

Prevalence of undernourishment in adults in 195 countries and territories

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Abstract

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The prevalence of undernourishment (POU) is one of two primary indicators used to track progress towards sustainable development goal 2, which aims to end hunger and bolster food security by 2030. The United Nations Food and Agriculture Organization has historically been responsible for producing global estimates of the PoU in order to track progress towards the SDG target; however, the established methodology of PoU estimation is flawed across several dimensions, including no disaggregation by age or sex, a lack of estimated uncertainty, and, most importantly, the definition of an energy requirement that excludes a significant proportion of the population from being considered undernourished. In this study, we utilized copula methods to reconstruct the joint distribution of energy intake and the energy requirement for 195 countries by age and sex from 1990 to 2017 and compute the PoU accounting for undernourished individuals across the entire distribution of energy intake. We found that globally PoU in adults consistently declined from 9.9 (95% UI 9.5, 10.4)% in 1990 to 6.60 (95% UI 6.28, 6.81)% in 2017, though the effects of population growth have caused the number of undernourished adults to significantly increase over that period. We also found that by 2017 no countries to date had

achieved SDG targets of 0% PoU and just under half were not trending downward. In comparing our estimates to those of the FAO, we found that ours were generally lower but show high correlation ($\rho = 0.807$). Sensitivity analyses showed that differences in inputs are a likely explanation and that our copula based method indeed accounted for a substantial number of additional undernourished individuals compared to the existing cutoff-based methods, holding inputs constant.

Introduction

Malnutrition is one of the leading drivers of sub-optimal health worldwide, though it takes several distinct forms related to both the quantity and quality of consumption. One significant variant of malnutrition is undernourishment, which refers to a systematic deficit in an individual's habitual energy consumption with respect to their energy requirement. The factors underlying these deficits in populations worldwide are wide-ranging – from shocks to the food system due to conflict or drought to market forces rendering certain foods regularly unaffordable or inaccessible¹. Regardless the source, sustained undernourishment poses a significant health risk to both individuals and populations. Alongside other forms of undernutrition, undernourishment early in the life-course has specifically been linked to childhood mortality, long-term detrimental changes in physiology, and poor mental and behavioral health outcomes². Little evidence exists with respect to the long-term health consequences of undernourishment in adulthood, but acutely undernutrition at this age has been associated with increased mortality and morbidity, decreased routine function, and decreased quality of life³.

Recognizing how key a role ensuring basic sustenance plays in contemporary population health and well-being, the global development community specifically oriented sustainable development target 2.1 towards “end[ing] hunger and ensur[ing] access by all people, in particular the poor and people in vulnerable situations... to safe, nutritious, and sufficient food all year round” by the 2030⁴. Progress towards this target globally has been tracked conventionally by the United Nations Food and Agriculture Organization (FAO), who produce country-level estimates of the prevalence of undernourishment back to the year 2000, with smaller, more local efforts managed by national statistical offices.

The PoU indicator comprises of an estimate of habitual energy intake compared to a defined energy requirement, the latter of which is up for much debate. Energy requirements have been the subject of multiple WHO expert consultation groups over the past several decades and vary largely as a function of height, weight, age, sex, level of physical activity, though evidence about the exact quantitative contributions of each of these factors is mixed⁵. Also comprising part of individual energy requirements are individual efficiencies in metabolism, activities of daily living (not purposeful physical activity), and thermogenic effects of food. In order to classify an individual as undernourished, data needs to be available with respect to both their regular intake but also their individual requirement (e.g capturing both information about anthropometry and physical activity). Due to prohibitive costs and complexity of administration, surveys that capture all these components are very rare (two major example include the National Health and Nutrition Examination Survey in the United States and its South Korean counterpart); thus other sources of information must be used to estimate population-level energy intake and population-level energy requirements separately.

