Saharan Africa (for example, Ethiopia, Kenya, Malawi, South Africa and Zimbabwe) and south Asia (for example, Bangladesh and India), followed by parts of Latin America (for example, Mexico and Peru). The urban–rural BMI gap in the two sexes in the named countries ranged from 0.4 to 1.2 kg m⁻², and the PP of children and adolescents living in urban areas having a higher BMI than those in rural areas was \geq 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 below, the thresholds of being underweight (>1 s.d. below the median of the World Health Organization (WHO) reference population).

From 1990 to 2020, the BMI of successive cohorts of children and adolescents in both urban and rural areas increased in all but a few mostly high-income countries (for example, Denmark, Italy and Spain) (Figs. 5 and 6). There was heterogeneity in low-income and middle-income countries in how much the BMI increased in cities compared with rural areas. In the majority of countries in sub-Saharan Africa and south Asia, the 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 urban-rural BMI gap declined by up to 0.65 kg m⁻² for both girls and boys, and the PP that the urban-rural BMI difference declined 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 boys and girls in rural areas out of the range for being underweight, Moreover, 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 (>1 s.d. above the median of the WHO reference population). The opposite, a larger increase in urban BMI, happened in most other low-income 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 small range $(-0.3 \text{ to } 0.6 \text{ kg m}^{-2} \text{ for})$ 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 Fig. 3). Urban excess BMI was larger in boys than girls in only about one-half of the countries. For the other half, mostly in high-income western countries and those in sub-Saharan Africa, urban excess BMI was larger in girls than boys. The urban height advantage was slightly larger at 5 years of age than at 19 years of age in most low-income 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 Fig. 4).

Since the introduction of modern sanitation in the nineteenth century, cities provided substantial nutritional and health advantages in high-income and subsequently low-income and middle-income countries¹⁹. Our results show that in the twenty-first century, during school

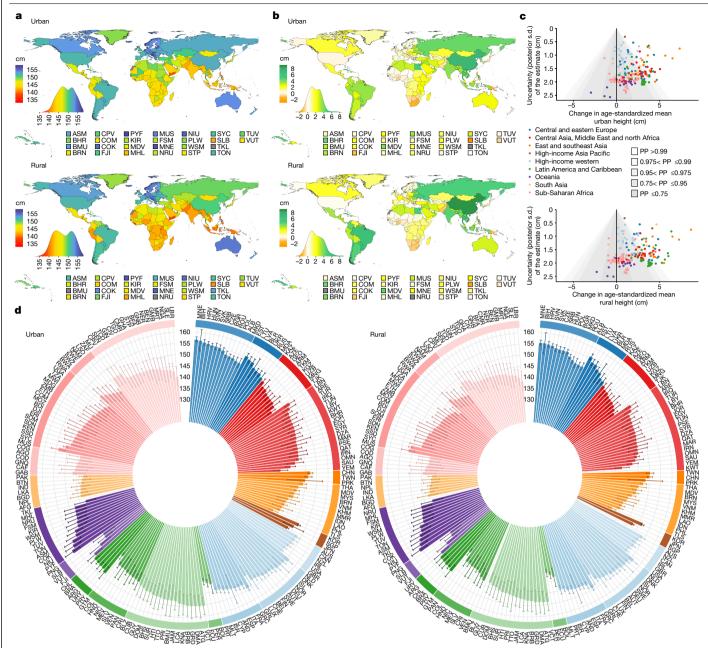


Fig. 3 | **Urban and rural height in 2020 and change from 1990 to 2020 for boys. a**-d, See the caption for Fig. 2 for descriptions of the contents of the figure and for definitions. We did not estimate mean rural height in countries

classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore), mean urban height in countries classified as entirely rural (Tokelau) or their change over time, as indicated in grey.

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 these settings, 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 by 2020, typically in the unhealthy range (Fig. 7). This contrasted with the poorest region in the world: sub-Saharan Africa. In this region, the urban height advantage persisted or even expanded, whereas 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. Notably, 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, which is consistent with evidence from a few countries that show 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

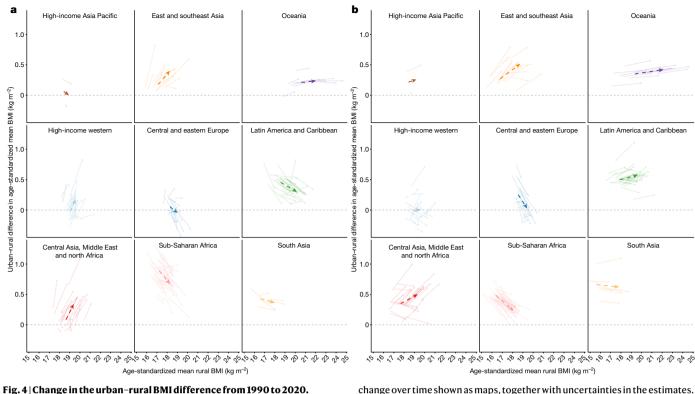


Fig. 4 | **Change in the urban-rural BMI difference from 1990 to 2020. a,b**, Change in urban-rural difference in age-standardized mean BMI for girls (**a**) and boys (**b**) in relation to change in age-standardized mean rural BMI. See the caption for Fig. 1 for a description of the contents of this figure. See Extended Data Fig. 3 for urban-rural differences in age-standardized mean BMI and their

See Supplementary Fig. 4b for results at ages 5, 10, 15 and 19 years. We did not estimate the difference between rural and urban BMI for countries classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or entirely rural (Tokelau).

adults in these same regions²¹. Additional analyses of data collected by the NCD Risk Factor Collaboration (NCD-RisC) 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 Figs. 6 and 7), a period during which there is substantial, but variable, weight gain among population subgroups³¹. 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 nutrients². Studies that use data on household socioeconomic and environmental factors have indicated that these physiological determinants of height are themselves affected by income, education, quality of the living environment and access to healthcare in rural as well as urban areas³⁵. 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 education and 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 the 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 (for example, food assistance or school food programmes) that improve nutrition in disadvantaged groups 30,36,37 . The more marked 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 children and adolescents living in rural and urban areas 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 groups³⁸⁻⁴⁰. In countries in central and eastern Europe, transition to a market economy and increases in trade may have reduced the disparity in access to, and seasonality of, healthy foods between urban and rural areas⁴¹, and partly underlie the convergence of height seen in our results. By contrast, case studies in some countries have shown that where economic growth was accompanied by large inequalities in income, nutrition and/or services, the urban advantage persisted⁴²⁻⁴⁴.

The notable exception in the global trends was sub-Saharan Africa, where a stagnation or reversal of height gain in rural areas led to the persistence or widening of urban-rural height differences, whereas 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 poorest people in the world live, started from macroeconomic shocks in the late twentieth century⁴⁵ and subsequent agriculture, trade and development policies that limited improvements in income and services, and emphasized agricultural exports over local food security and diversity⁴⁵. These macroeconomic factors in turn led to less diverse diets, with higher caloric intake rather than a shift to protein-rich and nutrient-rich foods (for example, animal products, seafood, fruits and vegetables)⁴⁶⁻⁴⁸. Moreover, the slow expansion of infrastructure and services in rural areas restricted improvements in other determinants of healthy growth, such as clean water, sanitation and health care⁴⁹.

Several other factors may 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

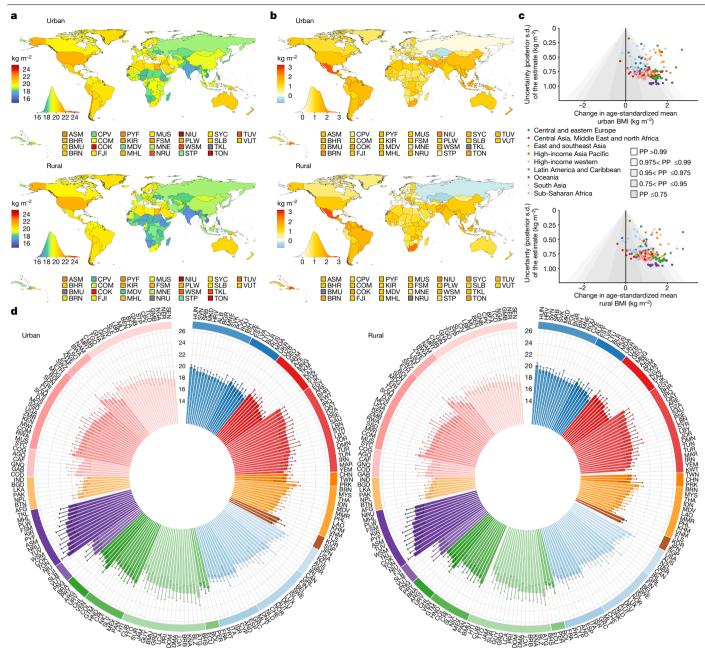


Fig. 5 | Urban and rural BMI in 2020 and change from 1990 to 2020 for girls. **a**-**d**, See the caption for Fig. 2 for descriptions of the contents of the figure and for definitions. See Extended Data Fig. 5 for a map of PP of the estimated change. See Supplementary Fig. 6 for results at ages 5, 10, 15 and 19 years. See Supplementary Table 4 for numerical results, including CrIs, as age-standardized

and at ages 5, 10, 15 and 19 years. We did not estimate mean rural BMI in countries classified as entirely urban (Singapore, Bermuda and Nauru), mean urban BMI in areas classified as entirely countries (Tokelau) or their change over time, as indicated in grey.

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 industrialize may account for some of the observed population-level trends. However, migration tends to be less common in childhood and adolescence than in adulthood in most countries. Finally, improvements in survival among children aged under 5 years in rural areas, particularly low-birthweight children, may have influenced the height and weight of those who survive beyond 5 years of age. However, 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, 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 increase in poverty and the cost of food, especially of nutrient-rich foods, as a result of the macroeconomic changes resulting from the COVID-19 pandemic and the war in Ukraine, may hinder further gains or even set back healthy growth and development in children and adolescents.

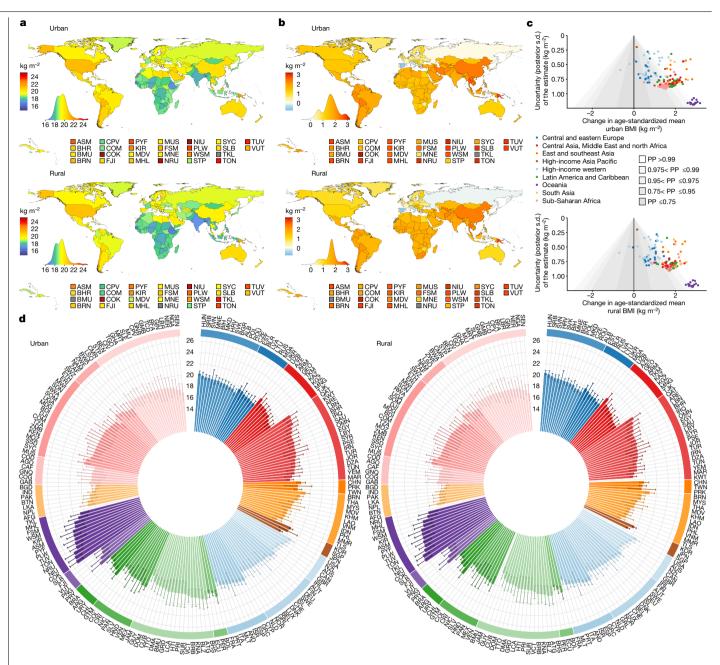


Fig. 6 | **Urban and rural BMI in 2020 and change from 1990 to 2020 for boys. a**–**d**, See the caption for Fig. 2 for descriptions of the contents of the figure and for definitions. We did not estimate mean rural BMI in countries classified as entirely urban (Singapore, Bermuda and Nauru), mean urban BMI in countries classified as entirely rural (Tokelau) or their change over time, as indicated in grey.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-023-05772-8.

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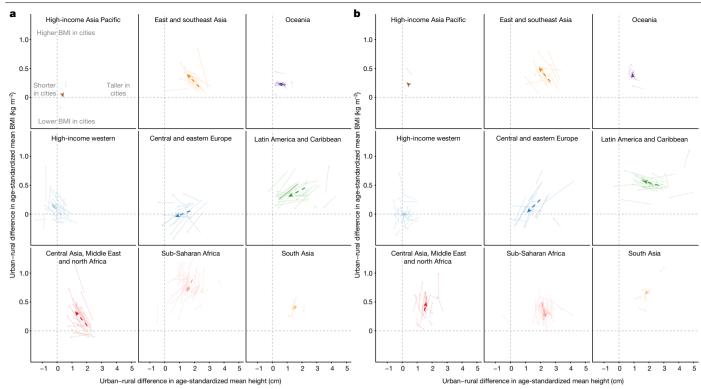


Fig. 7 | **Change in the urban-rural height and BMI difference from 1990 to 2020. a**, **b**, Change in the urban-rural difference in age-standardized mean height and the urban-rural difference in age-standardized mean BMI in girls (**a**) and boys (**b**). See the caption for Fig. 1 for a description of the contents of

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this figure. See Supplementary Fig. 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 countries classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or entirely rural (Tokelau).

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NCD Risk Factor Collaboration (NCD-RisC)

Anu Mishra^{1,776}, Bin Zhou^{1,776}, Andrea Rodriguez-Martinez^{1,776}, Honor Bixby^{2,3,776}, Rosie K. Singleton¹, Rodrigo M. Carrillo-Larco¹, Kate E. Sheffer¹, Christopher J. Paciorek⁴, James E. Bennett¹, Victor Lhoste¹, Maria L. C. Iurilli¹, Mariachiara Di Cesare³, James Bentham⁵, Nowell H. Phelps¹, Marisa K. Sophiea¹, Gretchen A. Stevens⁶, Goodarz Danaei⁷, Melanie J. Cowan⁶, Stefan Savin⁶, Leanne M. Riley⁶, Edward W. Gregg¹, Wichai Aekplakorn⁸, Noor Ani Ahmad⁹, Jennifer L. Baker¹⁰, Adela Chirita-Emandi¹¹, Farshad Farzadfar¹², Günther Fink^{13,14}, Mirjam Heinen¹⁵, Nayu Ikeda¹⁶, Andre P. Kengne¹⁷, Young-Ho Khang¹⁸, Tiina Laatikainen^{19,20}, Avula Laxmaiah²¹, Jun Ma²², Michele Monroy-Valle²³, Malay K. Mridha²⁴, Cristina P. Padez²⁵, Andrew Reynolds²⁶, Maroje Sorić^{27,28}, Gregor Starc²⁸, James P. Wirth²⁹, Leandra Abarca-Gómez³⁰, Ziad A. Abdeen³¹, Shynar Abdrakhmanova³², Suhaila Abdul Ghaffar⁹, Hanan F. Abdul Rahim³³, Zulfiya Abdurrahmonova³⁴, Niveen M. Abu-Rmeileh³⁵, Jamila Abubakar Garba³⁶, Benjamin Acosta-Cazares³⁷, Ishag Adam³⁸, Marzena Adamczyk³⁹, Robert J. Adams⁴⁰, Seth Adu-Afarwuah⁴¹, Kaosar Afsana²⁴, Shoaib Afzal^{42,43}, Valirie N. Agbor⁴⁴, Imelda A. Agdeppa⁴⁵, Javad Aghazadeh-Attari⁴⁶, Hassan Aguenaou⁴⁷ Carlos A. Aguilar-Salinas⁴⁸, Charles Agyemang⁴⁹, Mohamad Hasnan Ahmad⁹, Ali Ahmadi⁵⁰, Naser Ahmadi¹², Nastaran Ahmadi⁵¹, Imran Ahmed⁵², Soheir H. Ahmed⁵³, Wolfgang Ahrens⁵⁴, Gulmira Aitmurzaeva⁵⁵, Kamel Ajlouni⁵⁶, Hazzaa M. Al-Hazzaa⁵⁷, Badreya Al-Lahou⁵⁸, Rajaa Al-Raddadi⁵⁹, Huda M. Al Hourani⁶⁰, Nawal M. Al Qaoud⁶¹, Monira Alarouj⁶² Fadia AlBuhairan⁶³, Shahla AlDhukair⁶⁴, Maryam A. Aldwairji⁶¹, Sylvia Alexius⁶⁵, Mohamed M. Ali⁶, Abdullah Alkandari⁶², Ala'a Alkerwi⁶⁶, Buthaina M. Alkhatib⁶⁰, Kristine Allin¹⁰, Mar Alvarez-Pedrerol⁶⁷, Eman Aly⁶⁸, Deepak N. Amarapurkar⁶⁹, Pilar Amiano Etxezarreta⁷⁰, John Amoah⁷¹, Norbert Amougou⁷², Philippe Amouyel^{73,74} Lars Bo Andersen⁷⁵, Sigmund A. Anderssen⁷⁶, Odysseas Androutsos⁷⁷, Lars Ängquist⁴², Ranjit Mohan Anjana⁷⁸, Alireza Ansari-Moghaddam⁷⁹, Elena Anufrieva⁸⁰, Hajer Aounallah-Skhiri⁸¹, Joana Araújo⁸², Inger Ariansen⁸³, Tahir Aris⁹, Raphael E. Arku⁸⁴, Nimmathota Arlappa²¹, Krishna K. Aryal⁸⁵, Nega Aseffa⁸⁶, Thor Aspelund⁸⁷, Felix K. Assah⁸⁸, Batyrbek Assembekov⁸⁹, Maria Cecília F. Assunção⁹⁰, May Soe Aung⁹¹, Juha Auvinen^{92,9} Mária Avdičová⁹⁴, Shina Avi^{95,96}, Ana Azevedo⁹⁷, Mohsen Azimi-Nezhad⁹⁸, Fereidoun Azizi⁹⁹, Mehrdad Azmin¹², Bontha V. Babu¹⁰⁰, Maja Bæksgaard Jørgensen¹⁰¹, Azli Baharudin⁹, Suhad Bahijri⁵⁹, Marta Bakacs¹⁰², Nagalla Balakrishna²¹, Yulia Balanova¹⁰ Mohamed Bamoshmoosh¹⁰⁴, Maciej Banach¹⁰⁵, José R. Banegas¹⁰⁶, Joanna Baran¹⁰⁷, Rafał Baran¹⁰⁷, Carlo M. Barbagallo¹⁰⁸, Valter Barbosa Filho¹⁰⁹, Alberto Barceló¹ Maja Baretić¹¹¹, Amina Barkat¹¹², Joaquin Barnoya¹¹³, Lena Barrera¹¹⁴, Marta Barreto^{115,116} Aluisio J. D. Barros⁹⁰, Mauro Virgílio Gomes Barros¹¹⁷, Anna Bartosiewicz¹⁰⁷, Abdul Basit¹¹⁸, Joao Luiz D. Bastos¹¹⁹, Igbal Bata¹²⁰, Anwar M. Batieha¹²¹, Aline P. Batista¹²² Rosangela L. Batista¹²³, Zhamilya Battakova³², Louise A. Baur¹²⁴, Pascal M. Bayauli¹²⁵, Robert Beaglehole¹²⁶, Silvia Bel-Serrat¹²⁷, Antonisamy Belavendra¹²⁸, Habiba Ben Romdhane¹²⁹, Judith Benedics¹³⁰, Mikhail Benet¹³¹, Gilda Estela Benitez Rolandi¹³², Elling Bere¹³³, Ingunn Holden Bergh⁸³, Yemane Berhane¹³⁴, Salim Berkinbayev¹³¹ Antonio Bernabe-Ortiz¹³⁶, Gailute Bernotiene¹³⁷, Ximena Berrios Carrasola¹⁵ Heloísa Bettiol¹³⁹, Manfred E. Beutel¹⁴⁰, Augustin F. Beybey⁸⁸, Jorge Bezerra¹¹⁷, Aroor Bhagyalaxmi¹⁴¹, Sumit Bharadwaj¹⁴², Santosh K. Bhargava¹⁴³, Hongsheng Bi¹⁴⁴, Yufang Bi¹⁴⁵, Daniel Bia¹⁴⁶, Katia Biasch¹⁴⁷, Elysée Claude Bika Lele¹⁴⁸, Mukharram M. Bikbov¹⁴⁹, Bihungum Bista¹⁵⁰, Dusko J. Bjelica¹⁵¹, Anne A. Bjerregaard¹⁰, Peter Bjerregaard¹⁵², Espen Bjertness⁵³, Marius B. Bjertness⁵³, Cecilia Björkelund¹⁵ Katia V. Bloch¹⁵⁴, Anneke Blokstra¹⁵⁵, Moran Blychfeld Magnazu^{156,157}, Simona Bo¹⁵⁸, Martin Bobak¹⁵⁹, Lynne M. Boddy¹⁶⁰, Bernhard O. Boehm¹⁶¹, Jolanda M. A. Boer¹⁵⁵, Jose G. Boggia¹⁴⁶, Elena Bogova¹⁶², Carlos P. Boissonnet¹⁶³, Stig E. Bojesen^{43,42}, Marialaura Bonaccio¹⁶⁴, Vanina Bongard¹⁶⁵, Alice Bonilla-Vargas³⁰, Matthias Bopp¹⁶⁶ Herman Borghs¹⁶⁷, Pascal Bovet^{168,169}, Khadichamo Boymatova¹⁷⁰, Lien Braeckevelt¹⁷¹ Lutgart Braeckman¹⁷², Marjolijn C. E. Bragt¹⁷³, Imperia Brajkovich¹⁷⁴, Francesco Branca⁶, Juergen Breckenkamp¹⁷⁵, João Breda¹⁷⁶, Hermann Brenner¹⁷⁷, Lizzy M. Brewster⁴⁹, Garry R. Brian¹⁷⁸, Yajaira Briceño¹⁷⁹, Lacramioara Brinduse¹⁸⁰, Miguel Brito¹⁸ Sinead Brophy¹⁸², Johannes Brug¹⁵⁵, Graziella Bruno¹⁵⁸, Anna Bugge¹⁸³, Frank Buntinx¹⁶⁷, Marta Buoncristiano¹⁵, Genc Burazeri¹⁸⁴, Con Burns¹⁸⁵, Antonio Cabrera de León¹⁸⁶, Joseph Cacciottolo¹⁸⁷, Hui Cai¹⁸⁸, Roberta B. Caixeta¹⁸⁹, Tilema Cama¹⁹⁰ Christine Cameron¹⁹¹, José Camolas¹⁹², Günay Can¹⁹³, Ana Paula C. Cândido¹⁹ Felicia Cañete¹³², Mario V. Capanzana⁴⁵, Naděžda Čapková¹⁹⁵, Eduardo Capuano¹⁹⁶, Rocco Capuano¹⁹⁶, Vincenzo Capuano¹⁹⁶, Marloes Cardol¹⁹⁷, Viviane C. Cardoso¹³⁹, Axel C. Carlsson¹⁹⁸, Esteban Carmuega¹⁹⁹, Joana Carvalho²⁰⁰, José A. Casajús²⁰¹, Felicia C. Carlsson¹⁹⁸, Esteban Carmuega¹⁹⁹, Joana Carvalho²⁰⁰, José A. Casajús²⁰¹, Felipe F. Casanueva²⁰, Maribel Casa⁵⁷, Erugul Celikcan²⁰³, Laura Cens²⁷⁰ Marvin Cervantes-Loaiza³⁰, Juraci A. Cesar²⁰⁵, Snehalatha Chamukuttan²⁰⁶ Angelique Chan²⁰⁷, Queenie Chan¹, Himanshu K. Chaturvedi²⁰⁸, Nish Chaturvedi⁵⁵, Norsyamlina Che Abdul Rahim⁹, Miao Li Chee²⁰⁹, Chien-Jen Chen²¹⁰, Fangfang Chen²¹¹, Huashuai Chen²¹², Shuohua Chen²¹³, Zhengming Chen⁴⁴, Ching-Yu Cheng²¹⁴, Yiling J. Cheng²¹⁵, Bahman Cheraghian²¹⁶, Angela Chetrit²¹⁷, Ekaterina Chikova-Iscener²¹⁸, Mai J. M. Chinapaw²¹⁹, Anne Chinnock²²⁰, Arnaud Chiolero²²¹, Shu-Ti Chiou²²² María-Dolores Chirlaque²²³, Belong Cho²²⁴, Kaare Christensen²²⁵, Diego G. Christofaro²²⁶, Jerzy Chudek²²⁷, Renata Cifkova^{228,229}, Michelle Cilia²³⁰, Eliza Cinteza¹⁸⁰, Massimo Cirillo²³¹, Frank Claessens¹⁶⁷, Janine Clarke²³², Els Clays¹⁷², Emmanuel Cohen⁷² Laura-María Compañ-Gabucio²³³, Hans Concin²³⁴, Susana C. Confortin¹²³, Cyrus Cooper²³⁵, Tara C. Coppinger¹⁸⁵, Eva Corpeleijn¹⁹⁷, Lilia Yadira Cortés²³⁶, Simona Costanzo¹⁶ Dominique Cottel²³⁷, Chris Cowell¹²⁴, Cora L. Craig¹⁹¹, Amelia C. Crampin²³⁸, Amanda J. Cross¹, Ana B. Crujeiras²³⁹, Juan J. Cruz¹⁰⁶, Tamás Csányi²⁴⁰, Semánová Csilla²⁴¹, Alexandra M. Cucu^{242,243}, Liufu Cui²¹³, Felipe V. Cureau²⁴⁴, Sarah Cuschieri¹⁸⁷ Ewelina Czenczek-Lewandowska¹⁰⁷, Graziella D'Arrigo²⁴⁵, Eleonora d'Orsi¹¹ Liliana Dacica²⁴⁶, Jean Dallongeville²³⁷, Albertino Damasceno²⁴⁷, Camilla T. Damsgaard⁴², Rachel Dankner²¹⁷, Thomas M. Dantoft¹⁰, Parasmani Dasgupta²⁴⁸, Saeed Dastgiri² Luc Dauchet^{73,74}, Kairat Davletov⁸⁹, Maria Alice Altenburg de Assis¹¹⁹, Guy De Backer¹⁷², Dirk De Bacquer¹⁷², Amalia De Curtis¹⁶⁴, Patrícia de Fragas Hinnig¹¹⁹, Giovanni de Gaetano¹⁶⁴, Stefaan De Henauw¹⁷², Pilar De Miguel-Etayo^{239,201}, Paula Duarte de Oliveira⁹⁰ David De Ridder²⁵⁰, Karin De Ridder²⁵¹, Susanne R. de Rooij^{252,49}, Delphine De Smedt¹⁷², Mohan Deepa⁷⁸, Alexander D. Deev²⁵³, Vincent DeGennaro Jr²⁵⁴, Hélène Delisle²⁵⁵

Francis Delpeuch²⁵⁶, Stefaan Demarest²⁵¹, Elaine Dennison²³⁵, Katarzyna Dereń¹⁰⁷, Valérie Deschamps²⁵⁷, Meghnath Dhimal¹⁵⁰, Augusto Di Castelnuovo²⁵ Juvenal Soares Dias-da-Costa²⁵⁹, María Elena Díaz-Sánchez²⁶⁰, Alejandro Diaz²⁶¹, Pedro Díaz Fernández⁸⁶⁷, María Pilar Díez Ripollés⁸⁶³, Zivka Díka²⁷, Shirin Djalalinia²⁶⁴, Visnja Djordjic²⁶⁵, Ha T. P. Do²⁶⁶, Annette J. Dobson²⁶⁷, Liria Dominguez²⁶⁸, Maria Benedetta Donati⁶⁴, Chiara Donfrancesco²⁶⁹, Guanghui Dong²⁷⁰, Yanhui Dong²², Silvana P. Donoso²⁷¹, Angela Döring²⁷², Maria Dorobantu¹⁸⁰, Ahmad Reza Dorosty²⁷³ Kouamelan Doua²⁷⁴, Nico Dragano²⁷⁵, Wojciech Drygas^{276,105}, Jia Li Duan²⁷⁷, Charmaine A. Duante⁴⁵, Priscilla Duboz²⁷⁹, Vesselka L. Duleva²¹⁸, Virginija Dulskiene¹³⁷, Samuel C. Dumith²⁰⁵, Anar Dushpanova^{279,280}, Azhar Dyussupova²⁸¹, Vilnis Dzerve²⁸², Elzbieta Dziankowska-Zaborszczyk¹⁰⁵, Guadalupe Echeverría¹³⁸, Ricky Eddie²⁸ Ebrahim Eftekhar²⁸⁴, Eruke E. Egbagbe²⁸⁵, Robert Eggertsen¹⁵³, Sareh Eghtesad²⁷³, Gabriele Eiben²⁸⁶, Ulf Ekelund⁷⁶, Mohammad El-Khateeb⁵⁶, Laila El Ammari²⁸⁷, Jalila El Ati²⁸⁸, Denise Eldemire-Shearer²⁸⁹, Marie Eliasen¹⁰, Paul Elliott¹, Ronit Endevelt^{156,29} Reina Engle-Stone²⁹¹, Rajiv T. Erasmus²⁹², Raimund Erbel²⁹³, Cihangir Erem²⁹⁴, Gul Ergor²⁹⁵, Louise Eriksen¹⁵², Johan G. Eriksson²⁹⁶, Jorge Escobedo-de la Peña³⁷, Saeid Eslami² Ali Esmaeili²⁹⁸, Alun Evans²⁹⁹, David Faeh¹⁶⁶, Ildar Fakhradiyev¹³⁵, Albina A. Fakhretdinova¹⁴⁹, Caroline H. Fall²³⁵, Elnaz Faramarzi³⁰⁰, Mojtaba Farjam³⁰¹, Victoria Farrugia Sant'Angelo²³⁰, Mohammad Reza Fattahi³⁰², Asher Fawwad³⁰³, Wafaie W. Fawzi⁷, Edit Feigl¹⁰ Francisco J. Felix-Redondo³⁰⁴, Trevor S. Ferguson²⁸⁹, Romulo A. Fernandes²²⁶, Daniel Fernández-Bergés³⁰⁵, Daniel Ferrante³⁰⁶, Thomas Ferrao²³², Gerson Ferrari³⁰⁷ Marika Ferrari²⁰⁴, Marco M. Ferrario³⁰⁸, Catterina Ferreccio¹³⁸, Haroldo S. Ferreira³⁰⁹ Eldridge Ferrer⁴⁵, Jean Ferrieres¹⁶⁵, Thamara Hubler Figueiró¹¹⁹, Anna Fijalkowska³¹ Mauro Fisberg³¹¹, Krista Fischer³¹², Leng Huat Foo³¹³, Maria Forsner³¹⁴, Heba M. Fouad⁶⁸, Damian K. Francis²⁸⁹, Maria do Carmo Franco³¹⁵, Zlatko Fras³¹⁶, Guillermo Frontera³¹ Flavio D. Fuchs³¹⁸, Sandra C. Fuchs³¹⁹, Isti I. Fujiati³²⁰, Yuki Fujita³²¹, Matsuda Fumihiko³²² Viktoriya Furdela³²³, Takuro Furusawa³²², Zbigniew Gaciong³²⁴, Mihai Gafencu¹¹, Manuel Galán Cuesta³²⁵, Andrzej Galbarczyk³²⁶, Henrike Galenkamp⁴⁹, Daniela Galeone³ Myriam Galfo²⁰⁴, Fabio Galvano³²⁸, Jingli Gao²¹³, Pei Gao²², Manoli Garcia-de-la-Hera²²³ María José García Mérida²⁶², Marta García Solano³²⁹, Dickman Gareta³³⁰, Sarah P. Garnett¹²⁴, Jean-Michel Gaspoz³³¹, Magda Gasull²²³, Adroaldo Cesar Araujo Gaya³¹⁹, Anelise Reis Gaya³¹⁹, Andrea Gazzinelli³³², Ulrike Gehring³³³, Harald Geiger²³⁴, Johanna M. Geleijnse³³⁴, Ronnie George³³⁵, Ebrahim Ghaderi³³⁶, Ali Ghanbari¹², Erfan Ghasemi¹², Oana-Florentina Gheorghe-Fronea¹⁸⁰, Alessandro Gialluisi³⁰⁰ Simona Giampaoli²⁶⁹, Francesco Gianfagna^{308,258}, Christian Gieger²⁷², Tiffany K. Gill³³⁷, Jonathan Giovannelli^{17,3,7}, Glen Gironella⁴⁵, Aleksander Giwercman³³⁸, Konstantinos Gkiouras³³⁹, Natalya Glushkova^{280,89}, Natalya Gluškova³⁴⁰, Ramesh Godara³⁴¹, Justyna Godos³²⁸, Sibel Gogen²⁰³, Marcel Goldberg^{342,343}, David Goltzman², Georgina Gómez²²⁰, Jesús Humberto Gómez Gómez³⁴⁴, Luis F. Gomez²³⁰ Santiago F. Gómez^{345,346}, Aleksandra Gomula³⁴⁷, Bruna Gonçalves Cordeiro da Silva⁹⁰, Helen Gonçalves⁹⁰, Mauer Gonçalves³⁴⁸, Ana D. González-Álvarez³⁴⁶ David A. Gonzalez-Chica³³⁷, Esther M. González-Gil²⁰¹, Marcela Gonzalez-Gross Margot González-Leon³⁷, Juan P. González-Rivas³⁵¹, Clicerio González-Villalpando³⁵², María-Elena González-Villalpando³⁵³, Angel R. Gonzalez³⁵⁴, Frederic Gottrand Antonio Pedro Graça³⁵⁵, Sidsel Graff-Iversen⁸³, Dušan Grafnetter³⁵⁶, Aneta Grajda³⁵⁷, Maria G. Grammatikopoulou³⁵⁸, Ronald D. Gregor¹²⁰, Maria João Gregório³¹ Else Karin Grøholt⁸³, Anders Grøntved²²⁵, Giuseppe Grosso³²⁸, Gabriella Gruden¹⁵⁸ Dongfeng Gu³⁵⁹, Viviana Guajardo³⁶⁰, Emanuela Gualdi-Russo³⁶¹, Pilar Guallar-Castillón¹⁰⁶ Andrea Gualtieri³⁶², Elias F. Gudmundsson³⁶³, Vilmundur Gudnason⁸⁷, Ramiro Guerrero³⁶⁴, Idris Guessous²⁵⁰, Andre L. Guimaraes³⁶⁵, Martin C. Gulliford³⁶ Johanna Gunnlaugsdottir³⁶³, Marc J. Gunter³⁶⁷, Xiu-Hua Guo³⁶⁸, Yin Guo³⁶⁹, Prakash C. Gupta³⁷⁰, Rajeev Gupta³⁷¹, Oye Gureje³⁷², Finique Gutiérrez González³²⁹, Laura Gutierrez³⁷³, Felix Gutzwiller¹⁶⁶, Xinyi Gwee²¹⁴, Seongjun Ha³⁷⁴, Farzad Hadaegh³⁷⁵, Charalambos A. Hadjigeorgiou³⁷⁶, Rosa Haghshenas¹², Hamid Hakimi²⁹⁸, Jytte Halkjær³⁷⁷, Ian R. Hambleton³⁷⁸, Behrooz Hamzeh³⁷⁹, Willem A. Hanekom³⁸⁰, Dominique Hange¹⁵³, Abu A. M. Hanif²⁴, Sari Hantunen¹⁹, Jie Hao³⁶⁹, Carla Menêses Hardman³⁸¹ Rachakulla Hari Kumar²¹, Tina Harmer Lassen¹⁰¹, Javad Harooni³⁸² Seyed Mohammad Hashemi-Shahri⁷⁹, Maria Hassapidou³⁸³, Jun Hata³⁸⁴, Teresa Haugsgjerd³⁸⁵, Alison J. Hayes¹²⁴, Jiang He³⁸⁶, Yuan He³⁸⁷, Yuna He³⁸⁸, Regina Heidinger-Felső³⁸⁹, Margit Heier²⁷², Tatjana Hejgaard³⁹⁰ Marleen Elisabeth Hendriks³⁹¹, Rafael dos Santos Henrique³⁸¹, Ana Henriques⁸², Leticia Hernandez Cadena³⁵², Sauli Herrala⁹², Marianella Herrera-Cuenca¹⁷⁴ Victor M. Herrera³⁹², Isabelle Herter-Aeberli³⁹³, Karl-Heinz Herzig^{93,92}, Ramin Heshmat³⁹⁴, Allan G. Hill²⁵⁵, Sai Yin Ho³⁹⁵, Suzane C. Ho³⁹⁶, Michael Hobs³⁷⁷, Doroteia A. Höfelmann³⁸⁶, Michelle Holdsworth²⁵⁶, Reza Homayounfa³⁹⁹, Clara Homs^{400,407}, Wilma M. Hopman⁴⁰², Andrea R. V. R. Horimoto¹³⁹, Claudia M. Hormiga⁴⁰³, Bernardo L. Horta⁹⁰, Leila Houti⁴⁰⁴ Christina Howitt³⁷⁸, Thein Thein Htay⁴⁰⁵, Aung Soe Htet⁵³, Maung Maung Than Htike⁴⁰⁶, Yonghua Hu²², José María Huerta²²³, Ilpo Tapani Huhtaniemi¹, Laetitia Huiart⁴⁰⁷ Constanta Huidumac Petrescu²⁴², Martijn Huisman⁴⁰⁸, Abdullatif Husseini³⁵, Chinh Nguyen Huu²⁶⁶, Inge Huybrechts³⁶⁷, Nahla Hwalla⁴⁰⁹, Jolanda Hyska¹⁸⁴ Licia Iacoviello^{164,308}, Ellina M. Iakupova¹⁴⁹, Jesús M. Ibarluzea²²³, Mohsen M. Ibrahim⁴¹⁰, Norazizah Ibrahim Wong⁹, M. Arfan Ikram⁴¹¹, Carmen Iñiguez⁴¹², Violeta Iotova⁴ Vilma E. Irazola³⁷³, Takafumi Ishida⁴¹⁴, Godsent C. Isiguzo⁴¹⁵, Muhammad Islam⁴¹⁶ Sheikh Mohammed Shariful Islam⁴¹⁷, Duygu Islek⁴¹⁸, Ivaila Y. Ivanova-Pandourska⁴¹⁹, Masanori Iwasaki⁴²⁰, Tuija Jääskeläinen²⁰, Rod T. Jackson¹²⁶, Jeremy M. Jacobs⁴²¹, Michel Jadoul⁴²², Tazeen Jafar²⁰⁷, Bakary Jallow⁴²³, Kenneth James²⁸⁹, Kazi M. Jamil⁴²⁴ Konrad Jamrozik^{337,777}, Anna Jansson⁴²⁵, Imre Janszky⁴²⁶, Edward Janus⁴²⁷, Juel Jarani⁴²⁸, Marjo-Riitta Jarvelin^{1,93}, Grazyna Jasienska³²⁶, Ana Jelaković¹¹¹, Bojan Jelaković²⁷, Garry Jennings⁴²⁹, Chao Qiang Jiang⁴³⁰, Ramon O. Jimenez⁴³¹, Karl-Heinz Jöckel²⁹³ Michel Joffres⁴³², Jari J. Jokelainen⁹², Jost B. Jonas⁴³³, Jitendra Jonnagaddala⁴³ Torben Jørgensen¹⁰, Pradeep Joshi⁴³⁵, Josipa Josipović¹¹¹, Farahnaz Joukar⁴³ Jacek J. Jóźwiak⁴³⁷, Debra S. Judge³⁹⁷, Anne Juolevi²⁰, Gregor Jurak²⁸, Iulia Jurca Simina¹¹, Vesna Juresa²⁷, Rudolf Kaaks¹⁷⁷, Felix O. Kaducu⁴³⁸, Anthony Kafatos⁴³⁹, Mónika Kaj⁴⁴ Eero O. Kajantie²⁰, Natia Kakutia⁴⁴¹, Daniela Kállayová⁴⁴², Zhanna Kalmatayeva²⁴ Ofra Kalter-Leibovici²¹⁷, Yves Kameli²⁵⁶, Freja B. Kampmann¹⁰, Kodanda R. Kanala⁴⁴ Srinivasan Kannan⁴⁴⁴, Efthymios Kapantais⁴⁴⁵, Eva Karaglani⁴⁴⁶, Argyro Karakosta⁴ Line L. Kårhus¹⁰, Khem B. Karki⁴⁴⁸, Philippe B. Katchunga⁴⁴⁹, Marzieh Katibeh⁴⁵⁰,