In the absence of comprehensive and reliable individual-level data on energy intake and energy requirements, methods of estimating the PoU have historically involved inferring a population-level distribution of energy intake from data on household-level food availability and covariates and comparing it to a fixed cutoff representing a minimum population-level energy requirement⁶. This method, however, almost certainly yields an underestimate of the PoU, as it assumes that individuals in the population that on average consume more than the minimum required across that population are all meeting their individual energy requirements. Exploratory analyses of data from the NHANES have shown this to be untrue. Additionally, the minimum weight for height and physical activity thresholds used to define this requirement, while decided by expert groups,

are outdated by several decades and do not reflect the levels of either that contemporary evidence has shown to minimize health loss. Lastly, although significant quality concerns exist with respect to available data used to estimate energy intake and energy requirements, PoU estimates have to date been reported without quantified uncertainty. Considering the fairly dramatic improvements over time that have been spotlighted through the PoU indicator as currently estimated, concern abounds as to the validity of the current construct and by extension whether progress has in fact been more modest. In this analysis we provide a global overview of the PoU in adults from 1990 to 2017, accounting for undernourishment in individuals consuming more than minimum population-level requirements, an energy requirement based in levels of body-mass and physical activity optimal for health, and uncertainty in the input components. Our primary goal is to provide a more realistic magnitude for the PoU worldwide and thus improve monitoring for SDG target 2.1.

Methods

Overview

Characterization of the PoU was adapted from the existing FAO methodology, whereby the estimated distribution of energy intake for a population is compared to an estimated energy requirement for that population. In the existing methodology, the energy requirement takes the form of a single population-weighted cutoff aggregated across country, age, sex, and time and is compared to a single distribution of intake estimated for the population. In this analysis, we estimate the distribution of the intake and the requirement separately by country, age, sex, and year; simulate the joint distribution of intake and requirement; and calculate PoU at this level of

disaggregation. Further details about the estimation pipeline can be found in Supplementary Figure 1.

Anthropometrics

Country-level estimates of mean height in adult by 5-year age group and sex were generated from those produced by the NCD Risk Factor Collaboration (NCD-RisC)⁷. NCD-RisC provides these estimates at the country-level by sex and adult birth cohort at age 18 years covering the time period 1914-2014. Using the 5-year average rate of change at the beginning and ends of the NCD-RisC estimation period, we back and forward-projected the cohort estimates to extend the time series from 1903-2017. To convert these to period estimates of adult height we applied single-year cohort age patterns in height estimated from the National Health and Nutrition Examination Surveys, and collapsed these into five year age groups using age-specific populations from the GBD 2017 analysis⁸.

Distribution of energy intake

As reliable data on habitual individual intake are often unavailable—often due to the cost and complexity of data collection—this must be inferred from other sources of information. Supply utilization accounts (SUAs) produced by the FAO provide annual estimates of population-level food availability, accounting for commercial use and food system-level waste down to the retail level. We used mean level of per capita energy availability as a reliable proxy for mean per capita energy intake given the plethora of self-report and instrument biases from other data source types. Annualized estimates of mean per-capita energy availability were generated with uncertainty from the SUA data using spatio-temporal gaussian process regression. Draw level

estimates of the age-sex pattern of consumption from available 24-hr dietary recalls were generated from a GBD 2017 Dis-mod MR model and applied to the estimates of mean per-capita energy availability to yield annualized country-level estimates of mean energy intake by 5-year age group and sex from 1990 to 2017.

The shape of the distribution of energy intake was characterized from NHANES microdata using an ensemble approach adapted from the GBD 2017 risk factors analysis. A mean to standard deviation regression of intake from NHANES data was used to predict standard deviations of the distribution of intake at the draw-level from the estimates of the mean described above. Draws of the mean and standard deviation were combined with the estimated ensemble weights to produce the full distribution of energy intake by country, age, sex, and year, with uncertainty.

Distribution of the energy requirement

Energy requirements can be thought of as the level of habitual energy intake that balances the level of energy expenditure required for a healthy and active life. Energy expenditure comes from four primary components: basal metabolism, activities of daily living, purposeful physical activity, and the thermogenic effects of food, of which basal metabolism accounts largest proportion⁵. Basal metabolism represents the energy expenditure associated with sitting quietly (due to routine physiological demands) and has been shown to depend on a linear combination of height, weight, and age from experiments using direct and indirect calorimetry⁹. A number of different relationships have been estimated, and each of their performances is varied across sub-groups¹⁰⁻¹². We chose use those derived by Mifflin-StJeor, as they have the highest predictive validity across a diverse set of populations per a systematic review of studies making such comparisons¹³. For this analysis we ignore the thermogenic effects of food in their contribution

to the energy requirement, as very little (if any) data is available at a population-representative level globally.