Joanne Katz⁴⁵¹, Peter T. Katzmarzyk⁴⁵², Jussi Kauhanen¹⁹, Prabhdeep Kaur⁴⁵³ Maryam Kavousi⁴¹¹, Gyulli M. Kazakbaeva¹⁴⁹, François F. Kaze⁸⁸, Calvin Ke⁴⁵⁴, Ulrich Keil⁴⁵⁵, Lital Keinan Boker⁴⁵⁶, Sirkka Keinänen-Kiukaanniemi⁹², Roya Kelishadi⁴⁵⁷, Cecily Kelleher¹²⁷, Han C. G. Kemper²¹⁹, Maryam Keramati²⁹⁷, Alina Kerimkulova⁴⁵⁸, Mathilde Kersting⁴⁵⁹, Timothy Key⁴⁴, Yousef Saleh Khader¹²¹, Arsalan Khaledifar⁴⁶⁰, Davood Khalili³⁹⁹, Kay-Tee Khaw⁴⁶¹, Bahareh Kheiri³⁹⁹, Motahareh Kheradmand⁴⁶², Alireza Khosravi⁴⁶³, Ilse M. S. L. Khouw¹⁷³, Ursula Kiechl-Kohlendorfer⁴⁶⁴, Sophia J. Kiechl⁴⁶⁵, Stefan Kiechl^{464,465}, Japhet Killewo⁴⁶⁶, Hyeon Chang Kim⁴⁶⁷, Jeongseon Kim⁴⁶⁸, Jenny M. Kindblom^{153,469}, Andrew Kingston⁴⁷⁰, Heidi Klakk⁴⁷¹, Magdalena Klimek³²⁶, Jeannette Klimont⁴⁷², Jurate Klumbiene¹³⁷, Michael Knoflach⁴⁶⁴, Bhawesh Koirala⁴⁷³, Elin Kolle⁷⁶ Patrick Kolsteren¹⁷², Jürgen König⁴⁷⁴, Raija Korpelainen⁹³, Paul Korrovits⁴⁷⁵, Magdalena Korzycka³¹⁰, Jelena Kos¹¹¹, Seppo Koskinen²⁰, Katsuyasu Kouda⁴⁷⁶, Éva Kovács⁴⁷⁷, Viktoria Anna Kovacs⁴⁴⁰, Irina Kovalskys⁴⁷⁸, Sudhir Kowlessur⁴⁷⁹, Slawomir Koziel³⁴⁷ Jana Kratenova¹⁹⁵, Wolfgang Kratzer⁴⁸⁰, Vilma Kriaucioniene¹³⁷, Susi Kriemler¹⁶ Peter Lund Kristensen²⁵, Helena Krizan⁴⁸¹, Maria F. Kroker-Lobos⁴⁸², Steinar Krokstad⁴²⁶, Daan Kromhout¹⁹⁷, Herculina S. Kruger^{483,484}, Ruan Kruger^{483,484}, Łukasz Kryst⁴⁸⁵, Ruzena Kubinova¹⁹⁵, Renata Kuciene¹³⁷, Urho M. Kujala⁴⁸⁶, Enisa Kujundzic⁴ Zbigniew Kulaga³⁵⁷, Mukhtar Kulimbet^{280,89}, R. Krishna Kumar⁴⁸⁸, Marie Kunešová⁴⁸⁹, Pawel Kurjata²⁷⁶, Yadlapalli S. Kusuma⁴⁹⁰, Vladimir Kutsenko¹⁰³, Kari Kuulasmaa²⁰, Catherine Kyobutungi⁴⁹¹, Quang Ngoc La⁴⁹², Fatima Zahra Laamiri⁴⁹³ Carl Lacharitz, Karl J. Lackner¹⁴⁰, Youcef Laid¹⁴³⁴, Lachmie Lall⁴⁹⁵, Tai Hing Lam³⁸ Maritza Landaeta Jimenez¹⁷⁴, Edwige Landais²⁵⁶, Vera Lanska³⁵⁶, Georg Lappas Bagher Larijani⁴⁹⁷, Simo Pone Larissa⁴⁹⁸, Tint Swe Latt⁴⁹⁹, Martino Laurenzi⁵⁰⁰ Laura Lauria²⁶⁹, Maria Lazo-Porras¹³⁶, Gwenaëlle Le Coroller⁶⁶, Khanh Le Nguyen Bao²⁶⁶, Laura Laura²¹³, maria Lazu-Forras²¹, Gwenaette Leo Gorotter¹, Rutani Longu, Guena Agnès Le Port²⁵⁶, Tuyen D. Le²⁶⁶, Jeannette Lee^{214,501}, Jeonghee Lee⁴⁶⁸, Paul H. Lee⁵⁰² Nils Lehmann²⁸³, Terho Lehtimäki^{503,504}, Daniel Lemogoum⁵⁰⁵, Branimir Leskošek²⁸, Justyna Leszczak¹⁰⁷, Katja B. Leth-Møller¹⁰, Gabriel M. Leung³⁹⁵, Naomi S. Levitt⁸⁰⁶ Yanping Li⁷, Merike Liivak³⁴⁰, Christa L. Lilly⁵⁰⁷, Charlie Lim^{214,501}, Wei-Yen Lim^{214,501} M. Fernanda Lima-Costa⁵⁰⁸, Hsien-Ho Lin²²², Xu Lin⁵⁰⁹, Yi-Ting Lin⁵¹⁰, Lars Lind⁵¹⁰, Vijaya Lingam³³⁵, Birgit Linkohr²⁷², Allan Linneberg¹⁰, Lauren Lissner¹⁵³ Mieczysław Litwin³⁵⁷, Jing Liu⁵¹¹, Lijuan Liu³⁶⁹, Wei-Cheng Lo⁵¹², Helle-Mai Loit³⁴⁰, Khuong Quynh Long⁴⁹², Guadalupe Longo Abril⁵¹³, Luis Lopes²⁰⁰, Marcus V. V. Lopes¹¹⁹, Oscar Lopes⁵¹⁴, Esther Lopez-Garcia¹⁰⁶, Tania Lopez⁵¹⁵, Paulo A. Lotufo¹³⁹, José Eugenio Lozano⁵¹⁶, Janice L. Lukrafka⁵¹⁷, Dalia Luksiene¹³⁷, Annamari Lundqvist²⁰, Nuno Lunet²⁰⁰, Charles Lunogelo⁵¹⁸, Michala Lustigová^{228,195}, Edyta Łuszczki¹⁰⁷ Jean-René M'Buyamba-Kabangu⁵¹⁹, Guansheng Ma²², Xu Ma³⁸¹ George L. L. Machado-Coelho¹²², Aristides M. Machado-Rodrigues²⁵, Enguerran Macia²⁷⁸, Luisa M. Macieira⁵²⁰, Ahmed A. Madar⁵³, Anja L. Madsen¹⁰, Gladys F. Maestre⁵²¹, Stefania Maggi⁵²², Dianna J. Magliano⁵²³, Sara Magnacca²⁵⁸, Emmanuella Magriplis⁵²⁴, Gowri Mahasampath¹²⁸, Bernard Maire²⁵⁶, Marjeta Majer²⁷, Marcia Makdisse⁵ Päivi Mäki²⁰, Fatemeh Malekzadeh²⁷³, Reza Malekzadeh^{302,273}, Rahul Malhotra²⁰⁷ Kodavanti Mallikharjuna Rao²¹, Sofia K. Malyutina⁵²⁶, Lynell V. Maniego⁴⁵, Yannis Manios⁴⁴⁶, Masimango Imani Manix⁵²⁷, Jim I. Mann²⁶, Fariborz Mansour-Ghanaei⁴³⁶, Taru Manyanga⁵²⁸ Enzo Manzato⁵²⁹, Anie Marcil²³², Paula Margozzini¹³⁸, Joany Mariño⁵³⁰, Anastasia Markaki⁵³¹, Oonagh Markey⁵³², Eliza Markidou Ioannidou⁵³³, Pedro Margues-Vidal^{534,53} Larissa Pruner Marques⁵³⁶, Jaume Marrugat^{537,538}, Yves Martin-Prevel²⁵⁶, Rosemarie Martin⁵³⁹, Reynaldo Martorell⁴¹⁸, Eva Martos⁵⁴⁰, Katharina Maruszczak⁵⁴¹, Stefano Marventano³²⁸, Giovanna Masala⁵⁴², Luis P. Mascarenhas⁵⁴³, Shariq R. Masoodi⁵⁴⁴, Ellisiv B. Mathiesen⁵⁴⁵, Prashant Mathur⁵⁴⁶, Alicia Matijasevich¹³⁹, Piotr Matłosz¹⁰⁷ Tandi E. Matsha⁵⁴⁷, Victor Matsudo⁵⁴⁸, Christina Mavrogianni⁴⁴⁶, Artur Mazur¹⁰⁷ Jean Claude N. Mbanya⁸⁸, Shelly R. McFarlane²⁸⁹, Stephen T. McGarvey⁵⁴⁹, Martin McKee⁵⁵⁰, Stela McLachlan⁵⁵¹, Rachael M. McLean²⁶, Scott B. McLean²³², Margaret L. McNairy⁵⁵², Breige A. McNulty¹²⁷, Sounnia Mediene Benchekor⁴⁰⁴, Jurate Medzioniene¹³⁷ Parinaz Mehdipour¹², Kirsten Mehlig¹⁵³, Amir Houshang Mehrparvar⁵¹, Aline Meirhaeghe⁵⁵³, Jørgen Meisfjord⁸³, Christa Meisinger²⁷², Jesus D. Melgarejo¹⁶⁷, Marina Melkumova⁵⁵⁴, João Mello³¹⁹, Fabián Méndez¹¹⁴, Carlos O. Mendivil⁵⁵⁵, Ana Maria B. Menezes⁹⁰ Geetha R. Menon²⁰⁸, Gert B. M. Mensink⁵⁵⁶, Maria Teresa Menzano³²⁷, Indrapal I. Meshram²¹, Diane T. Meto⁵⁵⁷, Jie Mi²¹¹, Kim F. Michaelsen⁴², Nathalie Michels¹⁷², Kairit Mikkel³¹² Karolina Miłkowska³²⁶, Jody C. Miller²⁶, Olga Milushkina⁵⁵⁸, Cláudia S. Minderico⁵⁵ G. K. Mini⁵⁶⁰, Juan Francisco Miquel¹³⁸, J. Jaime Miranda¹³⁶, Mohammad Reza Mirjalili⁵¹, Daphne Mirkopoulou⁵⁶¹, Erkin Mirrakhimov⁴⁵⁸, Marjeta Mišigoj-Duraković²⁷, Antonio Mistretta³²⁸, Veronica Mocanu⁵⁶², Pietro A. Modesti⁵⁶³, Sahar Saeedi Moghaddam¹², Bahram Mohajer¹², Mostafa K. Mohamed⁵⁶⁴, Shukri F. Mohamed⁴⁹¹, Kazem Mohammad²¹ Mohammad Reza Mohammadi²⁷³, Zahra Mohammadi²⁷³, Noushin Mohammadifard⁵⁶⁵, Reza Mohammadpourhodki²⁹⁷, Viswanathan Mohan⁷⁸, Salim Mohanna¹¹ Muhammad Fadhli Mohd Yusoff⁹, Iraj Mohebbi⁴⁶, Farnam Mohebi⁴, Marie Moitry^{147,566}, Line T. Møllehave¹⁰, Niels C. Møller²²⁵, Dénes Molnár³⁸⁹, Amirabbas Momenan³⁶ Charles K. Mondo⁵⁶⁷, Roger A. Montenegro Mendoza⁵⁶⁸, Eric Monterrubio-Flores³⁵², Kotsedi Daniel K. Monyeki⁵⁶⁹, Jin Soo Moon²²⁴, Mahmood Moosazadeh⁴⁶² Hermine T. Mopa⁸⁸, Farhad Moradpour³³⁶, Leila B. Moreira³¹⁹, Alain Morejon⁵ Luis A. Moreno^{201,239}, Francis Morey⁵⁷¹, Karen Morgan⁵⁷², Suzanne N. Morin², Erik Lykke Mortensen⁴², George Moschonis⁵⁷³, Alireza Moslem⁵⁷⁴, Malgorzata Mossakowska⁵⁷⁵, Aya Mostafa⁵⁶⁴, Seyed-Ali Mostafavi²⁷³, Anabela Mota-Pinto²⁵, Jorge Mota²⁰⁰ Mohammad Esmaeel Motlagh²¹⁶, Jorge Motta⁵⁶⁸, Marcos André Moura-dos-Santos¹¹⁷, Yeva Movsesyan⁵⁵⁴, Kelias P. Msyamboza⁵⁷⁶, Thet Thet Mu⁵⁷⁷, Magdalena Muc²⁵ Florian Muca⁵⁷⁸, Boban Mugoša⁴⁸⁷, Maria L. Muiesan⁵⁷⁹, Martina Müller-Nurasyid¹⁴⁰, Thomas Münzel¹⁴⁰, Jaakko Mursu¹⁹, Elaine M. Murtagh⁵⁸⁰, Kamarul Imran Musa³¹³, Sanja Musić Milanović^{481,27}, Vera Musil²⁷, Geofrey Musinguzi⁵⁸¹, Muel Telo M. C. Muyer⁵⁸², Iraj Nabipour⁵⁸³, Shohreh Naderimagham¹², Gabriele Nagel⁵⁸⁴, Farid Najafi³⁷⁹ Harunobu Nakamura⁴⁷⁶, Hanna Nalecz³¹⁰, Jana Námešná⁹⁴, Ei Ei K. Nang^{214,501} Vinay B. Nangia⁵⁸⁵, Martin Nankap⁵⁸⁶, Sameer Narake³⁷⁰, Paola Nardone²⁶⁹, Take Naseri⁵⁸⁷, Matthias Nauck⁵³⁰, William A. Neal⁵⁰⁷, Azim Nejatizadeh²⁸⁴, Chandini Nekkantti⁴³⁴, Keiu Nelis³⁴⁰, Ilona Nenko³²⁶, Martin Neovius⁵⁸⁸, Flavio Nervi¹³⁸, Tze Pin Ng²¹⁴, Chung T. Nguyen⁵⁸⁹, Nguyen D. Nguyen⁵⁹⁰, Quang Ngoc Nguyen⁵⁹¹, Michael Y. Ni³⁹⁵, Rodica Nicolescu²⁴², Peng Nie⁵⁹², Ramfis E. Nieto-Martínez⁵⁹³, Yury P. Nikitin⁵²⁶ Guang Ning¹⁴⁵, Toshiharu Ninomiya³⁸⁴, Nobuo Nishi¹⁶, Sania Nishtar⁵⁹⁴, Marianna Noale⁵²², Oscar A. Noboa¹⁴⁶, Helena Nogueira²⁵, Maria Nordendahl³¹⁴, Børge G. Nordestgaard^{43,42},

Davide Noto¹⁰⁸, Natalia Nowak-Szczepanska³⁴⁷, Mohannad Al Nsour⁵⁹⁵, Irfan Nuhoğlu²⁹ Baltazar Nunes^{115,116}, Eha Nurk³⁴⁰, Fred Nuwaha⁵⁸¹, Moffat Nyirenda⁵⁵⁰, Terence W. O'Neill⁵⁹⁶, Dermot O'Reilly²⁹⁹, Galina Obreja⁵⁹⁷, Caleb Ochimana⁷, Angélica M. Ochoa-Avilés²⁷¹ Eiji Oda⁵⁹⁸, Augustine N. Odili⁵⁹⁹, Kyungwon Oh⁶⁰⁰, Kumiko Ohara⁴⁷⁶, Claes Ohlsson^{153,469}, Ryutaro Ohtsuka⁶⁰¹, Örn Olafsson³⁶³, Maria Teresa A. Olinto³¹⁹, Isabel O. Oliveira⁹⁰, Mohd Azahadi Omar⁹, Saeed M. Omar⁶⁰², Altan Onat^{603,777}, Sok King Ong⁶ N. Charlotte Onland-Moret³³³, Lariane M. Ono³⁹⁸, Pedro Ordunez¹⁸⁹, Rui Ornelas⁶⁰⁵ Ana P. Ortiz⁶⁰⁶, Pedro J. Ortiz¹³⁶, Merete Osler¹⁰, Clive Osmond²³⁵, Sergej M. Ostojic²⁶⁵, Afshin Ostovar⁶⁰⁷, Johanna A. Otero⁶⁰⁸, Kim Overvad⁴⁵⁰, Ellis Owusu-Dabo⁶ Fred Michel Paccaud¹⁶⁹, Ioannis Pagkalos³⁸³, Elena Pahomova²⁸², Karina Mary de Paiva¹¹⁹, Andrzej Pająk³²⁶, Alberto Palloni⁶¹⁰, Luigi Palmieri²⁶⁹, Wen-Harn Pan²¹⁰ Songhomitra Panda-Jonas⁶¹¹, Arvind Pandey²⁰⁸, Francesco Panza⁶¹², Mariela Paoli¹⁷⁹, Sousana K. Papadopoulou³⁸³, Dimitrios Papandreou⁶¹³, Rossina G. Pareja² Soon-Woo Park⁶¹⁴, Suyeon Park⁶⁰⁰, Winsome R. Parnell²⁶, Mahboubeh Parsaeian²⁷³, Ionela M. Pascanu⁶¹⁵, Patrick Pasquet⁷², Nikhil D. Patel⁶¹⁶, Marcos Pattussi² Halyna Pavlyshyn³²³, Raimund Pechlaner⁴⁶⁴, Ivan Pećin¹¹¹, Mangesh S. Pednekar³⁷⁰ João M. Pedro⁶¹⁷, Nasheeta Peer⁶¹⁸, Sergio Viana Peixoto⁵⁰⁸, Markku Peltonen²⁰ Alexandre C. Pereira¹³⁹, Marco A. Peres⁶¹⁹, Cvnthia M. Pérez⁶⁰⁶, Valentina Peterkova¹⁶² Annette Peters²⁷², Astrid Petersmann⁵³⁰, Janina Petkeviciene¹³⁷, Ausra Petrauskiene¹³⁷ Olga Petrovna Kovtun⁸⁰, Emanuela Pettenuzzo⁶²⁰, Niloofar Peykari²⁶⁴, Norbert Pfeiffer¹⁴ Modou Chevassin Phall⁴²³ Son Thai Pham⁶²¹ Rafael N. Pichardo⁶²² Daniela Pierannunzio²⁶⁹ Iris Pigeot⁵⁴, Hynek Pikhart¹⁵⁹, Aida Pilav⁶²³, Lorenza Pilotto⁶²⁴, Francesco Pistelli⁶² Freda Pitakaka⁶²⁶, Aleksandra Piwonska²⁷⁶, Andreia N. Pizarro²⁰⁰, Pedro Plans-Rubió⁶²⁷, Alina G. Platonova⁶²⁸, Bee Koon Poh⁶²⁹, Hermann Pohlabeln⁵⁴, Nadija S. Polka⁶² Raluca M. Pop⁶¹⁵, Stevo R. Popovic¹⁵¹, Miquel Porta⁵³⁸, Georg Posch²³⁴, Anil Poudyal¹⁵⁰ Dimitrios Poulimeneas³⁸³, Hamed Pouraram²⁷³, Farhad Pourfarzi⁶³⁰, Akram Pourshams²⁷³. Hossein Poustchi²⁷³, Rajendra Pradeepa⁷⁸, Alison J. Price⁵⁵⁰, Jacqueline F. Price⁵⁵¹ Antonio Prista⁶³¹, Rui Providencia¹⁵⁹, Jardena J. Puder⁵³⁴, Iveta Pudule⁶³², Maria Puiu¹¹, Margus Punab⁴⁷⁵, Muhammed S. Qadir⁶³³, Radwan F. Qasrawi³¹, Mostafa Qorbani⁶ Hedley K. Quintana⁵⁶⁸, Pedro J. Quiroga-Padilla⁵⁵⁵, Tran Quoc Bao⁶³⁵, Stefan Rach⁵⁴, Ivana Radic³⁶⁵, Ricardas Radisauskas¹³⁷, Salar Rahimikazerooni³⁰², Mahfuzar Rahman⁶³⁶, Mahmudur Rahman⁶³⁷, Olli Raitakari⁶³⁸, Manu Raj⁴⁸⁸, Tamerlan Rajabov⁶³⁹, Sherali Rakhmatulloev³⁴, Ivo Rakovac¹⁵, Sudha Ramachandra Rao⁴⁵³ Ambady Ramachandran²⁰⁶, Otim P. C. Ramadan⁶⁴⁰, Virgílio V. Ramires⁶⁴¹ Jacqueline Ramke¹²⁶, Elisabete Ramos⁹⁷, Rafel Ramos⁶⁴², Lekhraj Rampal⁶⁴³, Sanjay Rampal⁶⁴⁴, Lalka S. Rangelova²¹⁸, Vayia Rarra⁶⁴⁵, Ramon A. Rascon-Pacheco³⁷, Cassiano Ricardo Rech¹¹⁹, Josep Redon⁴¹², Paul Ferdinand M. Reganit⁶⁴⁶ Valéria Regecová⁶⁴⁷, Jane D. P. Renner⁶⁴⁸, Judit A. Repasy³⁸⁹, Cézane P. Reuter⁶⁴⁸, Luis Revilla⁵¹⁵, Abbas Rezaianzadeh³⁰², Yeunsook Rho³⁷⁴, Lourdes Ribas-Barba⁶⁴⁸ Robespierre Ribeiro^{650,777}, Elio Riboli¹, Adrian Richter⁵³⁰, Fernando Rigo⁶⁵¹, Attilio Rigotti¹³⁸, Natascia Rinaldo³⁶¹, Tobias F. Rinke de Wit⁶⁵², Ana I. Rito¹¹⁵, Raphael M. Ritti-Dias⁶⁵³ Juan A. Rivera³⁵², Reina G. Roa⁶⁵⁴, Louise Robinson⁴⁷⁰, Cynthia Robitaille⁶ Romana Roccaldo²⁰⁴, Daniela Rodrigues²⁵, Fernando Rodríguez-Artalejo¹⁰⁶, María del Cristo Rodriguez-Perez²⁶², Laura A. Rodríguez-Villamizar⁶⁵⁶, Andrea Y. Rodríguez⁶⁵⁷, Ulla Roggenbuck²⁹³, Peter Rohloff⁶⁵⁸, Fabian Rohner⁶⁵⁹, Rosalba Rojas-Martinez³⁵² Nipa Rojroongwasinkul⁸, Dora Romaguera²³⁹, Elisabetta L. Romeo⁶⁶⁰, Rafaela V. Rosario⁶⁶¹, Annika Rosengren^{153,469}, Ian Rouse⁶⁶², Vanessa Rouzier⁶⁶³, Joel G. R. Roy² Maira H. Ruano⁶⁶⁴, Adolfo Rubinstein³⁷³, Frank J. Rühli¹⁶⁶, Jean-Bernard Ruidavets¹⁶⁵. Blanca Sandra Ruiz-Betancourt³⁷, Maria Ruiz-Castell⁶⁶, Emma Ruiz Moreno⁶ Iuliia A. Rusakova¹⁴⁹, Kenisha Russell Jonsson⁴²⁵, Paola Russo⁶⁶⁶, Petra Rust⁴⁷ Marcin Rutkowski⁶⁶⁷, Marge Saamel³⁴⁰, Charumathi Sabanayagam²⁰⁹, Hamideh Sabbaghi³⁹⁹, Elena Sacchini³⁶², Harshpal S. Sachdev⁶⁶⁸, Alireza Sadjadi²⁷³, Ali Reza Safarpour³⁰ Sare Safi³⁹⁹, Saeid Safiri³⁰⁰, Mohammad Hossien Saghi⁵⁷⁴, Olfa Saidi¹²⁹, Nader Saki²¹⁶, Sanja Šalaj²⁷, Benoit Salanave²⁵⁷, Eduardo Salazar Martinez³⁵², Calogero Saleva⁵⁴², Diego Salmerón²²³, Veikko Salomaa²⁰, Jukka T. Salonen²⁹⁶, Massimo Salvetti⁵⁷⁹ Margarita Samoutian⁶⁶⁹, Jose Sánchez-Abanto⁶⁷⁰, Inés Sánchez Rodríguez³⁴⁴, Sandjaja⁶⁷¹, Susana Sans⁶⁷², Loreto Santa Marina⁶⁷³, Ethel Santacruz¹³², Diana A. Santos⁵⁵ Ina S. Santos⁹⁰, Lèlita C. Santos⁵²⁰, Maria Paula Santos²⁰⁰, Osvaldo Santos⁶⁷⁴, Rute Santos²⁰⁰, Tamara R. Santos⁶⁷⁵, Jouko L. Saramies⁶⁷⁶, Luis B. Sardinha⁵⁵⁹, Nizal Sarrafzadegan⁵ Thirunavukkarasu Sathish⁴¹⁸, Kai-Uwe Saum¹⁷⁷, Savvas Savva³⁷⁶, Mathilde Savy Norie Sawada⁶⁷⁷, Mariana Sbaraini³¹⁹, Marcia Scazufca⁶⁷⁸, Beatriz D. Schaan³ Angelika Schaffrath Rosario⁵⁵⁶, Herman Schargrodsky⁶⁷⁹, Anja Schienkiewitz⁵⁵⁶ Karin Schindler⁶⁸⁰, Sabine Schipf⁵³⁰, Carsten O. Schmidt⁵³⁰, Ida Maria Schmidt⁶⁸¹, Andrea Schneider²⁷², Peter Schnohr⁴³, Ben Schöttker¹⁷⁷, Sara Schramm²⁶ Stine Schramm²²⁵, Helmut Schröder²²³, Constance Schultsz⁶⁸², Matthias B. Schulze⁶⁸³, Aletta E. Schutte^{434,684}, Sylvain Sebert⁹³, Moslem Sedaghattalab³⁸², Rusidah Selamat⁹, Vedrana Sember²⁸, Abhijit Sen⁶⁸⁵, Idowu O. Senbanjo⁶⁸⁶, Sadaf G. Sepanlou²⁷³ Guillermo Sequera¹³², Luis Serra-Majem⁶⁸⁷, Jennifer Servais²³², Ľudmila Ševčíková⁶⁸⁸ Svetlana Shalnova¹⁰³, Teresa Shamah-Levy³⁵², Seyed Morteza Shamshirgaran⁹⁸, Coimbatore Subramaniam Shanthirani⁷⁸, Maryam Sharafkhah²⁷³, Sanjib K. Sharma⁴⁷ Jonathan E. Shaw⁵²³, Amaneh Shayanrad²⁷³, Ali Akbar Shayesteh²¹⁶, Lela Shengelia⁴⁴ Zumin Shi³³, Kenji Shibuya³⁶⁶, Hana Shimizu-Furusawa⁶⁵⁷, Tal Shimony⁴⁵⁶, Rahman Shiri⁵⁹⁰, Namuna Shrestha⁵⁵, Khairil Si-Ramlee⁶⁰⁴, Alfonso Siani⁵⁶⁶, Rosalynn Siantar²⁰⁹, Abla M. Sibai⁴⁰⁹, Labros S. Sidossis⁶⁹¹, Natalia Silitrari⁶⁹², Antonio M. Silva¹²³, Caroline Ramos de Moura Silva¹¹⁷, Diego Augusto Santos Silva¹¹⁹, Kelly S. Silva¹¹⁹, Xueling Sim^{214,501}, Mary Simon²⁰⁶, Judith Simons⁶⁹³, Leon A. Simons⁴³⁴, Agneta Sjöberg¹⁵³, Michael Sjöström^{588,777}, Natalia A. Skoblina⁵⁵⁸, Gry Skodje⁶⁹⁴, Tatyana Slazhnyova³², Jolanta Slowikowska-Hilczer¹⁰⁵, Przemysław Slusarczyk⁵⁷⁵, Liam Smeeth⁵⁵⁰, Hung-Kwan So³⁹⁵, Fernanda Cunha Soares¹¹⁷, Grzegorz Sobek¹⁰⁷, Eugène Sobngwi⁸⁸, Morten Sodemann²²⁵, Stefan Söderberg³¹⁴, Moesijanti Y. E. Soekatri⁶⁹⁵ Agustinus Soemantri^{696,777}, Reecha Sofat¹⁵⁹, Vincenzo Solfrizzi⁶⁹⁷, Mohammad Hossein Somi³⁰⁰, Emily Sonestedt³³⁸, Yi Song²², Sajid Soofi⁵², Thorkild I. A. Sørensen⁴², Elin P. Sørgjerd⁴²⁶, Charles Sossa Jérome⁶⁰ Victoria E. Soto-Rojas³⁶⁴, Aïcha Soumaré⁶⁹⁹, Alfonso Sousa-Poza⁷⁰⁰, Slavica Sovic²⁷ Bente Sparboe-Nilsen⁷⁰¹, Karen Sparrenberger³¹⁹, Phoebe R. Spencer³⁹⁷, Angela Spinelli²⁶⁹, Igor Spiroski^{702,703}, Jan A. Staessen¹⁶⁷, Hanspeter Stamm⁷⁰⁴, Kaspar Staub¹⁶⁶, Bill Stavreski⁴²⁹, Jostein Steene-Johannessen⁷⁶, Peter Stehle⁷⁰⁵, Aryeh D. Stein⁴¹⁸, George S. Stergiou⁴⁴⁷,