In defining the population energy requirement, we adapted the approach used by the FAO, which is based on the minimum daily energy requirement. The FAO calculates the minimum energy requirement using the BMR associated with estimated height, the 5th percentile weight for height by age and sex from WHO growth standards (BMI ~18.5), and the minimum level of healthy physical activity defined by a WHO expert group (1.55 BMR)⁶. Instead, we defined an optimal daily energy requirement, for which the weight-for-height and physical activity levels were given by estimated theoretical minimum risk exposure levels for body-mass index (20-25 kg/m²) and physical activity (3000-4500 MET-min/wk) from GBD 2017¹⁴. These provided a more realistic basis for determining the energy requirement, as they reflected harmonized evidence from cohort studies rather than relative measures or expert opinion. Processed NCD-Risc estimates of height were combined with draws of the aforementioned BMI and physical activity cutoffs to generate draw-level estimates of the mean optimal energy requirement by country, 5-year age group, sex, and year. Our analysis is restricted to adults aged 25 years and older, as GBD estimates of the optimal level of physical activity only apply to this age range, while GBD estimates of the optimal level of BMI only apply to those aged 20 years and older; thus, energy requirements could not be reliably computed for individuals younger than 25 years.

Like for energy intake, the shape of the distribution of the optimal energy requirement as well as the relationship between the mean and standard were characterized from NHANES microdata.

An ensemble approach was also used to derive the full distribution of the optimal energy requirement by country, age, sex, and year from draws of the mean and standard deviation.

Joint distribution of energy intake and energy requirement

Data regarding the joint distribution of energy intake and the energy requirement in populations are extremely limited, as these instruments would need to collect information on intake, physical activity, and anthropometrics simultaneously. In order to account for undernourished individuals that fall within the region of overlap between the marginal distributions of energy intake and the optimal energy requirement, we used a copula to link the estimated marginal distributions on the basis of a correlation structure observed in NHANES microdata. The copula family was selected on the basis of what which minimized AIC. Applying the estimated copula to the draws of the estimated marginal distributions, we were able to generate draws of the joint distribution by country, age, sex, and year.

Calculation of prevalence of undernourishment

The prevalence of undernourishment in a country, age, sex, year, is defined as the probability that a representative individual in the population is on average consuming less than their daily energy requirement. This corresponds to the proportion of individuals in the joint distribution of energy intake and requirement whose habitual intake is less than their optimal requirement. For 100 randomly sampled draws of the joint distribution for a given country, age, sex, and year, we simulated 10,000 individuals and determined those whose habitual intake fell below their optimal requirement. To account for uncertainty in the copula itself, for each draw of the joint distribution, we repeated the simulation 100 times, ordered simulated individuals by intake, and only counted individuals as undernourished whose habitual intake was less than their habitual requirement in at least 95% of the simulations.

Sensitivity Analysis

Estimation of the PoU relies heavily on the definition used for the energy requirement: this includes both cutoffs used to define optimal levels of BMI and physical activity, as well as the equations used to calculate basal metabolism from anthropometric characteristics. In transitioning from the FAO methodology to our own, we conducted our analysis in a stepwise fashion under the following scenarios: 1) using the minimum energy requirement as defined by the FAO, 2) using the optimal energy requirement (based on GBD cutoffs for BMI and physical activity) and the Schoefield equation for basal metabolism (used by FAO in energy requirement calculations), 3) using the optimal energy requirement and the Mifflin-StJeor equation for basal metabolism, and finally 4) characterizing PoU using the joint distribution of intake and the requirement characterized in scenario 3. Methodological details for each of these scenarios, as well as the FAO approach are detailed in Table 1.