Jochanan Stessman⁴²¹, Ranko Stevanović⁴⁸¹, Jutta Stieber^{272,777}, Doris Stöckl²⁷², Jakub Stokwiszewski⁷⁰⁶, Ekaterina Stoyanova⁷⁰⁷, Gareth Stratton¹⁸², Karien Stronks⁴⁹, Maria Wany Strufaldi³¹⁵, Lela Sturua⁴⁴¹, Ramón Suárez-Medina²⁶⁰, Machi Suka⁷⁰⁸ Chien-An Sun⁷⁰⁹, Liang Sun⁵⁰⁹, Johan Sundström⁵¹⁰, Yn-Tz Sung³⁹⁶, Jordi Sunyer⁶⁷ Paibul Suriyawongpaisal⁸, Nabil William G. Sweis⁷¹⁰, Boyd A. Swinburn¹²⁶, Rody G. Sy⁶⁴⁶, René Charles Sylva⁷¹¹, Moyses Szklo⁴⁵¹, Lucjan Szponar⁷⁰⁶, Lorraine Tabone²³⁰, E. Shyong Tai^{214,501}, Konstantinos D. Tambalis⁴⁴⁷, Mari-Liis Tammesoo³¹², Abdonas Tamosiunas¹³⁷, Eng Joo Tan⁷¹², Xun Tang²², Maya Tanrygulyyeva⁷¹³, Frank Tanser⁷¹⁴, Yong Tao²², Mohammed Rasoul Tarawneh⁷¹⁵, Jakob Tarp⁴⁵⁰, Carolina B. Tarqui-Mamani⁶⁷⁰, Radka Taxová Braunerová⁴⁸⁹, Anne Taylo¹³³⁷, Julie Taylo¹⁵⁹, Félicité Tchibindat⁷¹⁶, Saskia Te Velde⁷¹⁷, William R. Tebar²²⁶, Grethe S. Tell³⁸⁵, Tania Tello¹³⁶, Yih Chung Tham²⁰⁹, K. R. Thankappan³⁴¹, Holger Theobald¹⁹⁸, Xenophon Theodoridis³³⁹, Nihal Thomas¹²⁸, Barbara Thorand²⁷², Betina H. Thuesen¹⁰, Lubica Tichá⁶⁸⁸, Erik J. Timmermans⁷ Dwi H. Tjandrarini⁷¹⁹, Anne Tjonneland³⁷⁷, Hanna K. Tolonen²⁰, Janne S. Tolstrup¹⁵², Murat Topbas²⁴⁴, Roman Topór-Nądry³²⁶, Liv Elin Torheim⁷⁰¹, María José Tormo⁷²⁰, Michael J. Tornaritis³⁷⁶, Maties Torrent⁷²¹, Laura Torres-Collado²²³, Stefania Toselli⁷²², Giota Touloumi⁴⁴⁷, Pierre Traissac²⁵⁶, Thi Tuyet-Hanh Tran⁴⁹², Mark S. Tremblay⁷²³, Areti Triantafyllou³³⁹, Dimitrios Trichopoulos^{7,777}, Antonia Trichopoulou⁷ Oanh T. H. Trinh⁵⁹⁰, Atul Trivedi⁷²⁵, Yu-Hsiang Tsao⁷²⁶, Lechaba Tshepo⁷²⁷, Maria Tsigga³⁸³, Panagiotis Tsintavis³⁸³, Shoichiro Tsugane⁶⁷⁷, John Tuitele^{728,729}, Azaliia M. Tuliakova¹ Marshall K. Tulloch-Reid²⁸⁹, Fikru Tullu⁷³⁰, Tomi-Pekka Tuomainen¹⁹, Jaakko Tuomilehto²⁰ Maria L. Turley⁷³¹, Gilad Twig^{217,732}, Per Tynelius⁵⁸⁸, Evangelia Tzala¹, Themistoklis Tzotzas⁴⁴⁵, Christopher Zourio⁶⁹⁹, Peter Ueda⁵⁸⁸, Eunice Ugel⁷³³, Flora A. M. Ukol⁷³⁴, Hanno Ulmer⁴⁶⁴, Belgin Unal²⁹⁵, Zhamyila Usupova⁵⁵, Hannu M. T. Uusitalo⁷³⁵, Nalan Uysal⁷³⁶, Justina Vaitkeviciute¹³⁷, Gonzalo Valdivia¹³⁸, Susana Vale¹³⁷, Damaskini Valvi⁷³⁸, Rob M. van Dam⁷³⁹, Bert-Jan van den Born⁴⁹, Johan Van der Heyden²⁵¹, Yvonne T. van der Schouw³³³, Koen Van Herck¹⁷², Wendy Van Lippevelde¹⁷², Hoang Van Minh⁴⁹², Natasja M. Van Schoor⁴⁰⁸, Irene G. M. van Valkengoed⁴⁹ Dirk Vanderschueren¹⁶⁷, Diego Vanuzzo⁶²⁴, Anette Varbo^{43,42}, Gregorio Varela-Moreiras⁷⁴⁰, Luz Nayibe Vargas²³⁶, Patricia Varona-Pérez²⁶⁰, Senthil K. Vasan²³⁵, Daniel G. Vasques³¹ Tomas Vega⁵¹⁶, Toomas Veidebaum³⁴⁰, Gustavo Velasquez-Melendez³³², Biruta Velika⁶³², Maïté Verloigne¹⁷², Giovanni Veronesi³⁰⁸, W. M. Monique Verschuren¹⁵⁵, Cesar G. Victora⁹⁰ Giovanni Viegi⁷⁴¹, Lucie Viet¹⁵⁵, Frøydis N. Vik¹³³, Monica Vilar⁷⁴², Salvador Villalpando³⁵², Jesus Vioque⁷⁴³, Jyrki K. Virtanen¹⁹, Sophie Visvikis-Siest⁷⁴⁴, Bharathi Viswanathan¹⁶⁸ Mihaela Vladulescu⁷⁴⁵, Tiina Vlasoff⁷⁴⁶, Dorja Vocanec²⁷, Peter Vollenweider^{534,535} Henry Völzke⁵³⁰, Ari Voutilainen¹⁹, Martine Vrijheid⁶⁷, Tanja G. M. Vrijkotte^{252,49}, Alisha N. Wade⁷⁴⁷, Thomas Waldhör⁶⁸⁰, Janette Walton¹⁸⁵, Elvis O. A. Wambiya⁴⁹¹, Wan Mohamad Wan Bebakar³¹³, Wan Nazaimoon Wan Mohamud⁷⁴⁸, Rildo de Souza Wanderley Júnior¹¹⁷, Ming-Dong Wang⁶⁵⁵, Ningli Wang³⁶⁹, Qian Wang⁷⁴⁹, Xiangjun Wang⁷⁵⁰, Ya Xing Wang³⁶⁸, Ying-Wei Wang⁷⁵¹, S. Goya Wannamethee¹⁵⁹, Nicholas Wareham⁴ Adelheid Weber¹³⁰, Karen Webster-Kerr⁷⁵², Niels Wedderkopp²²⁵, Daniel Weghuber⁵⁴¹ Wenbin Wei³⁶⁸, Aneta Weres¹⁰⁷, Bo Werner⁷⁵³, Leo D. Westbury²³⁵, Peter H. Whincup⁷⁵⁴ Kremlin Wickramasinghe¹⁵, Kurt Widhalm⁶⁸⁰, Indah S. Widyahening⁷⁵⁵, Andrzej Więcek²²⁷, Philipp S. Wild¹⁴⁰, Rainford J. Wilks²⁸⁹, Johann Willeit⁴⁶⁴, Peter Wille⁴⁶⁴, Julianne Williams¹⁵, Tom Wilsgaard⁵⁴⁵, Rusek Wojciech⁷⁵⁶, Bogdan Wojtyniak⁷⁰⁶, Kathrin Wolf²⁷², Roy A. Wong-McClure³⁰, Andrew Wong¹⁵⁹, Emily B. Wong³⁸⁰, Jyh Eiin Wong⁶²⁹, Tien Yin Wong²⁰⁷, Jean Woo³⁹⁶, Mark Woodward^{1,434}, Frederick C. Wu⁵⁹⁶, Hon-Yen Wu⁷⁵⁷, Jianfeng Wu¹⁴⁴, Li Juan Wu³⁶⁸, Shouling Wu²¹³, Justyna Wyszyńska¹⁰⁷, Haiquan Xu⁷⁵⁸, Liang Xu⁷⁵⁹, Nor Azwany Yaacob³¹³, Uruwan Yamborisut⁸, Weili Yan⁷⁶⁰, Ling Yang⁴⁴, Xiaoguang Yang³⁸⁸, Yang Yang⁷⁵⁰, Nazan Yardim²⁰³, Tabara Yasuharu²²⁷, Martha Yépez García⁷⁴², Panayiotis K. Yiallouros⁷⁶¹, Agneta Yngve⁵¹⁰, Moein Yoosefi¹², Akihiro Yoshihara⁷⁶², Qi Sheng You³⁸⁸, San-Lin You⁷⁰⁹, Novie O. Younger-Coleman²⁸⁹, Yu-Ling Yu¹⁶⁷, Yunjiang Yu⁷⁶³, Safiah Md Yusof⁷⁶⁴, Ahmad Faudzi Yusoff⁹, Luciana Zaccagni³⁶¹, Vassilis Zafiropulos⁷⁶⁵, Ahmad A. Zainuddin⁹, Seyed Rasoul Zakavi²⁹⁷, Farhad Zamani⁷⁶⁶, Sabina Zambon⁵²⁹, Antonis Zampelas⁵²⁴, Hana Zamrazilová⁴⁸⁹, Maria Elisa Zapata¹⁹⁹, Abdul Hamid Zargar⁷⁶⁷, Ko Ko Zaw⁴⁹⁹, Ayman A. Zayed⁷¹⁰, Tomasz Zdrojewski⁶⁶⁷, Magdalena Żegleń⁷⁶⁸, Kristyna Zejglicova¹⁹⁵, Tajana Zeljkovic Vrkic¹¹¹, Yi Zeng^{22,760} Luxia Zhang⁷⁷⁰, Zhen-Yu Zhang¹⁶⁷, Dong Zhao⁵¹¹, Ming-Hui Zhao⁷⁷⁰, Wenhua Zhao³⁸⁸ Yanitsa V. Zhecheva⁴¹⁹, Shiqi Zhen⁷⁷¹, Wei Zheng¹⁸⁸, Yingfeng Zheng²⁷⁰, Bekbolat Zholdin⁷⁷², Maigeng Zhou³⁸⁸, Dan Zhu⁷⁷³, Marie Zins^{342,343}, Emanuel Zitt²³⁴, Yanina Zocalo¹⁴⁰ Nada Zoghlami⁸¹, Julio Zuñiga Cisneros⁵⁶⁸, Monika Zuziak⁷⁷⁴, Zulfiqar A. Bhutta^{416,52}, Robert E. Black⁷⁷⁵ & Majid Ezzati^{1,41}

¹Imperial College London, London, UK. ²McGill University, Montreal, Québec, Canada. ³University of Essex, Colchester, UK. ⁴University of California Berkeley, Berkeley, CA, USA. ⁵University of Kent, Canterbury, UK. ⁶World Health Organization, Geneva, Switzerland. ⁷Harvard T. H. Chan School of Public Health, Boston, MA, USA. ⁸Mahidol University, Nakhon Pathom, Thailand. ⁹Ministry of Health, Kuala Lumpur, Malaysia. ¹⁰Bispebjerg and Frederiksberg Hospital, Copenhagen, Denmark. "Victor Babes University of Medicine and Pharmacy, Timisoara, Romania. ¹²Non-Communicable Diseases Research Center, Tehran, Iran. ¹³Swiss Tropical and Public Health Institute, Basel, Switzerland. ¹⁴University of Basel, Basel, Switzerland.¹⁵World Health Organization Regional Office for Europe, Copenhagen, Denmark. ¹⁶National Institutes of Biomedical Innovation, Health and Nutrition, Tokyo, Japan. ¹⁷South African Medical Research Council, Cape Town, South Africa.¹⁸Seoul National University College of Medicine, Seoul, Republic of Korea.¹⁹University of Eastern Finland, Kuopio, Finland. 20 Finnish Institute for Health and Welfare, Helsinki, Finland. 21 ICMR-National Institute of Nutrition, Hyderabad, India.²²Peking University, Beijing, China.²³Universidad de San Carlos, Guatemala City, Guatemala.²⁴BRAC James P. Grant School of Public Health, Dhaka, Bangladesh.²⁵University of Coimbra, Coimbra, Portugal.²⁶University of Otago, Dunedin, New Zealand. ²⁷University of Zagreb, Zagreb, Croatia. ²⁸University of Ljubljana, Ljubljana, Slovenia. ²⁹GroundWork, Geneva, Switzerland. ³⁰Caja Costarricense de Seguro Social, San José, Costa Rica. ³¹Al-Quds University, East Jerusalem, State of Palestine. ³²National Center of Public Health, Astana, Kazakhstan. ³³Qatar University, Doha, Qatar. ³⁴Ministry of Health and Social Protection, Dushanbe, Tajikistan. ³⁵Birzeit University, Birzeit, State of Palestine. ³⁶Usmanu Danfodiyo University Teaching Hospital, Sokoto, Nigeria. 37 Instituto Mexicano del Seguro Social, Mexico City, Mexico. ³⁸Qassim University, Unaizah, Saudi Arabia. ³⁹RehaKlinika,