Input	FAO	V1	V2	V3	V4
<i>Intake</i>	Household-level availability (skew-lognormal)	Country-level availability + age-sex intake pattern (ensemble)	Country-level availability + age-sex intake pattern (ensemble)	Country-level availability + age-sex intake pattern (ensemble)	Country-level availability + age-sex intake pattern (ensemble)
<i>Height</i>	Available survey data	NCD-Risc	NCD-Risc	NCD-Risc	NCD-Risc
<i>BMI cutoff</i>	5%ile weight for height (~18.5)	5%ile weight for height (~18.5)	20-25 kg/m²	20-25 kg/m ²	20-25 kg/m ²
<i>BMR Equation</i>	Schofield	Schofield	Schofield	Mifflin-StJeor	Mifflin-StJeor
<i>Physical activity cutoff</i>	.55 BMR	.55 BMR	3000-4500 MET-min/wk	3000-4500 MET-min/wk	3000-4500 MET-min/wk
<i>Copula</i>	No	No	No	No	Yes

Table 1. Variants of PoU Indicator Tested

Software

All analysis were conducted using R version 3.5.0. Per compliance with GATHER requirements, all code used for the analysis is available through GitHub.

Results

Global level

Globally the all-age prevalence of undernourishment in adults in 2017 was 6.60 (95% UI 6.28, 6.81)%, representing 292.7 (95% UI 278.6, 302.3) million total adults worldwide (Figure 1). The PoU has steadily decreased at the global level since 1990, when it was 9.9 (95% UI 9.5, 10.4)% , with the largest decreases observed after the year 2000. While PoU itself has been decreasing, the number of undernourished adults has steadily and significantly increased since 1990, demonstrating an increase over that period of 33.8 (95% UI 21.3, 44.9) million adults. The total number of undernourished adults peaked in 2017 at 292.7 (95% UI 278.6, 302.3) million individuals.

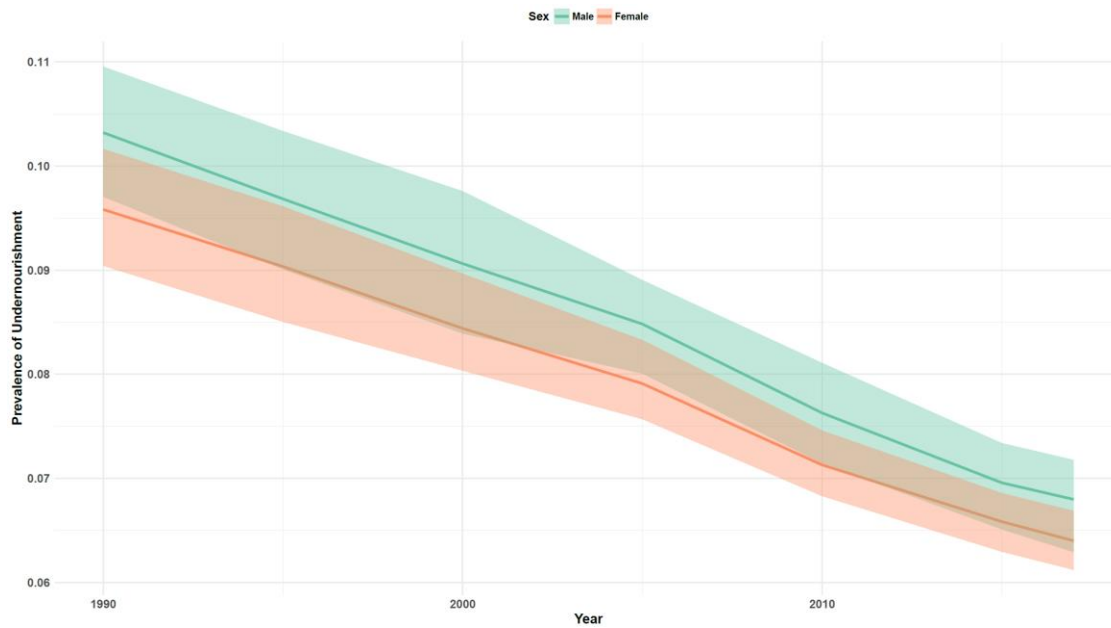


Figure 1. Global trends in all-age prevalence of undernourishment in adults by sex, 1990-2017

At the global level, men exhibited slightly higher PoU than women over the estimation period; however these differences were also not significant (Figure 1). We observed that globally, PoU generally decreases with increasing age, with the highest levels in 2017 observed in 25 to 29 year olds at 9.2 (95% UI 8.4, 10.1) % (Figure 2). A non-significant but larger number of men than women were undernourished in 2017 in the younger adult age groups, though this pattern reverses at 60 to 64 years of age. In addition, the age pattern of PoU dramatically flattened from 1990 to 2017. In 1990 the difference in prevalence between 25 to 29 year olds and 60 to 64 year olds was 7.5 (95% UI 6.8, 8.3)%. In 2017 this difference had converged, shrinking by nearly half to 4.36 (95% UI 4.05, 4.74)%. This suggests that much of the progress that has been made in the last several decades in addressing undernourishment in adults has come at the younger ages.

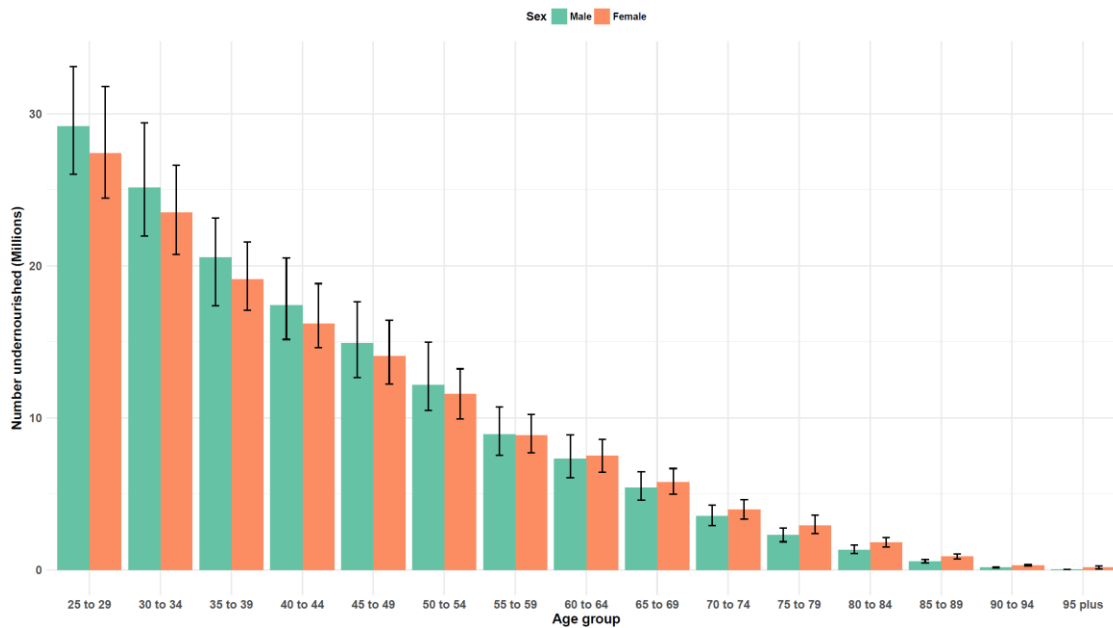


Figure 2. Global count of undernourished adults by 5-year age group and sex, 2017

Regional level

In addition to global patterns, given that the PoU is a SDG indicator, we were interested in examining region and country-specific trajectories in order to highlight areas that have made significant progress as well as those that are lagging behind. At a high level, the majority of the world's undernourished adults have resided in Southeast Asia, East Asia, and Oceania, comprising 30.9 (95% UI 29.5, 32.1)% of the global total in 2017 (Figure 3). This was largely driven by China, which alone comprised 20.9 (95% UI 19.1, 22.2)% of the global total. South Asia and Sub-saharan Africa accounted for 19.8 (95% UI 18.7, 20.8) and 18.7 (95% UI 17.9, 19.7)%, respectively of the global total of undernourished adults. The fewest of the world's undernourished adults in 2017 resided in North Africa and Middle East, representing only 4.92 (95% UI 4.71, 5.04)% of the global total that year. Examining patterns related to socio-

demographic development, 27.9 (95% UI 26.3, 29.1)% of the worlds undernourished adults in 2017 resided in High-middle SDI countries, which again was largely driven by China. 28.6 (95% UI 27.5, 29.8)% of the remaining undernourished adults resided in Low-middle SDI countries, with 15.7 (95% UI 14.6, 16.9)% of the global total accounted for by India. Additional details about the generation of SDI-groupings can be found in the supplementary appendix.