Rzeszów, Poland. 40 Flinders University, Adelaide, South Australia, Australia. 41 University of Ghana, Accra, Ghana. ⁴²University of Copenhagen, Copenhagen, Denmark. ⁴³Copenhagen University Hospital, Copenhagen, Denmark. ⁴⁴University of Oxford, Oxford, UK. ⁴⁵Food and Nutrition Research Institute, Taguig, The Philippines. ⁴⁶Urmia University of Medical Sciences, Urmia, Iran. ⁴⁷Ibn Tofail University, Kénitra, Morocco. ⁴⁸Instituto Nacional de Ciencias Médicas y Nutrición, Mexico City, Mexico. 49 University of Amsterdam, Amsterdam, The Netherlands ⁵⁰Modeling in Health Research Center, Shahrekord, Iran. ⁵¹Shahid Sadoughi University of Medical Sciences, Yazd, Iran. 52 The Aga Khan University, Karachi, Pakistan. 53 University of Oslo, Oslo, Norway. ⁵⁴Leibniz Institute for Prevention Research and Epidemiology–BIPS, Bremen, Germany. ⁵⁵Republican Center for Health Promotion, Bishkek, Kyrgyzstan. ⁵⁶National Center for Diabetes, Endocrinology and Genetics, Amman, Jordan. 57 Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia. 58 Kuwait Institute for Scientific Research, Kuwait City, Kuwait.⁵⁹King Abdulaziz University, Jeddah, Saudi Arabia.⁶⁰The Hashemite University, Zarga, Jordan.⁶¹Ministry of Health, Kuwait City, Kuwait.⁶²Dasman Diabetes Institute, Kuwait City, Kuwait.⁶³Aldara Hospital and Medical Center, Riyadh, Saudi Arabia. ⁶⁴King Abdullah International Medical Research Center, Riyadh, Saudi Arabia. ⁶⁵Universidade Federal da Integração Latino-Americana, Foz do Iguaçu, Brazil. 66 Luxembourg Institute of Health, Strassen, Luxembourg, ⁶⁷Barcelona Institute for Global Health CIBERESP, Barcelona, Spain, ⁶⁸World Health Organization Regional Office for the Eastern Mediterranean, Cairo, Egypt. ⁶⁹Bombay Hospital and Medical Research Centre, Mumbai, India. ⁷⁰Departamento de Salud del Gobierno Vasco, San Sebastián, Spain. ⁷¹Ghana Health Service, Kintampo, Ghana. ⁷²UMR CNRS-MNHN 7206, Paris, France. ⁷³University of Lille, Lille, France. ⁷⁴Lille University Hospital, Lille, France. ⁷⁵Western Norway University of Applied Sciences, Sogndal, Norway, ⁷⁶Norwegian School of Sport Sciences, Oslo, Norway. ⁷⁷University of Thessaly, Trikala, Greece. ⁷⁸Madras Diabetes Research Foundation, Chennai, India. ⁷⁹Zahedan University of Medical Sciences, Zahedan, Iran. ⁸⁰Yekaterinburg State Medical Academy, Yekaterinburg, Russia. ⁸¹National Institute of Public Health, Tunis, Tunisia. ⁸²Institute of Public Health of the University of Porto, Porto, Portugal. ⁸³Norwegian Institute of Public Health, Oslo, Norway. ⁸⁴University of Massachusetts Amherst, Amherst, MA, USA.⁸⁵Public Health Promotion and Development Organization, Kathmandu, Nepal.⁸⁶Haramaya University, Dire Dawa, Ethiopia.⁸⁷University of Iceland, Reykjavik, Iceland. 88 University of Yaoundé 1, Yaoundé, Cameroon. 89 Asfendiyarov Kazakh National Medical University, Almaty, Kazakhstan. 90 Federal University of Pelotas, Pelotas, Brazil.⁹¹University of Medicine 1, Yangon, Myanmar.⁹²Oulu University Hospital, Oulu, Finland. ⁹³University of Oulu, Oulu, Finland. ⁹⁴Regional Authority of Public Health, Banska Bystrica, Slovakia.⁹⁵Tel Aviv University, Tel Aviv, Israel.⁹⁶Hebrew University of Jerusalem, Jerusalem, Israel.⁹⁷University of Porto Medical School, Porto, Portugal.⁹⁸Neyshabur University of Medical Sciences, Neyshabur, Iran. 99Research Institute for Endocrine Sciences, Tehran, Iran. ¹⁰⁰Indian Council of Medical Research, New Delhi, India. ¹⁰¹National Institute of Public Health, Copenhagen, Denmark. ¹⁰²National Institute of Pharmacy and Nutrition, Budapest, Hungary. ¹⁰³National Medical Research Centre for Therapy and Preventive Medicine, Moscow, Russia.¹⁰⁴University of Science and Technology, Sana'a, Yemen.¹⁰⁵Medical University of Lodz, Lodz, Poland. ¹⁰⁶Universidad Autónoma de Madrid CIBERESP, Madrid, Spain. ¹⁰⁷University of Rzeszów, Rzeszów, Poland. ¹⁰⁸University of Palermo, Palermo, Italy. ⁰⁹Federal Institute of Education, Science and Technology of Ceara, Ceara, Brazil, ¹¹⁰University of Miami, Miami, FL, USA. ¹¹¹University Hospital Center Zagreb, Zagreb, Croatia. ¹¹²Mohammed V University, Rabat, Morocco. ¹¹³Unidad de Cirugia Cardiovascular, Guatemala City, Guatemala. ¹¹⁴Universidad del Valle, Cali, Colombia. ¹¹⁵National Institute of Health Doutor Ricardo Jorge, Lisbon, Portugal. ¹¹⁸NOVA University Lisbon, Lisbon, Portugal. ¹¹⁷University of Pernambuco, Recife, Brazil. ¹¹⁸Baqai Institute of Diabetology and Endocrinology, Karachi, Pakistan. ¹¹⁹Federal University of Santa Catarina, Florianópolis, Brazil. ¹²⁰Dalhousie University, Halifax, Nova Scotia, Canada. ¹²¹ Jordan University of Science and Technology, Irbid, Jordan ¹²²Universidade Federal de Ouro Preto, Ouro Preto, Brazil. ¹²³Federal University of Maranhão, São Luís, Brazil. ¹²⁴University of Sydney, Sydney, New South Wales, Australia. ¹²⁵Cliniques Universitaires de Kinshasa, Kinshasa, Democratic Republic of the Congo. ¹²⁶University of Auckland, Auckland, New Zealand. 127 University College Dublin, Dublin, Ireland. 128 Christian Medical College, Vellore, India. 129 University Tunis El Manar, Tunis, Tunisia. 130 Federal Ministry of Social Affairs, Health, Care and Consumer Protection, Vienna, Austria. ¹³¹Cafam University Foundation, Bogotá, Colombia.¹³²Ministerio de Salud Pública y Bienestar Social, Asunción, Paraguay. ¹³³University of Agder, Kristiansand, Norway. ¹³⁴Addis Continental Institute of Public Health, Addis Ababa, Ethiopia. ¹³⁵Kazakh National Medical University, Almaty, Kazakhstan. ¹³⁶Universidad Peruana Cayetano Heredia, Lima, Peru. ¹³⁷Lithuanian University of Health Sciences, Kaunas, Lithuania. ¹³⁸Pontificia Universidad Católica de Chile, Santiago, Chile. ¹³⁹University of São Paulo, São Paulo, Brazil. ¹⁴⁰Johannes Gutenberg University, Mainz, Germany.¹⁴¹B. J. Medical College, Ahmedabad, India.¹⁴²Chirayu Medical College, New Delhi, India.¹⁴³Sunder Lal Jain Hospital, Delhi, India.¹⁴⁴Shandong University of Traditional Chinese Medicine, Jinan, China. ¹⁴⁵Shanghai Jiao-Tong University School of Medicine, Shanghai, China. ⁴⁶Universidad de la República, Montevideo, Uruguay. ¹⁴⁷University of Strasbourg, Strasbourg, France.¹⁴⁸Institute of Medical Research and Medicinal Plant Studies, Yaoundé, Cameroon. ¹⁴⁹Ufa Eye Research Institute, Ufa, Russia. ¹⁵⁰Nepal Health Research Council, Kathmandu, Nepal. ¹⁵¹University of Montenegro, Niksic, Montenegro. ¹⁵²University of Southern Denmark, Copenhagen, Denmark.¹⁵³University of Gothenburg, Gothenburg, Sweden.¹⁵⁴Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil. ¹⁵⁵National Institute for Public Health and the Environment, Bilthoven, The Netherlands. ¹⁵⁶University of Haifa, Haifa, Israel. ¹⁵⁷Ministry of Health, Ramat Gan, Israel. ¹⁵⁸University of Turin, Turin, Italy. ¹⁵⁹University College London, London, UK. ¹⁶⁰Liverpool John Moores University, Liverpool, UK. ¹⁶¹Nanyang Technological University, Singapore, Singapore. ¹⁶²National Medical Research Center for Endocrinology, Moscow, Russia. 163 Centro de Educación Médica e Investigaciones Clínicas, Buenos Aires, Argentina. ¹⁶⁴IRCCS Neuromed, Pozzilli, Italy. ¹⁶⁵Toulouse University School of Medicine, Toulouse, France. ¹⁶⁶University of Zurich, Zurich, Switzerland. ¹⁶⁷KU Leuven, Leuven, Belgium. ¹⁶⁸Ministry of Health, Victoria, Seychelles. ¹⁶⁹Unisanté, Lausanne, Switzerland. ¹⁷⁰World Health Organization Country Office in Tajikistan, Dushanbe, Tajikistan. ¹⁷¹Flemish Agency for Care and Health, Brussels, Belgium. ¹⁷²Ghent University, Ghent, Belgium. ¹⁷³FrieslandCampina, Amersfoort, The Netherlands. ¹⁷⁴Universidad Central de Venezuela, Caracas, Venezuela. ¹⁷⁵Bielefeld University, Bielefeld, Germany. ¹⁷⁶World Health Organization Athens Quality of Care Office, Athens, Greece. ¹⁷⁷German Cancer Research Center, Heidelberg, Germany. ¹⁷⁸The Fred Hollows Foundation, Auckland, New Zealand. ¹⁷⁹University of the Andes, Mérida, Venezuela. ¹⁸⁰Carol Davila University of Medicine and Pharmacy, Bucharest, Romania.

¹⁸¹Instituto Politécnico de Lisboa, Lisbon, Portugal. ¹⁸²Swansea University, Swansea, UK. ¹⁸³University College Copenhagen, Copenhagen, Denmark. ¹⁸⁴Institute of Public Health, Tirana, Albania. 185 Munster Technological University, Cork, Ireland. 186 Universidad de La Laguna, Santa Cruz de Tenerife, Spain. ¹⁸⁷University of Malta, Msida, Malta. ¹⁸⁸Vanderbilt University, Nashville, TN, USA. 189 Pan American Health Organization, Washington, DC, USA ¹⁹⁰Ministry of Health, Tongatapu, Tonga. ¹⁹¹Canadian Fitness and Lifestyle Research Institute, Ottawa, Ontario, Canada.¹⁹²Hospital Santa Maria, Lisbon, Portugal.¹⁹³Istanbul University-Cerrahpasa, Istanbul, Turkey. ¹⁹⁴Universidade Federal de Juiz de Fora, Juiz de Fora, Brazil. ¹⁹⁵National Institute of Public Health, Prague, Czech Republic. ¹⁹⁶Gaetano Fucito Hospital, Mercato San Severino, Italy. ¹⁹⁷University of Groningen, Groningen, The Netherlands. ¹⁹⁸Karolinska Institutet, Huddinge, Sweden. ¹⁹⁹Centro de Estudios Sobre Nutrición Infantil, Buenos Aires, Argentina.²⁰⁰University of Porto, Porto, Portugal.²⁰¹University of Zaragoza, Zaragoza, Spain.²⁰²Santiago de Compostela University, Santiago de Compostela, Spain. ²⁰³Ministry of Health, Ankara, Turkey. ²⁰⁴Council for Agricultural Research and Economics, Rome, Italy.²⁰⁵Federal University of Rio Grande, Rio Grande, Brazil.²⁰⁶India Diabetes Research Foundation, Chennai, India.²⁰⁷Duke–NUS Medical School, Singapore, Singapore.²⁰⁸ICMR– National Institute of Medical Statistics, New Delhi, India. 209 Singapore Eye Research Institute, Singapore, Singapore, ²¹⁰Academia Sinica, Taipei, Taiwan, ²¹¹Capital Institute of Pediatrics, Beijing, China.²¹²Xiangtan University, Xiangtan, China.²¹³Kailuan General Hospital, Tangshan, China.²¹⁴National University of Singapore, Singapore, Singapore.²¹⁵US Centers for Disease Control and Prevention, Atlanta, GA, USA, ²¹⁶Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran. ²¹⁷The Gertner Institute for Epidemiology and Health Policy Research, Ramat Gan. Israel.²¹⁸National Centre of Public Health and Analyses, Sofia, Bulgaria. ²¹⁹Amsterdam UMC Public Health Research Institute, Amsterdam, The Netherlands. ²²⁰Universidad de Costa Rica, San José, Costa Rica. ²²¹University of Fribourg, Fribourg, Switzerland. ²²²National Taiwan University, Taipei, Taiwan. ²²³CIBERESP, Madrid, Spain. ²²⁴Seoul National University, Seoul, Republic of Korea. 225 University of Southern Denmark, Odense, Denmark. 226 Universidade Estadual Paulista, Presidente Prudente, Brazil. 227 Medical University of Silesia, Katowice, Poland. 228 Charles University, Prague, Czech Republic. 229 Thomayer Hospital, Prague, Czech Republic. ²³⁰Primary Health Care, Floriana, Malta. ²³¹University of Salerno, Fisciano, Italy. 232 Statistics Canada, Ottawa, Ontario, Canada. 233 Alicante Institute for Health and Biomedical Research, Alicante, Spain. 234 Agency for Preventive and Social Medicine, Bregenz, Austria.²³⁵University of Southampton, Southampton, UK.²³⁶Pontificia Universidad Javeriana, Bogotá, Colombia.²³⁷Institut Pasteur de Lille, Lille, France.²³⁸Malawi Epidemiology and Intervention Research Unit, Lilongwe, Malawi.²³⁹CIBEROBN, Madrid, Spain. ²⁴⁰Hungarian University of Sports Science, Budapest, Hungary. ²⁴¹University of Debrecen, Debrecen, Hungary.²⁴²National Institute of Public Health, Bucharest, Romania.²⁴³University of Medicine and Pharmacy, Bucharest, Romania.²⁴⁴Universidade Federal do Rio Grande do Norte, Natal, Brazil.²⁴⁵National Research Council, Reggio Calabria, Italy.²⁴⁶Eftimie Murgu University Resita, Resita, Romania. 247 Eduardo Mondlane University, Maputo, Mozambique. ²⁴⁸Indian Statistical Institute, Kolkata, India. ²⁴⁹Tabriz Health Services Management Research Center, Tabriz, Iran.²⁵⁰Geneva University Hospitals, Geneva, Switzerland.²⁵¹Sciensano, Brussels, Belgium.²⁵²University Medical Centers, Amsterdam, The Netherlands.²⁵³National Research Centre for Preventive Medicine, Moscow, Russia.²⁵⁴Innovating Health International, Port-au-Prince, Haiti. 255University of Montreal, Montreal, Quebec, Canada. 256French National Research Institute for Sustainable Development, Montpellier, France. ²⁵⁷French Public Health Agency, St Maurice, France. ²⁵⁹Mediterranea Cardiocentro, Naples, Italy. ²⁵⁹Universidade do Vale do Rio dos Sinos, São Leopoldo, Brazil. 260 National Institute of Hygiene, Epidemiology and Microbiology, Havana, Cuba. 261 National Council of Scientific and Technical Research, Buenos Aires, Argentina.²⁶²Servicio Canario de la Salud del Gobierno de Canarias, Santa Cruz de Tenerife, Spain. ²⁶³Consejería de Salud del Gobierno de La Rioja, Logroño, Spain ²⁶⁴Ministry of Health and Medical Education, Tehran, Iran. ²⁶⁵University of Novi Sad, Novi Sad, Serbia. ²⁶⁶National Institute of Nutrition, Hanoi, Vietnam. ²⁶⁷University of Queensland, Brisbane, Queensland, Australia.²⁶⁸Instituto de Investigación Nutricional, Lima, Peru. ²⁶⁹Istituto Superiore di Sanità, Rome, Italy. ²⁷⁰Sun Yat-sen University, Guangzhou, China. ²⁷¹Universidad de Cuenca, Cuenca, Ecuador. ²⁷²Helmholtz Zentrum München, Munich, Germany. 273 Tehran University of Medical Sciences, Tehran, Iran. 274 Ministère de la Santé et de l'Hygiène Publique, Abidjan, Côte d'Ivoire.²⁷⁵University Hospital Düsseldorf, Düsseldorf, Germany. 276 National Institute of Cardiology, Warsaw, Poland. 277 Beijing Center for Disease Prevention and Control, Beijing, China. 278 IRL 3189 ESS, Marseille, France. 279 Scuola Superiore Sant'Anna, Pisa, Italy. 280 Al-Farabi Kazakh National University, Almaty, Kazakhstan. 281 Semey Medical University, Semey, Kazakhstan. 282 University of Latvia, Riga, Latvia. 283 Ministry of Health and Medical Services, Gizo, Solomon Islands. ²⁸⁴Hormozgan University of Medical Sciences, Bandar Abbas, Iran. 285 University of Benin, Benin City, Nigeria. 286 University of Skövde, Skövde, Sweden. 287 Ministry of Health, Rabat, Morocco. 288 National Institute of Nutrition and Food Technology, Tunis, Tunisia. 289 The University of the West Indies, Kingston, Jamaica, 290 Ministry of Health, Jerusalem, Israel, 291 University of California Davis, Davis, CA, USA. ²⁹²University of Stellenbosch, Cape Town, South Africa. ²⁹³University of Duisburg-Essen, Essen, Germany. ²⁹⁴Karadeniz Technical University, Trabzon, Turkey. ²⁹⁵Dokuz Eylul University, Izmir, Turkey. ²⁹⁶University of Helsinki, Helsinki, Finland. ²⁹⁷Mashhad University of Medical Sciences, Mashhad, Iran.²⁹⁸Rafsanjan University of Medical Sciences, Rafsanjan, Iran. ²⁹⁹Queen's University Belfast, Belfast, UK. ³⁰⁰Tabriz University of Medical Sciences, Tabriz, Iran. ³⁰¹Fasa University of Medical Sciences, Fasa, Iran. ³⁰²Shiraz University of Medical Sciences, Shiraz, Iran. ³⁰³Baqai Medical University, Karachi, Pakistan. ³⁰⁴Centro de Salud Villanueva Norte, Badajoz, Spain. 305 Hospital Don Benito-Villanueva de la Serena, Badajoz, Spain. ³⁰⁶Ministry of Health, Buenos Aires, Argentina. ³⁰⁷Universidad de Santiago de Chile, Santiago, Chile. ³⁰⁸University of Insubria, Varese, Italy. ³⁰⁹Federal University of Alagoas, Alagoas, Brazil. ³¹⁰Institute of Mother and Child, Warsaw, Poland. ³¹¹Hospital Infantil Sabará, São Paulo, Brazil. ³¹²University of Tartu, Tartu, Estonia. ³¹³Universiti Sains Malaysia, Kelantan, Malaysia. ³¹⁴Umeå University, Umeå, Sweden. ³¹⁵Federal University of São Paulo, São Paulo, Brazil. ³¹⁶University Clinical Centre Ljubljana, Ljubljana, Slovenia. ³¹⁷Hospital Universitario Son Espases, Palma, Spain. ³¹⁸Hospital de Clinicas de Porto Alegre, Porto Alegre, Brazil. ³¹⁹Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil. 320 Universitas Sumatera Utara, Medan, Indonesia. 321 Kindai University, Osaka-Sayama, Japan. 322 Kyoto University, Kyoto, Japan. 323 I. Horbachevsky Ternopil National Medical University, Ternopil, Ukraine. ³²⁴Medical University of Warsaw, Warsaw, Poland. 325 Consejería de Sanidad del Gobierno de Cantabria, Santander, Spain. ³²⁶ Jagiellonian University Medical College, Kraków, Poland. ³²⁷ Ministero della Salute DG