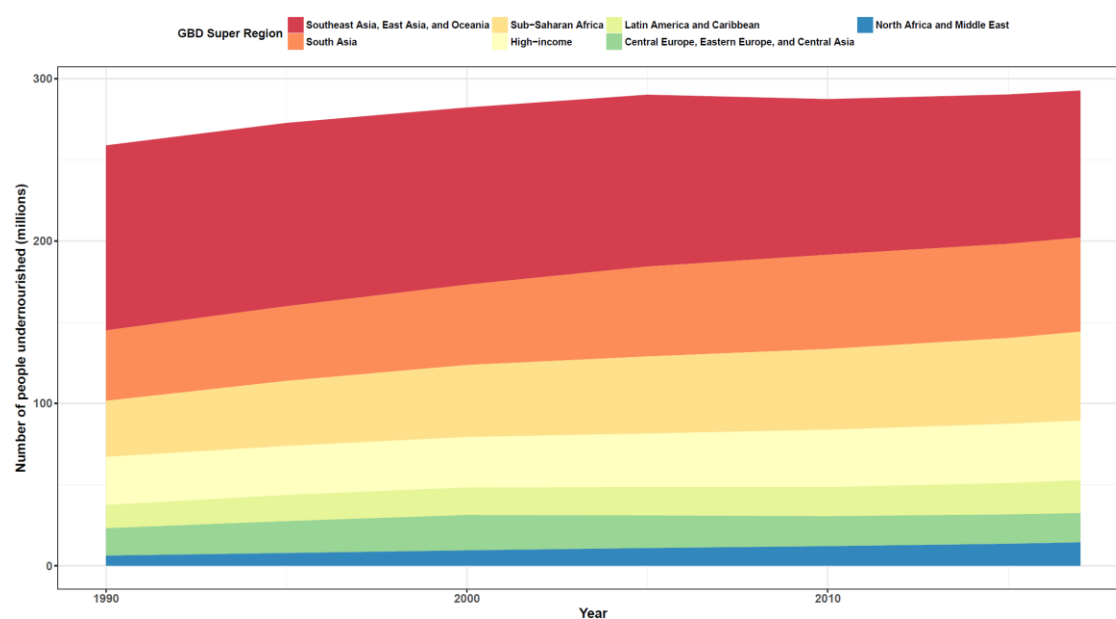


Figure 3. Global count of undernourished adults by GBD Super Region, 1990-2017

Country level

At the country-level, the highest age-standardized PoUs in adults of both sexes in 2017 were observed in Haiti, Somalia, and North Korea, at 37.0 (95% UI 34.7, 39.8)%, 33.5 (95% UI 30.6, 36.3)%, and 29.5 (95% UI 26.7, 32.3)%, respectively (Figure 4). In contrast, the lowest age-standardized PoUs in adults of both sexes that same year were observed in Turkey, Guam, and Qatar, at 1.98 (95% UI 1.70, 2.20)%, 2.16 (95% UI 1.96, 2.37)%, and 2.27 (95% UI 2.02,

2.56)%, respectively. The highest age-standardized PoU over the entire estimation period was observed in Ethiopia in 1995 at 56.7 (95% UI 52.3, 60.7)%, while the lowest age-standardized PoU over the entire estimation period was observed in Turkey in 1990 at 1.83 (95% UI 1.60, 2.05)% (Supplementary figure 1). Of countries with the 20 largest populations in 2017, only 2 fell within the 50 highest age-standardized PoUs, which included Ethiopia (4), and Democratic Republic of the Congo (6). 17 of these countries fell outside the top 100, in all of which a PoU under 8% was observed.