Prevenzione Sanitaria, Rome, Italy. 328 University of Catania, Catania, Italy. 329 Agencia Española de Seguridad Alimentaria y Nutrición, Madrid, Spain. 330 Africa Health Research Institute, Mtubatuba, South Africa. 331 Geneva University Medical School, Geneva, Switzerland. ³³²Universidade Federal de Minas Gerais, Belo Horizonte, Brazil. ³³³Utrecht University, Utrecht, The Netherlands. ³³⁴Wageningen University, Wageningen, The Netherlands. ³³⁵Medical Research Foundation, Chennai, India. ³³⁶Kurdistan University of Medical Sciences, Sanandaj, Iran. ³³⁷University of Adelaide, Adelaide, South Australia, Australia. ³³⁸Lund University, Lund, Sweden. ³³⁹Aristotle University of Thessaloniki, Thessaloniki, Greece. ³⁴⁰National Institute for Health Development, Tallinn, Estonia. ³⁴¹Central University of Kerala, Kasaragod, India. ³⁴²Institut National de la Santé et de la Recherche Médicale, Paris, France. ³⁴³Paris University, Paris, France. ³⁴⁴Instituto Murciano de Investigación Biosanitaria Virgen de la Arrixaca, Murcia, Spain. ³⁴⁵Gasol Foundation, Sant Boi de Llobregat, Spain. ³⁴⁶University of Lleida, Sant Boi de Llobregat, Spain. ³⁴⁷PASs Hirszfeld Institute of Immunology and Experimental Therapy, Wroclaw, Poland. ³⁴⁸University Agostinho Neto, Luanda, Angola. ³⁴⁹Kansas State University, Manhattan, KS, USA. ³⁵⁰Universidad Politécnica de Madrid, Madrid, Spain. ³⁵¹International Clinical Research Center, Brno, Czech Republic. 352 National Institute of Public Health, Cuernavaca, Mexico.³⁵³Centro de Estudios en Diabetes A.C., Mexico City, Mexico. ³⁵⁴Universidad Autónoma de Santo Domingo, Santo Domingo, Dominican Republic. ³⁵⁵Ministry of Health, Lisbon, Portugal. ³⁵⁶Institute for Clinical and Experimental Medicine, Prague, Czech Republic. ³⁵⁷Children's Memorial Health Institute, Warsaw, Poland. ³⁵⁸University of Thessaly Larissa Greece ³⁵⁹National Center of Cardiovascular Diseases, Beijing, China ⁶⁶⁰International Life Science Institute, Buenos Aires, Argentina. ³⁶¹University of Ferrara, Ferrara, Italy. ³⁶²Authority Sanitaria San Marino, San Marino, San Marino. ³⁶³Icelandic Heart Association, Kopavogur, Iceland. ³⁶⁴Universidad Icesi, Cali, Colombia. ³⁶⁵State University of Montes Claros, Montes Claros, Brazil. ³⁶⁶King's College London, London, UK. ³⁶⁷International Agency for Research on Cancer, Lyon, France. ³⁶⁸Capital Medical University, Beijing, China. ³⁶⁹Capital Medical University Beijing Tongren Hospital, Beijing, China. ³⁷⁰Healis-Sekhsaria Institute for Public Health, Navi Mumbai, India. 371 Eternal Heart Care Centre and Research Institute, Jaipur, India. ³⁷²University of Ibadan, Ibadan, Nigeria. ³⁷³Institute for Clinical Effectiveness and Health Policy, Buenos Aires, Argentina. 374 National Health Insurance Service, Wonju, Republic of Korea. 375 Prevention of Metabolic Disorders Research Center, Tehran, Iran. ³⁷⁶Research and Education Institute of Child Health, Nicosia, Cyprus. ³⁷⁷Danish Cancer Society Research Center, Copenhagen, Denmark. ³⁷⁸The University of the West Indies, Cave Hill, Barbados. 379Kermanshah University of Medical Sciences, Kermanshah, Iran. ³⁸⁰Africa Health Research Institute, Durban, South Africa. ³⁸¹Federal University of Pernambuco, Recife, Brazil. ³⁸²Yasuj University of Medical Sciences, Yasuj, Iran. ³⁸³International Hellenic University, Thessaloniki, Greece. ³⁸⁴Kyushu University, Fukuoka, Japan. ³⁸⁵University of Bergen, Bergen, Norway. ³⁸⁶Tulane University, New Orleans, LA, USA. ³⁸⁷National Research Institute for Health and Family Planning, Beijing, China. ³⁸⁸Chinese Center for Disease Control and Prevention, Beijing, China. ³⁸⁹University of Pécs, Pécs, Hungary. ³⁹⁰Danish Health Authority, Copenhagen, Denmark.³⁹¹Joep Lange Institute, Amsterdam, The Netherlands.³⁹²Universidad Autónoma de Bucaramanga, Bucaramanga, Colombia.³⁹³ETH Zurich, Zurich, Switzerland. ³⁹⁴Chronic Diseases Research Center, Tehran, Iran. ³⁹⁵University of Hong Kong, Hong Kong, China. ³⁹⁰The Chinese University of Hong Kong, Hong Kong, China. ³⁹⁰University of Western Australia, Australia. ³⁹⁸Universidade Federal do Paraná, Curitiba, Brazil. ³⁹⁹Shahid Beheshti University of Medical Sciences, Tehran, Iran. ⁴⁰⁰Gasol Foundation, Barcelona, Spain. ⁴⁰¹University Ramon Llull, Sant Boi de Llobregat, Spain. ⁴⁰²Kingston Health Sciences Centre, Kingston, Ontario, Canada. ⁴⁰⁶Fundación Oftalmológica de Santander, Bucaramanga, Colombia. ⁴⁰⁴University Oran 1, Oran, Algeria. ⁴⁰⁵Independent Public Health Specialist, Nay Pyi Taw, Myanmar.⁴⁰⁶Ministry of Health and Sports, Nay Pyi Taw, Myanmar. ⁴⁰⁷Santé publique France, Saint-Maurice, France.⁴⁰⁸VU University Medical Center, Amsterdam, The Netherlands.⁴⁰⁹American University of Beirut, Beirut, Lebanon.⁴¹⁰Cairo University, Cairo, Egypt. ⁴¹¹Erasmus Medical Center Rotterdam, Rotterdam, The Netherlands. ⁴¹²University of Valencia, Valencia, Spain. ⁴¹³Medical University Varna, Varna, Bulgaria. ⁴¹⁴The University of Tokyo, Tokyo, Japan. ⁴¹⁵Alex Ekwueme Federal University Teaching Hospital, Abakaliki, Nigeria. ⁴¹⁶The Hospital for Sick Children, Toronto, Ontario, Canada. ⁴¹⁷Deakin University, Geelong, Victoria, Australia. ⁴¹⁹Emory University, Atlanta, GA, USA. ⁴¹⁹Bulgarian Academy of Sciences, Sofia, Bulgaria. ⁴²⁰Tokyo Metropolitan Institute of Gerontology, Tokyo, Japan.⁴²¹Hadassah University Medical Center, Jerusalem, Israel.⁴²²Université Catholique de Louvain, Brussels, Belgium. 423 Gambia National Nutrition Agency, Banjul, The Gambia. ⁴²⁴Kuwait Institute for Scientific Research, Safat, Kuwait. ⁴²⁵Public Health Agency of Sweden, Solna, Sweden. ⁴²⁶Norwegian University of Science and Technology, Trondheim, Norway. ⁷University of Melbourne, Melbourne, Victoria, Australia. ⁴²⁸Sports University of Tirana, Tirana, Albania. ⁴²⁹Heart Foundation, Melbourne, Victoria, Australia. ⁴³⁰Guangzhou 12th Hospital, Guangzhou, China. ⁴³¹Universidad Eugenio Maria de Hostos, Santo Domingo, Dominican Republic. ⁴³²Simon Fraser University, Burnaby, British Columbia, Canada. ¹³Institute of Molecular and Clinical Ophthalmology Basel, Basel, Switzerland. ⁴³⁴University of New South Wales, Sydney, New South Wales, Australia. ⁴³⁵World Health Organization Country Office, Delhi, India. 436 Guilan University of Medical Sciences, Rasht, Iran. 437 University of Opole, Opole, Poland. ⁴³⁸Gulu University, Gulu, Uganda. ⁴³⁹University of Crete, Heraklion Greece. 440 Hungarian School Sport Federation, Budapest, Hungary. 441 National Center for Disease Control and Public Health, Tbilisi, Georgia. ⁴⁴²Ministry of Health, Bratislava, Slovakia. ⁴⁴³Sri Venkateswara University, Tirupati, India. ⁴⁴⁴Sree Chitra Tirunal Institute for Medical Sciences and Technology, Trivandrum, India. ⁴⁴⁵Hellenic Medical Association for Obesity, Athens, Greece. ⁴⁴⁶Harokopio University, Athens, Greece. ⁴⁴⁷National and Kapodistrian University of Athens, Athens, Greece. ⁴⁴⁸Maharajgunj Medical Campus, Kathmandu, Nepal ⁴⁴⁹Université Officielle de Bukavu, Bukavu, Democratic Republic of the Congo. ⁴⁵⁰Aarhus University, Aarhus, Denmark.⁴⁵¹Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, USA. ⁴⁵²Pennington Biomedical Research Center, Baton Rouge, LA, USA. ⁴⁵³National Institute of Epidemiology, Chennai, India. ⁴⁵⁴University of Toronto, Toronto, Ontario, Canada. ⁴⁵⁵University of Münster, Münster, Germany. ⁴⁵⁶Israel Center for Disease Control, Ramat Gan, Israel. ⁴⁵⁷Research Institute for Primordial Prevention of Non-communicable Disease, Isfahan, Iran. ⁴⁵⁸Kyrgyz State Medical Academy, Bishkek, Kyrgyzstan. ⁴⁵⁹Research Institute of Child Nutrition, Dortmund, Germany. 460 Shahrekord University of Medical Sciences, Shahrekord, Iran. ⁴⁶¹University of Cambridge, Cambridge, UK. ⁴⁶²Mazandaran University of Medical Sciences, Sari, Iran. 463 Hypertension Research Center, Isfahan, Iran. 464 Medical University of Innsbruck, Innsbruck, Austria. 465 VASCage, Innsbruck, Austria. 466 Muhimbili University of

Health and Allied Sciences, Dar es Salaam, Tanzania. 467Yonsei University College of Medicine, Seoul, Republic of Korea. 468 National Cancer Center, Goyang-si, Republic of Korea. 469 Sahlgrenska University Hospital, Gothenburg, Sweden. 470 Newcastle University, Newcastle, UK. 471University College South Denmark, Haderslev, Denmark. 472Statistics Austria, Vienna, Austria. 473B. P. Koirala Institute of Health Sciences, Dharan, Nepal. 474University of Vienna, Vienna, Austria. 475 Tartu University Clinics, Tartu, Estonia. 476 Kansai Medical University, Hirakata, Japan. ⁴⁷⁷District Department of State Public Health Service, Hildburghausen Germany. 478 Pontificia Universidad Católica Argentina, Buenos Aires, Argentina. 479 Ministry of Health and Wellness, Port Louis, Mauritius. 480 University Hospital Ulm, Ulm, Germany. ⁴⁸¹Croatian Institute of Public Health, Zagreb, Croatia. ⁴⁸²Institute of Nutrition of Central America and Panama, Guatemala City, Guatemala. 483North-West University, Potchefstroom, South Africa. ⁴⁸⁴South African Medical Research Council, Potchefstroom, South Africa. ⁴⁸⁵University of Physical Education, Kraków, Poland. ⁴⁸⁶University of Jyväskylä, Jyväskylä, Finland. ⁴⁸⁷Institute of Public Health, Podgorica, Montenegro. ⁴⁸⁸Amrita Institute of Medical Sciences, Cochin, India. 489 Institute of Endocrinology, Prague, Czech Republic. 490 All India Institute of Medical Sciences, New Delhi, India. 491 African Population and Health Research Center, Nairobi, Kenya.⁴⁹²Hanoi University of Public Health, Hanoi, Vietnam.⁴⁹³Hassan First University of Settat, Settat, Morocco, 494 Ministry of Health, Algiers, Algeria, 495 Ministry of Health, Georgetown, Guyana. ⁴⁹⁶Sahlgrenska Academy, Gothenburg, Sweden. ⁴⁹⁷Endocrinology and Metabolism Research Center, Tehran, Iran. ⁴⁹⁸Clinical Research Education, Networking & Consultancy, Douala, Cameroon. 499 University of Public Health, Yangon, Myanmar.⁵⁰⁰Centro Studi Epidemiologici di Gubbio, Gubbio, Italy.⁵⁰¹National University Health System, Singapore, Singapore. ⁵⁰²University of Leicester, Leicester, UK. ⁵⁰³Tampere University Hospital, Tampere, Finland. ⁵⁰⁴Tampere University, Tampere, Finland. ⁵⁰⁵University of Douala, Douala, Cameroon. ⁵⁰⁸University of Cape Town, Cape Town, South Africa. ⁵⁰⁷West Virginia University, Morgantown, WV, USA. ⁵⁰⁸Oswaldo Cruz Foundation Rene Rachou Research Institute, Belo Horizonte, Brazil.⁵⁰⁹Shanghai Institute of Nutrition and Health of Chinese Academy of Sciences, Shanghai, China.⁵¹⁰Uppsala University, Uppsala, Sweden. ⁵¹¹Capital Medical University Beijing An Zhen Hospital, Beijing, China. ⁵¹²Taipei Medical University, Taipei, Taiwan. ⁵¹³Servicio Andaluz de Salud, Sevilla, Spain. ⁵¹⁴Sports Medical Center of Minho, Braga, Portugal. ⁵¹⁵Universidad San Martín de Porres, Lima, Peru. ⁵¹⁶Consejería de Sanidad Junta de Castilla y León, Valladolid, Spain. ⁵¹⁷Universidade Federal de Ciências da Saúde de Porto Alegre, Porto Alegre, Brazil. ⁵¹⁸Ilembula Lutheran Hospital, Ilembula, Tanzania. ⁵¹⁹University of Kinshasa Hospital, Kinshasa, Democratic Republic of the Congo. ⁵²⁰Coimbra University Hospital Center, Coimbra, Portugal. ⁵²¹University of Texas Rio Grande Valley, Harlingen, TX, USA. 522 Institute of Neuroscience of the National Research Council, Padua, Italy. 523 Baker Heart and Diabetes Institute, Melbourne, Victoria, Australia. ⁵²⁴Agricultural University of Athens, Athens, Greece. ⁵²⁵Academia VBHC, São Paulo, Brazil. ⁵²⁶SB RAS Federal Research Center Institute of Cytology and Genetics, Novosibirsk, Russia. ⁵²⁷Université Catholique de Bukavu, Bukavu, Democratic Republic of the Congo. ⁵²⁸University of Northern British Columbia, Prince George, British Columbia, Canada. 529 University of Padua, Padua, Italy. 530 University Medicine Greifswald, Greifswald, Germany. 531 Hellenic Mediterranean University, Siteia, Greece. ⁵³²Loughborough University, Loughborough, UK. ³³Ministry of Health, Nicosia, Cyprus. ⁵³⁴Lausanne University Hospital, Lausanne, Switzerland. ⁵³⁵University of Lausanne, Lausanne, Switzerland. ⁵³⁶Secretaria de Estado da Saúde de Santa Catarina, Florianópolis, Brazil, ⁵³⁷CIBERCV, Barcelona, Spain, ⁵³⁸Institut Hospital del Mar d'Investigacions Mèdiques, Barcelona, Spain, ⁵³⁹Mary Immaculate College, Limerick, Ireland. ⁵⁴⁰Hungarian Society of Sports Medicine, Budapest, Hungary. ⁵⁴¹Paracelsus Medical University, Salzburg, Austria.⁵⁴²Institute for Cancer Research, Prevention and Clinical Network, Florence, Italy.⁵⁴³Universidade Estadual do Centro-Oeste, Guarapuava, Brazil. ⁵⁴⁴Sher-i-Kashmir Institute of Medical Sciences, Srinagar, India.⁵⁴⁵UiT The Arctic University of Norway, Tromsø, Norway. 546 ICMR-National Centre for Disease Informatics and Research, Bengaluru, India. 547Sefako Makgatho Health Sciences University, Pretoria, South Africa. ⁵⁴⁸Centro de Estudos do Laboratório de Aptidão Física de São Caetano do Sul, São Paulo, Brazil. ⁵⁴⁹Brown University, Providence, RI, USA. ⁵⁵⁰London School of Hygiene & Tropical Medicine, London, UK. 551University of Edinburgh, Edinburgh, UK. 552Weill Cornell Medicine, New York City, NY, USA. 553 Institut National de la Santé et de la Recherche Médicale, Lille, France. 554 Arabkir Medical Centre–Institute of Child and Adolescent Health, Yerevan, Armenia. ⁵⁵⁵Universidad de los Andes, Bogotá, Colombia. ⁵⁵⁶Robert Koch Institute, Berlin, Germany.⁵⁵⁷University of Abidjan, Abidjan, Côte d'Ivoire. ⁵⁵⁸Pirogov Russian National Research Medical University, Moscow, Russia. 559 Universidade de Lisboa, Lisbon, Portugal. 560 Saveetha Dental Colleges & Hospitals, Chennai, India. ⁵⁶¹Democritus University, Alexandroupolis, Greece. ²Grigore T Popa University of Medicine and Pharmacy, Iasi, Romania. ⁵⁶³Università degli Studi di Firenze, Florence, Italy. 564 Ain Shams University, Cairo, Egypt. 565 Isfahan Cardiovascular Research Center, Isfahan, Iran. 566 Strasbourg University Hospital, Strasbourg, France. ⁵⁶⁷Mulago Hospital, Kampala, Uganda. ⁵⁶⁸Instituto Conmemorativo Gorgas de Estudios de la Salud, Panama City, Panama. 569 University of Limpopo, Sovenga, South Africa. 570 University of Medical Sciences of Cienfuegos, Cienfuegos, Cuba. ⁵⁷¹Ministry of Health and Wellness, Belmopan, Belize. ⁵⁷²Royal College of Surgeons in Ireland, Dublin, Ireland. ⁵⁷³La Trobe University, Melbourne, Victoria, Australia. ⁵⁷⁴Sabzevar University of Medical Sciences, Sabzevar, Iran. 575 International Institute of Molecular and Cell Biology, Warsaw, Poland. ⁵⁷⁶World Health Organization Country Office, Lilongwe, Malawi. ⁵⁷⁷Department of Public Health, Nay Pyi Taw, Myanmar. ⁵⁷⁸Albanian Sports Science Association, Tirana, Albania. ⁵⁷⁹University of Brescia, Brescia, Italy. ⁵⁸⁰University of Limerick, Limerick, Ireland. ⁵⁸¹Makerere University School of Public Health, Kampala, Uganda. ⁵⁸²University de Kinshasa, Kinshasa, Democratic Republic of the Congo. ⁵⁸³Bushehr University of Medical Sciences, Bushehr, Iran. ⁵⁸⁴Ulm University, Ulm, Germany. ⁵⁸⁵Suraj Eye Institute, Nagpur, India. ⁵⁸⁶UNICEF, Yaoundé, Cameroon. 587 Ministry of Health, Apia, Samoa. 588 Karolinska Institutet, Stockholm, Sweden. ⁵⁸⁹National Institute of Hygiene and Epidemiology, Hanoi, Vietnam. ⁵⁹⁰University of Medicine and Pharmacy, Ho Chi Minh City, Vietnam. 591 Hanoi Medical University, Hanoi, Vietnam. 592 Xi'an Jiaotong University, Xi'an, China. ⁵⁹³LifeDoc Health, Memphis, TN, USA. ⁵⁹⁴Heartfile, Islamabad, Pakistan. 595 Eastern Mediterranean Public Health Network, Amman, Jordan. 596 University of Manchester, Manchester, UK. 597State University of Medicine and Pharmacy, Chisinau, Moldova. 598 Tachikawa General Hospital, Nagaoka, Japan. 599 University of Abuja College of Health Sciences, Abuja, Nigeria. 600 Korea Centers for Disease Control and Prevention, Cheongju-si, Republic of Korea. 601 Japan Wildlife Research Center, Tokyo, Japan. 602 Gadarif University, Gadarif, Sudan. 603 Istanbul University, Istanbul, Turkey. 604 Ministry of Health,