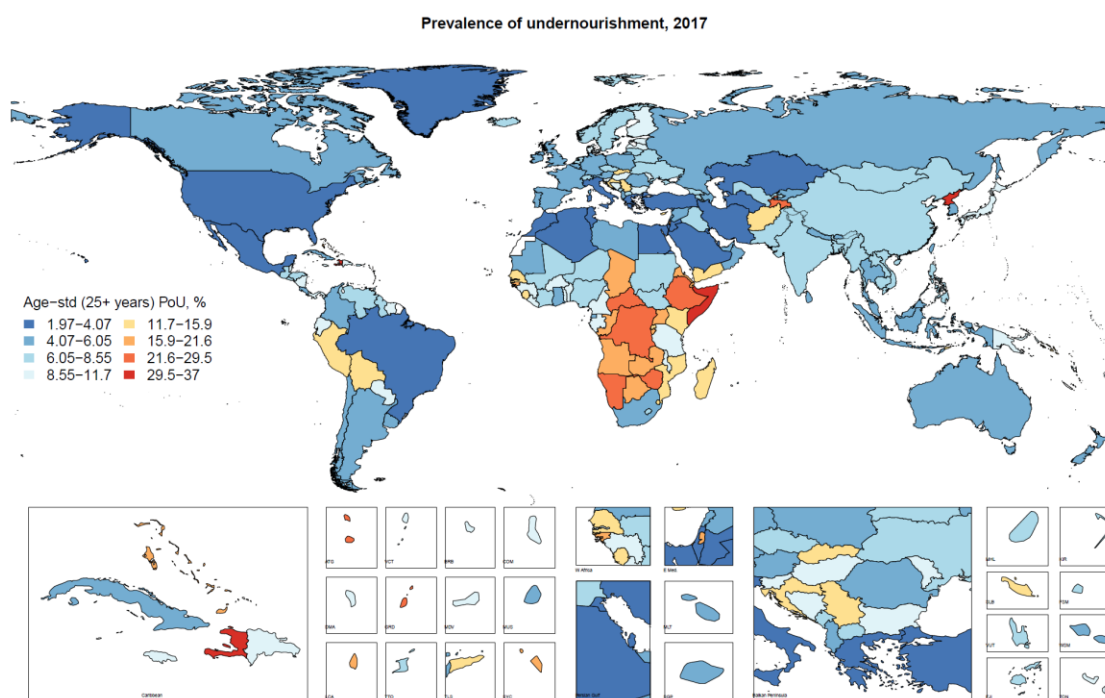


Figure 4. Age-standardized prevalence of undernourishment, Both sexes, 2017

Trends over time and progress towards SDG 2.1.1

From 1990 to 2017, 107 countries experienced significant decreases in the PoU, with a median absolute decrease of 2.69% over that period; the largest absolute decreases in the age-standardized PoU were observed in Djibouti, Angola, and Myanmar. Over this same period 45

countries experienced significant increases in the PoU, with an median absolute increase of 1.71%; the largest absolute increases in the age-standardized PoU were observed in Democratic Republic of the Congo, Somalia, and Bermuda. 43 countries exhibited no change in the age-standardized PoU, 11 of which had PoUs of over 10%. SDG 2.1.1 endeavors to reduce the all-age PoU to 0%—which no country has achieved to date, even in high-SDI settings. Due to significant uncertainty in estimation at low PoU, the FAO reports estimates down to a limit of 2.5%. Using this threshold, the only countries in line with SDG targets in 2017 were Turkey and Guam. All-age, both sex country-specific results are visualized in Supplementary Figure 2.

Sensitivity Analysis

PoU estimates under the first 3 scenarios generally showed extremely high correlation with each other ($\rho_{1,2} = 0.988$, $\rho_{1,3} = 0.93$, $\rho_{2,3} = 0.952$), but each significantly underestimated FAO, suggesting systematic differences in the underlying models of the intake distribution and mean height used between the two groups (Supplementary Figure 3). As expected, the PoU estimates under scenario 4 are consistently much higher than under scenario 3, as undernourishment in individuals within the overlap of the intake and requirement distributions is being accounted for. These differences appear to follow a clear curvilinear functional relationship, likely as a result of the same copula informing the joint distribution across all locations, ages, sexes, and years. Finally, while closer in magnitude than the other three scenarios, our country-level estimates of PoU using the copula (scenario 4) generally overestimate those of the FAO, even though they by definition account for more of the undernourished population within the intake distribution. Correlation between our all-age, both sex estimates and the latest FAO all-age, both sex estimates for years of overlap (2000, 2005, 2010, and 2015) was also quite high ($\rho = 0.807$).