Bandar Seri Begawan, Brunei. 605 University of Madeira, Funchal, Portugal. 606 University of Puerto Rico, San Juan, Puerto Rico.⁶⁰⁷Osteoporosis Research Center, Tehran, Iran. ⁶⁰⁸Universidad de Santander, Bucaramanga, Colombia.⁶⁰⁹Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. ⁶¹⁰University of Wisconsin-Madison, Madison, WI, USA. 611 Privatpraxis Prof Jonas und Dr Panda-Jonas, Heidelberg, Germany. 612 IRCCS Ente Ospedaliero Specializzato in Gastroenterologia S. de Bellis, Bari, Italy. 613 Zayed University, Abu Dhabi, United Arab Emirates. ⁶¹⁴Catholic University of Daegu, Daegu, Republic of Korea 615 University of Medicine, Pharmacy, Science and Technology of Târgu Mures, Târgu Mures Romania.⁶¹⁶ Jivandeep Hospital, Anand, India.⁶¹⁷ Centro de Investigação em Saúde de Angola, Caxito, Angola. 618 South African Medical Research Council, Durban, South Africa. 619 National Dental Care Centre Singapore, Singapore, Singapore. 620 University Hospital of Varese, Varese, Italy. 621 Vietnam National Heart Institute, Hanoi, Vietnam. 622 Clínica de Medicina Avanzada Dr. Abel González, Santo Domingo, Dominican Republic. 623 University of Sarajevo, Sarajevo, Bosnia and Herzegovina. 624 Cardiovascular Prevention Centre Udine, Udine, Italy. 625 University of Pisa, Pisa, Italy. 626 Ministry of Health and Medical Services, Honiara, Solomon Islands. 627 Public Health Agency of Catalonia, Barcelona, Spain. 628 O. M. Marzeyev Institute for Public Health of the National Academy of the Medical Sciences of Ukraine, Kyiv, Ukraine, 629Universiti Kebangsaan Malaysia, Kuala Lumpur, Malaysia, 630 Ardabil University of Medical Sciences, Ardabil, Iran. ⁶³¹Universidade Pedagógica, Maputo, Mozambique. ⁶³²Centre for Disease Prevention and Control, Riga, Latvia. ⁶³³Sulaimani Polytechnic University, Sulaymaniyah, Iraq. ⁴Alborz University of Medical Sciences, Karaj, Iran. ⁶³⁵Ministry of Health, Hanoi, Vietnam. Abol 2 oniversity of Medical Sciences, Karaj, itali. Ministry of Health, Handi, Vietnam, ⁶⁵Pure Earth, Dhaka, Bangladesh. ⁶³Institute of Epidemiology Disease Control and Research, Dhaka, Bangladesh. ⁶³⁸University of Turku, Turku, Finland. ⁶³⁹UNICEF, Baku, Azerbaijan. ⁶⁴⁰World Health Organization Country Office, Juba, South Sudan. ⁶⁴¹Instituto Federal Vordi Heatti Organization County onice, Juda, South Sudani. Instituto redefat Riograndense, Rio Grande, Brazil. ⁶⁴²Institut Universitari d'Investigació en Atenció Primària Jordi Gol, Girona, Spain. ⁶⁴³Universiti Putra Malaysia, Serdang, Malaysia. ⁶⁴⁴University of Malaya, Kuala Lumpur, Malaysia.⁶⁴⁵Sotiria Hospital, Athens, Greece.⁶⁴⁶University of the Philippines, Manila, The Philippines.⁶⁴⁷Slovak Academy of Sciences, Bratislava, Slovakia. ⁶⁴⁸University of Santa Cruz do Sul, Santa Cruz do Sul, Brazil.⁶⁴⁹Nutrition Research Foundation, Barcelona, Spain. 650 Minas Gerais State Secretariat for Health, Belo Horizonte, Brazil. 651 CS S. Agustín Ibsalut, Palma, Spain. 652 Amsterdam Institute for Global Health and Development, Amsterdam, The Netherlands. ⁶⁵³Universidade Nove de Julho, São Paulo, Brazil. ⁶⁵⁴Ministerio de Salud, Panama City, Panama. 655 Public Health Agency of Canada, Ottawa, Ontario, Canada. 656 Universidad Industrial de Santander, Bucaramanga, Colombia. 657 Ministry of Health and Social Protection, Bogotá, Colombia. 658 Wuqu' Kawoq, Tecpan, Guatemala. 659 Ground Work, Fläsch, Switzerland. 660 Associazione Calabrese di Epatologia, Reggio Calabria, Italy. ⁶⁶¹University of Minho, Braga, Portugal. ⁶⁶²Fiji National University, Suva, Fiji. ⁶⁶³GHESKIO Clinics, Port-au-Prince, Haiti. 664 Universidad de San Carlos, Quetzaltenango, Guatemala. ⁵National Center for Epidemiology CIBERESP, Madrid, Spain. ⁶⁶⁶Institute of Food Sciences of the National Research Council, Avellino, Italy. 667 Medical University of Gdansk, Gdansk, Poland. 668 Sitaram Bhartia Institute of Science and Research, New Delhi, India. 669 Kindergarten of Avlonari, Evia, Greece. ⁶⁷⁰National Institute of Health, Lima, Peru. ⁶⁷¹Ministry of Health, Jakarta, Indonesia. ⁶⁷²Catalan Department of Health, Barcelona, Spain. ⁶⁷³Biodonostia Health Research Institute, San Sebastián, Spain, ⁶⁷⁴Instituto de Saúde Ambiental, Lisbon, Portugal, ⁶⁷⁵Federal University of Alagoas, Maceió, Brazil. ⁶⁷⁶South Karelia Social and Health Care District, Lappeenranta, Finland. ⁶⁷⁷National Cancer Center, Tokyo, Japan. ⁶⁷⁸University of São Paulo Clinics Hospital, São Paulo, Brazil. ⁶⁷⁹Hospital Italiano de Buenos Aires, Buenos Aires, Argentina. 680 Medical University of Vienna, Vienna, Austria. 681 Rigshospitalet, Copenhagen, Denmark. 682 Academic Medical Center of University of Amsterdam, Amsterdam, The Netherlands. 683German Institute of Human Nutrition Potsdam-Rehbruecke, Nuthetal, Germany. 684 The George Institute for Global Health, Sydney, New South Wales, Australia. ⁶⁸⁵Center for Oral Health Services and Research Mid-Norway, Trondheim, Norway, ⁶⁸⁶Lagos State University College of Medicine, Lagos, Nigeria. ⁶⁸⁷University of Las Palmas de Gran Canaria, Las Palmas de Gran Canaria, Spain.⁶⁸⁸Comenius University, Bratislava, Slovakia. ⁶⁸⁹Teikyo University, Tokyo, Japan.⁶⁹⁰Finnish Institute of Occupational Health, Helsinki, Finland. 691 Rutgers University, New Brunswick, NJ, USA. 692 National Agency for Public Health, Chisinau, Moldova. 693 St Vincent's Hospital, Sydney, New South Wales, Australia. 694 Nes Municipality, Årnes, Norway. 695 Health Polytechnic Jakarta II Institute, Jakarta, Indonesia. ¹⁹⁶Diponegoro University, Semarang, Indonesia. ⁶⁹⁷University of Bari, Bari, Italy. ⁶⁹⁸Institut Régional de Santé Publique, Ouidah, Benin. 699 University of Bordeaux, Bordeaux, France. ⁷⁰⁰University of Hohenheim, Stuttgart, Germany. ⁷⁰¹Oslo Metropolitan University, Oslo, Norway. 702 Institute of Public Health, Skopje, North Macedonia. 703 Ss. Cyril and Methodius University, Skopje, North Macedonia. ⁷⁰⁴Lamprecht und Stamm Sozialforschung und Beratung AG, Zurich, Switzerland. 705Bonn University, Bonn, Germany. 706National Institute of Public Health-National Institute of Hygiene, Warsaw, Poland. 707 Kalina Malina Kindergarten, Pazardjik, Bulgaria.⁷⁰⁸The Jikei University School of Medicine, Tokyo, Japan.⁷⁰⁹Fu Jen Catholic University, Taipei, Taiwan, ⁷¹⁰University of Jordan, Amman, Jordan, ⁷¹¹National Statistical Office, Praia, Cabo Verde. ⁷¹²Monash University, Melbourne, Victoria, Australia. ⁷¹³Scientific Research Institute of Maternal and Child Health, Ashgabat, Turkmenistan. 714University of Lincoln, Lincoln, UK. ⁷¹⁵Ministry of Health, Amman, Jordan. ⁷¹⁶UNICEF, Niamey, Niger. ⁷¹⁷University of Applied Sciences Utrecht, Utrecht, The Netherlands. ⁷¹⁸University Medical Center Utrecht, Utrecht, The Netherlands. ⁷¹⁹National Research and Innovation Agency, Jakarta, Indonesia. ⁷²⁹ Health Service, Murcia, Spain. ⁷²¹Institut d'Investigacio Sanitaria Illes Balears, Menorca, Spain. ⁷²²University of Bologna, Bologna, Italy. ⁷²³Children's Hospital of Eastern Ontario Research Institute, Ottawa, Ontario, Canada. ⁷²⁴Hellenic Health Foundation, Athens, Greece.
 ⁷²⁵ Government Medical College, Bhavnagar, India. ⁷²⁶Institute of Epidemiology and Preventive Medicine, Taipei, Taiwan. ⁷²⁷Sefako Makgatho Health Sciences University, Ga-Rankuwa, South Africa. ⁷²⁸Department of Health, Faga'alu, American Samoa. ⁷²⁹LBJ Hospital, Faga'alu, American Samoa. 730 Addis Ababa University, Addis Ababa, Ethiopia. 731 Ministry of Health, Wellington, New Zealand. 732 Israel Defense Forces Medical Corps, Tel HaShomer, Israel. ⁷³³Universidad Centro-Occidental Lisandro Alvarado, Barquisimeto, Venezuela. ⁷³⁴Meharry Medical College, Nashville, TN, USA. 735 University of Tampere Tays Eye Center, Tampere, Finland. ⁷³⁶Sabiha Gokcen Ilkokulu, Ankara, Turkey. ⁷³⁷Polytechnic Institute of Porto, Porto, Portugal. 738 Icahn School of Medicine at Mount Sinai, New York City, NY, USA. 739 George Washington University, Washington, DC, USA. 740 Universidad CEU San Pablo, Madrid, Spain. ⁷⁴¹Institute of Clinical Physiology of National Research Council, Pisa, Italy. ⁷⁴²Universidad San Francisco de Quito, Quito, Ecuador. ⁷⁴³University Miguel Hernandez, Alicante, Spain.

⁷⁴⁴Université de Lorraine, Nancy, France. ⁷⁴⁵Sunflower Nursery School, Craiova, Romania. ⁷⁴⁶North Karelia Center for Public Health, Joensuu, Finland. ⁷⁴⁷University of the Witwatersrand, Johannesburg, South Africa. ⁷⁴⁸Institute for Medical Research, Kuala Lumpur, Malaysia. ⁷⁴⁹Xinjiang Medical University, Urumqi, China. ⁷⁵⁰Shanghai Educational Development Co. Ltd, Shanghai, China. ⁷⁵¹Ministry of Health and Welfare, Taipei, Taiwan. ⁷⁵²Ministry of Health and Wellness, Kingston, Jamaica. ⁷⁵³Örebro University, Örebro, Sweden. ⁷⁵⁴St George's, University of London, London, UK. ⁷⁵⁵Universitas Indonesia, Jakarta, Indonesia. ⁷⁵⁶Rehamed-Center, Taipeina, Poland. ⁷⁵⁷National Yang Ming Chiao Tung University, Taipei, Taiwan. ⁷⁵⁸Institute of Food and Nutrition Development of Ministry of Agriculture and Rural Affairs, Beijing, China. ⁷⁵⁹Beijing Institute of Ophthalmology, Beijing, China. ⁷⁶⁰Children's Hospital of Fudan University, Shanghai, China. ⁷⁶¹University of Cyprus, Nicosia, Cyprus. ⁷⁶²Niigata University, Niigata, Japan. ⁷⁶³South China Institute of Environmental Sciences, Guangzhou, China. ⁷⁶⁴International Medical University, Shah Alam, Malaysia. ⁷⁶⁵Hellenic Mediterranean University, Heraklion, Greece. ⁷⁶⁶Iran University of Medical Sciences, Tehran, Iran. ⁷⁶⁷Center for Diabetes and Endocrine Care, Srinagar, India. ⁷⁶⁹Jagiellonian University, Kraków, Poland. ⁷⁶⁹Duke University, Durham, NC, USA. ⁷⁷⁰Peking University First Hospital, Beijing, China. ⁷⁷¹Jiangsu Provincial Center for Disease Control and Prevention, Nanjing, China. ⁷⁷²West Kazakhstan Medical University, Aktobe, Kazakhstan. ⁷⁷³Inner Mongolia Medical University, Hohhot, China. ⁷⁷⁴Przedszkole No. 81, Warsaw, Poland. ⁷⁷⁵Johns Hopkins University, Baltimore, MD, USA. ⁷⁷⁶These authors contributed equally: Anu Mishra, Bin Zhou, Andrea Rodriguez-Martinez, Honor Bixby. ⁷⁷⁷Deceased: Konrad Jamrozik, Altan Onat, Robespierre Ribeiro, Michael Sjöström, Agustinus Soemantri, Jutta Stieber, Dimitrios Trichopoulos. ⁵⁶e-mail: majid.ezzati@imperial.ac.uk

Methods

We estimated trends in mean height and BMI for children and adolescents aged 5–19 years from 1990 to 2020 by rural and urban place of residence for the 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 (that is, for successive cohorts) in rural and urban settings for each country.

Data sources

We used a database on cardiometabolic risk factors collated by NCD-RisC. Data were obtained from publicly available multi-country and national measurement surveys, for example, Demographic and Health Surveys (DHS), WHO-STEPwise approach to Surveillance (STEPS) surveys, and those identified through the Inter-University Consortium for Political and Social Research, UK Data Service and European Health Interview & Health Examination Surveys Database. With the help of the WHO and its regional and country offices as well as the World Heart Federation, we identified and accessed population-based survey data from national health and statistical agencies. We searched and reviewed published studies as previously detailed54 and invited eligible studies to join NCD-RisC, as we did with data holders from earlier pooled analyses of cardiometabolic risk factors⁵⁵⁻⁵⁸. The NCD-RisC database is continuously updated through all the above routes and through periodic requests to NCD-RisC members to ask them 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, with similar samples, 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 met the inclusion criteria and were not duplicates.

For each data source, we recorded the study population, the sampling approach, the years of measurement and the measurement methods. Only data that were representative of the population were included. All data sources were assessed in terms of whether they covered the entire country, one or more subnational regions (that is one or more provinces or 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 the 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 individuals. Questions and clarifications were discussed with NCD-RisC members and resolved before data were incorporated into the database.

Anonymized individual data from the studies in the NCD-RisC database were re-analysed according to a common protocol. We calculated the mean height and the mean BMI, and the associated standard errors, by sex, single year of age from 5 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 in height with age begins in the third and fourth decades of life⁵⁹. 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 the mean as the average of all individuals within the group and the associated standard error (s.d. 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 estimated standard error through Taylor series linearization, as implemented in the R'survey' package⁶⁰. Computer code was provided to NCD-RisC members who requested assistance. For surveys without information on the place of residence, we calculated summary statistics stratified by age and sex for the entire sample, which represented the population-weighted sum of rural and urban means; data on the share of population in urban and rural areas were from the United Nations Population Division⁶¹.

Additionally, summary statistics for nationally representative data from sources that were identified but not accessed using 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 study⁵⁸, when not accessed through the above routes.

Data inclusion and exclusion

Data sources were included in the NCD-RisC height and weight database if the following criteria were met: measured data on height and weight were available; study participants were 5 years of age or 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 characteristics⁶²⁻⁶⁴. Owing to these variations, approaches to correcting self-reported data may leave residual bias. We also excluded data sources on population subgroups for which anthropometric status may differ systematically from the general population, including the following: studies that had included or excluded people based on their health status or cardiovascular risk; studies in which 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 that 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 for which the 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 participants whose age was <18 years and whose data were not reported by single year of age (<0.01% of all participants) because height and weight may have nonlinear 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: <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, or who had recorded weight: <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 <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 analysis⁵⁸, the mean BMI was not reported but data were available for the prevalence of one or more BMI categories, for example BMI \geq 30 kg m⁻². To use these data, we used previously validated conversion regressions⁶⁵ to estimate the missing primary outcome from the available BMI prevalence metric or metrics. Additional details on regression model specifications along with the regression coefficients are reported at https://github.com/NCD-RisC/ncdrisc-methods/.

Statistical model overview

We used a Bayesian hierarchical meta-regression model to estimate the mean height and BMI by country, year, sex, age and place of residence using the aforementioned data. For presentation, we summarized the 15 age-specific estimates, for single years of age from 5 to 19 years, through age standardization, which puts the child and adolescent population for each country-year on the same age distribution, and hence enables comparisons to be made over time and across countries. We generated age-standardized estimates by taking weighted means of age-specific estimates using age weights from the WHO standard population⁶⁶. We also show results, graphically and numerically, for index ages of 5, 10, 15 and 19 years in the Supplementary Information.

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 and territories were organized into 21 regions, mostly based on geography and national income (Supplementary Table 1). Regions were in turn organized into nine super-regions.

We used observation year, that is, the year in which data were collected, as the timescale for the analysis of BMI and birth year as the timescale 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 nonlinear trends⁷¹, both modelled hierarchically. The age associations of height and BMI were modelled, using cubic splines, to allow for nonlinear changes over age, including periods of rapid and slow rise. Periods of rapid rise representing adolescent growth spurts, which occur earlier in girls than boys⁷²⁻⁷⁴, were reflected in the 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, informed by their own data as well as data from other countries as specified by a hierarchical structure, as previously described⁶⁹.

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 and year. 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 children residing in rural versus urban areas. If data for a country-year-age group contained a mix of children living in urban and rural areas but were not stratified by place of residence (21% of all data sources), the estimated height or 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 on how many age groups were represented in the study and whether 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 hereafter) and age group *h*, with age z_h , from study *i*, carried out in country *j* at time *t* is as follows:

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

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 the section 'Linear components of country time trends'. Letting *T* = 31 be the total number of years from 1990 to 2020, the *T*-length vector u_j captures smooth non-linear change over time in country *j*, as described in the section 'Non-linear change'. The age effects of the *h*th age group (with age z_h) in study *i* are denoted by p_i ; we describe the age model in the section 'Age model'. The matrix *X* contains terms describing whether studies were representative at the national, subnational or community level. In addition, a random effect, e_i , is estimated for each study, described in the section 'Study-level term and study-specific random effects'.

Linear components of country time trends. The model had a hierarchical structure, whereby studies were nested in countries, which were nested in regions (indexed by k), which were nested in super-regions (indexed by l), which were all nested in the globe (see Supplementary Table 1 for a list of countries and territories 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 (for example, had a small sample size or were not nationally representative) and, to a lesser extent, in data-rich countries and regions⁷⁵.

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:

$$\begin{aligned} a_{j} &= a_{j}^{c} + a_{k[j]}^{r} + a_{l[k]}^{s} + a^{g} \\ b_{j} &= b_{j}^{c} + b_{k[j]}^{r} + b_{l[k]}^{s} + b^{g} \\ a_{j}^{x} &\sim N(0, \kappa_{a}^{x}), \\ b_{j}^{x} &\sim N(0, \kappa_{b}^{x}), \end{aligned}$$

where *x* = {*c*, *r*, *s*}.

The κ terms were each assigned a flat prior on the s.d. scale⁷⁶. We also assigned flat priors to a^{g} and b^{g} .

Nonlinear change. Mean BMI or height may change nonlinearly over time^{7,54,58,65,70}. We captured smooth nonlinear 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

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

To allow the model to differentiate between the degrees of nonlinearity that exist at the country, region, super-region and global levels, we assigned the four components of each *u* a Gaussian autoregressive prior^{71,77}. In particular, the *T* vectors $u_j^c(j=1...f)$, $u_k^r(k=1...K)$, $u_l^s(l=1...L)$ 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 as follows:

	1	0	0		0							
	-2	1	0		0	1	-2	1	0	0		0
	1	-2	1		0	0	1	-2	1	0		0
P =	0	1	-2		0	0	0	1	-2	1		0
	0	0	1		0	:	÷	÷	:	:	۰.	:
	:	÷	:	۰.	:	0	0	0	0	0		1
	0	0	0		1							
	1	-2	1	0	0		0					
	-2	5	-4	1	0		0					
	1	-4	6	-4	1		0					
=	0	1	-4	6	-4		0					
	0	0	1	-4	6		0					
	÷	÷	:	÷	÷	۰.	:					
	0	0	0	0	0		1]					

P is multiplied by the estimated precision parameters λ_c , λ_r , λ_s and λ_g , thus upweighting or downweighting 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 s.d. scale $(1/\sqrt{\lambda})^{76}$. We truncated these priors such that $\log \lambda \le 20$ for each of the four λ' s. This upper bound is enforced as a computational convenience, whereby models with $\log \lambda > 20$ are treated as equivalent to a model with $\log \lambda = 20$ as they essentially have no extralinear variability in time. In practice, this upper bound had little effect on the parameter estimates. Furthermore, we ordered the λ' s a priori as follows: $\lambda_c < \lambda_r < \lambda_s < \lambda_g$. This prior constraint conveys the natural expectation that, for example, the global height or BMI trend has less extralinear variability than the trend of any given region, which in turn has less variability than those of constituent countries.

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 and the $u_j^{s'}$ s and u^{g} , and is not invertible⁷⁸. Thus, we had a proper prior in a reduced-dimension space⁷¹, with the prior expressed as follows:

$$P(u_j^{\rm c}|\lambda_{\rm c}) \propto \lambda_{\rm c}^{\frac{T-2}{2}} \exp\left\{-\frac{\lambda_{\rm c}}{2}u_j^{\rm c'}Pu_j^{\rm c}\right\}.$$

Note that if u_j^c had a non-zero mean, this would introduce nonidentifiability with respect to a_j^c . By the same token, b_j^c would not be identifiable if u_j had a non-zero time slope, and similarly for the other means and slopes. Thus, 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 nonlinear portions of the time trends meant that each can be interpreted independently.

For the cases in which we have observations for at least two different time points, this improper prior will not lead to an improper posterior

because the data will provide information about the mean and slope. In order to enforce the desired orthogonality between the linear and nonlinear portions of the model, we constrained the mean and slope of the $u_i^{c_i}s$, $u_k^{t_i}s$ and $u_i^{s_i}s$ and of u^{g} to be zero⁷¹.

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 constrained the non-identified portions of the model to zero, as the corresponding variances are set to zero⁷⁷; in this case the Rue and Held correction⁷¹ 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 – 1because the mean but not the linear trend of u_j^c to zero by taking the generalized inverse of the full conditional precision. We then constrained the mean of u_j^c to zero using the one-dimensional version of the Rue and Held correction⁷¹.

Age model. To capture sex-specific patterns of growth, especially adolescent growth spurts, we modelled age using cubic splines. The number and position of the knots of the splines were selected on the basis of a combination of physiological and statistical considerations, as described in a national level analysis⁷. For age group *h* with age z_h , in study *i*, the age effect for height and BMI is given, respectively, as follows:

$$\gamma_{i}(z_{h}) = \gamma_{1i}z_{h} + \gamma_{2i}z_{h}^{2} + \gamma_{3i}z_{h}^{3} + \gamma_{4i}(z_{h} - k_{1})_{+}^{3} + \gamma_{5i}(z_{h} - k_{2})_{+}^{3}$$

+ $\gamma_{6i}(z_{h} - k_{3})_{+}^{3} + \gamma_{7i}(z_{h} - k_{4})_{+}^{3}$, (height)

$$\gamma_{i}(z_{h}) = \gamma_{1i}z_{h} + \gamma_{2i}z_{h}^{2} + \gamma_{3i}z_{h}^{3} + \gamma_{4i}(z_{h} - k_{1})_{+}^{3} + \gamma_{5i}(z_{h} - k_{2})_{+}^{3}.$$
 (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 paper⁶⁹, using the equation below, where ψ is the global intercept, and c, r and s are the country, region and super-region random intercepts, respectively. The kth age effect coefficients for study $i(\gamma_{k,i})$ for each age group h, with age z_h , are given as follows:

$$\begin{split} & \gamma_{k,i} = \psi_k + c_{k,j[i]} + r_{k,l[i]} + s_{k,m[i]}, \\ & c_{k,j} \sim N(0, \sigma_{k,c}^2), \\ & r_{k,l} \sim N(0, \sigma_{k,r}^2), \\ & s_{k,l} \sim N(0, \sigma_{k,s}^2). \end{split}$$

A flat improper prior was placed on 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 owing 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 subnational and community populations. Our model therefore included time-varying offsets (referred to as fixed effects above) for subnational and community data in the term $X_i\beta$:

$$\begin{aligned} \mathbf{X}_{i} \mathbf{\beta} &= \beta_{1} I \{ X_{j[i], t[i]}^{\text{cvrg}} = \text{subnational} \} + \beta_{2} I \{ X_{j[i], t[i]}^{\text{cvrg}} = \text{subnational} \} t_{i} \\ &+ \beta_{3} I \{ X_{j[i], t[i]}^{\text{cvrg}} = \text{community} \} + \beta_{4} I \{ X_{j[i], t[i]}^{\text{cvrg}} = \text{community} \} t_{i}, \end{aligned}$$

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

Even after accounting for sampling variability, national studies may still not reflect the true mean height or BMI level of a country with perfect accuracy, and subnational 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, subnational or community level. Random effects from national studies were constrained to have smaller variance (v_n) than random effects of subnational 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 arising from imperfections and variations in study design and implementation and from within-country variability of height or 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) :

$$I_{s,i}[p_{j[i]} + q_{j[i]}t_i + r_{j[i]}z_h + d_i],$$

where $I_{s,i} = -1 + 2X_{s,i}^{\text{urb}}$, with

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

In other words, for data not stratified by place of residence, the model treated the unstratified mean height or BMI as equivalent to the weighted sum of the (unobserved) urban sample mean height or BMI and rural sample mean height or BMI, with the weights based on the proportion of the population of that country 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) as follows:

$$\begin{split} p_{j} &= p_{j}^{c} + p_{k[j]}^{r} + p_{l[k]}^{s} + p^{g}, \\ q_{j} &= q_{j}^{c} + q_{k[j]}^{r} + q_{l[k]}^{s} + q^{g}, \\ r_{j} &= r_{j}^{c} + r_{k[j]}^{r} + r_{l[k]}^{s} + r^{g}, \\ p_{j}^{x} &\sim N(0, \kappa_{p}^{x}), \\ q_{j}^{x} &\sim N(0, \kappa_{q}^{x}), \\ r_{j}^{x} &\sim N(0, \kappa_{p}^{x}), \end{split}$$

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 the overall age pattern of that country. This within-study variability cannot be captured by the *e* terms, which are equal across age-specific observations in each study, so we included an additional variance component for each study, τ^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 runs from randomly generated overdispersed 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 due to the overdispersed 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 to 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 of these chains, 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 one-year age groups from 5 to 19 years, as well as for age-standardized outcomes, by year. The reported Crls represent the 2.5th and the 97.5th percentiles of the posterior distributions. We also report the posterior s.d. of estimates, and PP that the estimated change in height or BMI in rural or urban areas, and in the 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-standardized) 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 the height for each birth cohort increased monotonically with age. In practice, this had little effect on the results, with height at age 19 years adjusted by an average of 0.26 cm or less for both boys and girls. All analyses were conducting using the statistical software R (v.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 a large number of population-based studies from 194 countries and territories covering around 99% of the population of the world. 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 during childhood and adolescence by using nonlinear time trends and age associations. The model used the available information on the urban-rural difference in height and BMI and estimated the age-varying and time-varying urban-rural difference for all countries and territories hierarchically.

Despite our extensive efforts to identify and access data, some countries had fewer data, especially those in the Caribbean, Polynesia, Micronesia and sub-Saharan Africa. Of the studies used, fewer than half had data for children aged 5-9 years compared to nearly 90% with data for children and adolescents aged 10-19 years. 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. Although urban and rural classifications are commonly based on definitions by national statistical offices, classification of cities and rural areas may, appropriately, vary by country according to their demographic characteristics (for example, population size or density), economic activities, administrative structures, infrastructure and environment. Similarly, urbanization 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 industrialize. 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 areas19,87-90

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Estimates of mean BMI and height by country, year, sex, single year of age as well as age-standardized, and place of residence (urban and rural) will be available from https://www.ncdrisc.org in machinereadable numerical format and as visualizations upon publication of the paper. Input data from publicly available sources and contact information for data providers can be downloaded from https://www. ncdrisc.org and Zenodo (https://doi.org/10.5281/zenodo.7355601).

Code availability

The computer code for the Bayesian hierarchical model and the code used to generate figures in this work will be available at https://www. ncdrisc.org and Zenodo (https://doi.org/10.5281/zenodo.7355601).

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Competing interests M.E. reports a charitable grant from the AstraZeneca Young Health Programme.

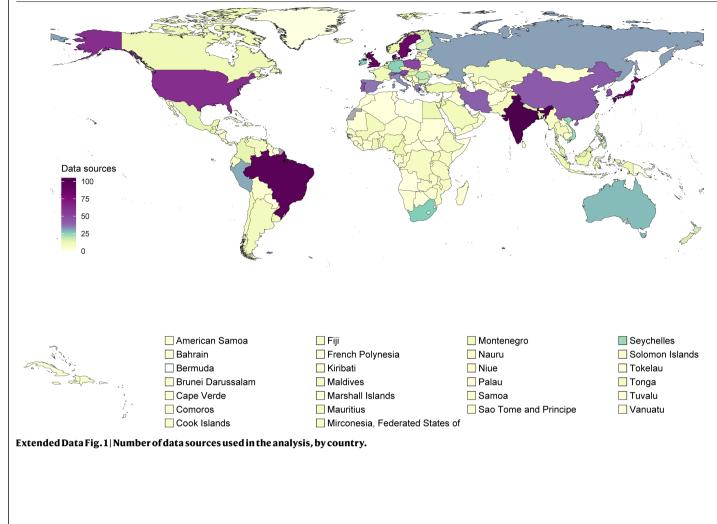
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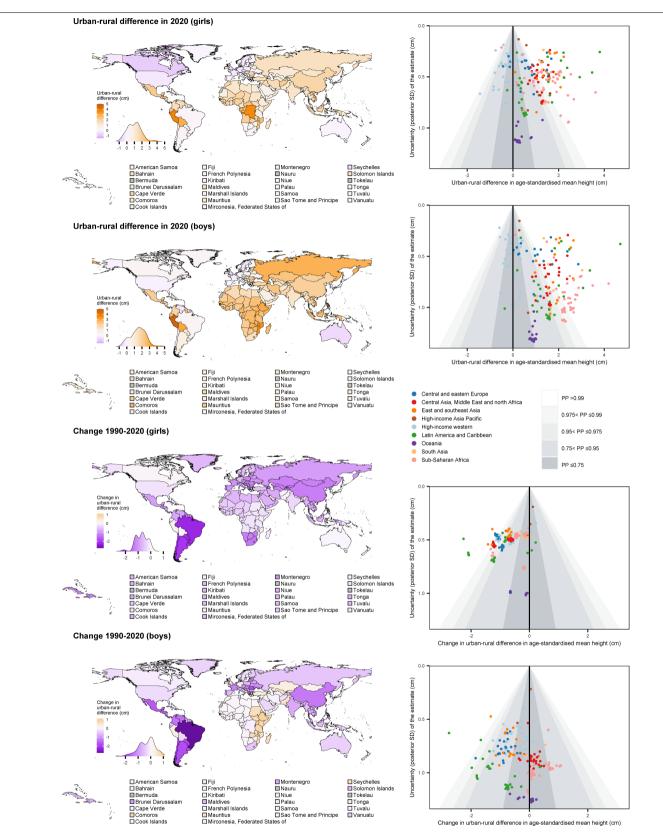
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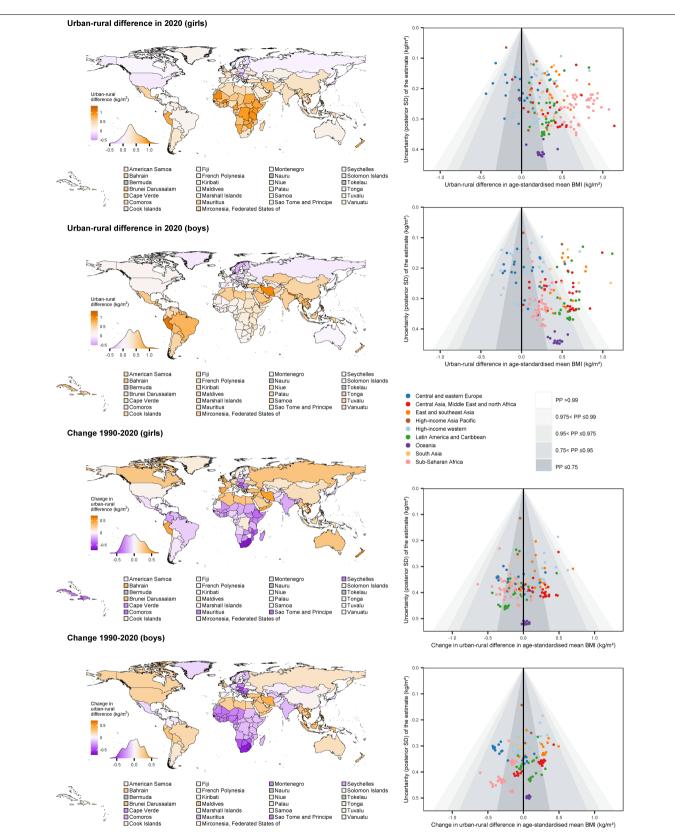






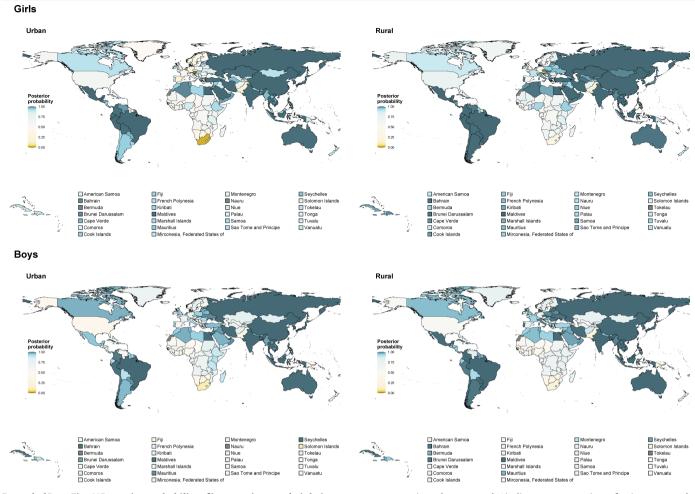
Extended Data Fig. 2 | See next page for caption.

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 agestandardised 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 agestandardised mean height in relation to the uncertainty of the difference measured by posterior s.d. The bottom two scatter plots 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 s.d. Each point in the scatter plots shows one country. Shaded areas approximately 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 Fig. 7 for results at ages 5, 10, 15 and 19 years. We did not estimate the difference between rural and urban height for countries classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or entirely rural (Tokelau), as indicated in grey.



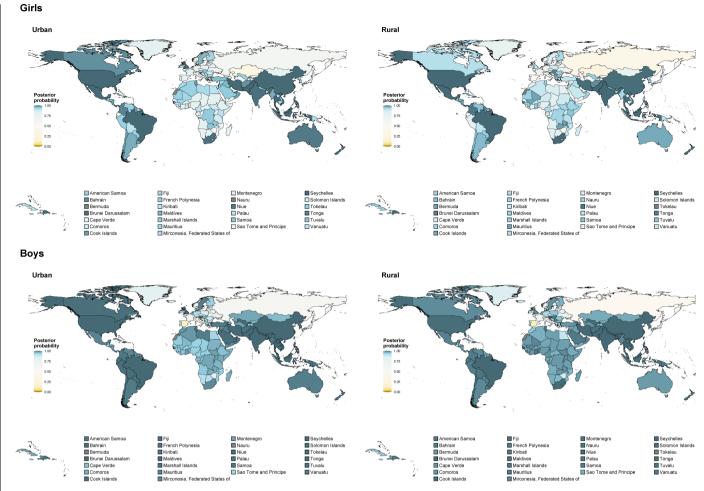
Extended Data Fig. 3 | Urban-rural body-mass index (BMI) difference in 2020 and change from 1990 to 2020. See Extended Data Fig. 2 caption for descriptions of the contents of the figure and for definitions. See Extended Data Fig. 9 for PP of the urban-rural difference in age-standardised mean BMI

and its change. See Supplementary Fig. 8 for results at ages 5, 10, 15 and 19 years. We did not estimate the difference between rural and urban BMI for countries classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or entirely rural (Tokelau), as indicated in grey.



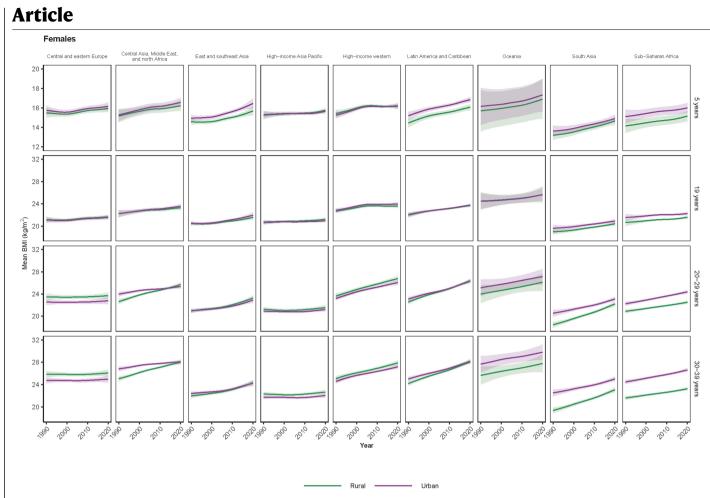
Extended Data Fig. 4 | Posterior probability of increase in mean height in urban and rural areas from 1990 to 2020. The maps show the PP that the age-standardised mean height increased from 1990 to 2020. The PP of a decrease is one minus that of an increase. If an increase in mean height is statistically 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 countries classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or change in mean urban height for countries classified as entirely rural (Tokelau), as indicated in grey.

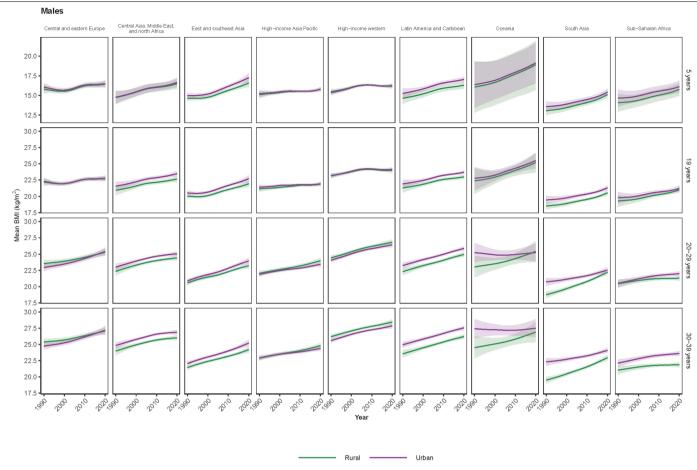


Extended Data Fig. 5 Posterior probability of increase in mean body-mass index (BMI) in urban and rural areas from 1990 to 2020. The maps show the posterior probability (PP) that the age-standardised mean BMI increased from 1990 to 2020. The PP of a decrease is one minus that of an increase. We did not

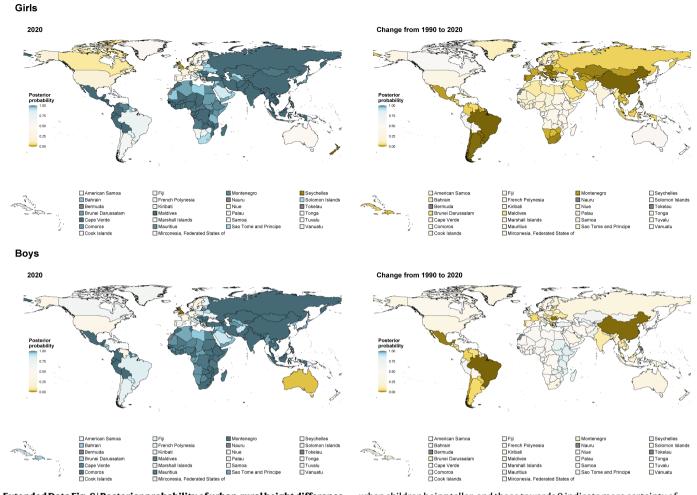
estimate PP for change in mean rural BMI in countries classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or change in mean urban BMI in countries classified as entirely rural (Tokelau), as indicated in grey.



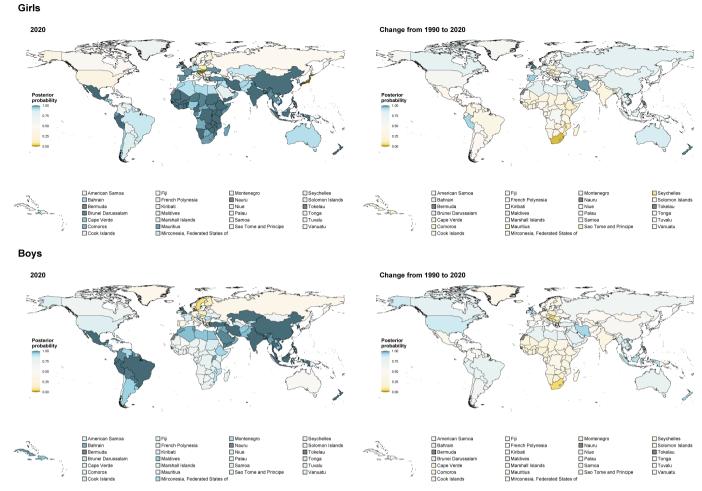
Extended Data Fig. 6 | Trends in body-mass index (BMI) by place of residence for children, adolescents and young adults for females. The figure shows trends in mean BMI at ages five and 19 years, and in age-standardised mean BMI for young adults (20–29 years and 30–39 years) for females. Shaded areas show the 95% CrIs. 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. For change, if an increase in urban-rural difference 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 in the urban-rural height difference, and those towards 0 indicate more certainty of a decrease. We did not estimate the PP for differences between rural and urban height for countries classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or entirely rural (Tokelau), as indicated in grey.



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 countries classified as entirely urban (Bermuda, Kuwait, Nauru and Singapore) or entirely rural (Tokelau), as indicated in grey.

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Software and code

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 Data collection
 Processing of secondary data was conducted using the statistical software R (version 4.1.2). We used R 'survey' package version 4.1-1.

 Data analysis
 All analyses were conducting using the statistical software R (version 4.1.2). The code for estimation of mean risk factor trends is available at www.ncdrisc.org.

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This is a data-pooling study that brings together 2,325 disparate data sources and uses a Bayesian hierarchical model to estimate population risk factor trends. Estimates of mean BMI and height by country, year, sex 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).

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Study description	We pooled and re-analysed population-based quantitative data that had measured height and weight for children and adolescents to estimate trends in mean BMI and height from 1990 to 2020 for 200 countries and territories, using a Bayesian hierarchical model.
Research sample	We used 2,325 population-based studies that had measured height and weight in 71 million participants in 194 countries. Studies were representative of a national, subnational or community population. We used all available and accessible data which met the criteria described below.
Sampling strategy	This is a data pooling study which used all available and accessible data. These are population-based studies, each with sample size set to detect measure of interest in that study. These were pooled in a meta regression which provides more confidence in results by borrowing strength across studies. We included data collected using a probabilistic sampling method with a defined sampling frame. We therefore included studies with simple random and complex survey designs but excluded convenience samples.
Data collection	We used 2,325 population-based studies that had measured height and weight in 71 million participants in 194 countries. We used data on measured height and weight to calculate mean BMI and height by sex and one-year age group. We excluded self-reported data.
Timing	For BMI, we pooled data collected from 1990 to 2020. For Height, we pooled data on those born from 1971 to 2015, after they had reached five years of age – i.e., data collected from 1976 to 2020. For BMI, we included national studies for the 3 years prior to start year, assigning them to the start year, so that they can inform the estimates in countries with slightly earlier national data. We used all available data within these years which met the criteria described below.
Data exclusions	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. 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 • women 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.
Non-participation	This was a secondary data analysis thus no participants were included in this study.
Randomization	Our study is an analysis of trends, and we did not carry out randomised experiments.

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