Discussion

While work is still needed to expand the scope of estimation to the entirety of the global population, this analysis provides a significantly improved method for estimating the PoU indicator, leveraging novel statistical methods to count individuals that previous attempts had entirely ignored. We observed that relative to using existing methods based on a single cutoff for the energy requirement, estimating the PoU based on the joint distribution of energy intake and the energy requirement accounted for additional undernourished individuals whose intakes fell within the range of plausible energy requirements in their population. This analysis also represents the first of its kind to assess patterns of undernourishment by age and sex. At the global level, we did not observe systematic differences by sex, and we observed a fairly consistent decline in the PoU with increasing age, the latter of which one would expect given decreasing energy requirements (as a function of BMR) over age against comparatively smaller decreases in intake. The reversal of the sex pattern in the number of undernourished adults at age 60 can likely be explained by lower female mortality in younger adult age groups, such that the overall denominator for PoU at older ages is larger. For the first time, we also provided a measure of uncertainty around PoU estimates that reflects the observed heterogeneity and uncertainty in the data input to all components of estimation in the hopes that stories of progress, stagnation, or regression in levels of undernourishment are no longer interpreted in absolute terms. From 1990 to 2017 we observed significant decreases in the PoU globally but significant increases in the number of undernourished. We additionally noted that no country has definitively reached the 0% target for PoU set by SDG 2.2.1 and that alarmingly, almost a quarter of the 195 countries in this analysis each demonstrated no significant change or a significant increase in the PoU over that period, suggesting that additional advances in food

system, nutrition-related interventions, and nutrition-based health policy are sorely needed in order to correct course.

In comparing our estimates to those most recently released by the FAO as part of the 2018 State of Food Insecurity report, we found that our optimal energy-copula method tends to produce significantly lower PoU than their minimum energy-cutoff method. This was unexpected, as the copula method was intended to account for undernourished individuals within the range of overlap between the intake and requirement distributions that the cutoff methods entirely excluded. One likely explanation for the differences could be the underlying input data for the two sets of estimates. We utilized GBD inputs for energy intake and populations and to compute the energy requirement, which are known to be not completely consistent with estimates produced by other groups in any of these domains. Additionally, when we assessed the effect of the copula alone on PoU – holding input data and the definition of the mean energy requirement constant – we observed that as expected the copula significantly increased PoU across the time series. Specifically, we posit that overestimation by our energy intake model is the primary contributing factor, as in the absence of appropriate bias corrections for energy misreporting in self-report intake data currently we rely on availability data and assume that mean per capita availability equals mean per capita intake. This does account for the effects of food waste up to the retail level but not at the household and individual levels, both of which represent bias with respect to the amount actually consumed. The FAO, on the other hand, relies on household-level availability to estimate intake, but these data have less geographic and temporal coverage than SUAs, which are produced annually for every country, and a reasonable argument exists that in some settings a significant proportion of consumption might occur outside the home¹⁵⁻¹⁷.

A second hypothesis for the discrepancies could be systematic differences in the underlying estimates of height. Minimum energy requirements computed through the FAO methodology and optimal energy requirements computed through our revised methodology both utilize pre-specified, location and time invariant cutoffs for healthy weight-for-height and physical activity; thus estimated energy requirements vary almost exclusively as a function of estimated height. In processing NCD-Risc estimates of height, we utilized smoothed cohort age-pattern in height from five NHANES surveys to convert reported estimates of height at age 18 by birth cohort to full age and period-specific estimates of height. Given that these five NHANES surveys only accounted for a 10-year window collectively, the estimated cohort age pattern might have been confounded by underlying period trends, where improvements in nutrition over time have led to increases in the attained height of younger cohorts. Were this the case, height at middle older ages for more recent birth cohorts would likely be underestimated. Given that BMR, which scales linearly as a function of height, contributes relatively more than other factors to the energy requirement, systematic underestimation of height in the processed NCD-Risc estimates with respect to the FAO estimates could explain significant underestimation of the energy requirement and thus adult PoU. Future work will focus on improving the intake model by harmonizing information from data sources at the systems, household, and individual levels; however, a direct assessment of adult height by age and sex needs to be undertaken for all subsequent efforts at PoU estimation.

A final plausible explanation for the differences could be age-composition. The FAO does not produce nor report estimates of PoU by age or sex, but rather averages intake and requirements over them. Extrapolating the age pattern of undernourishment from our analysis, we would anticipate that relative to middle and older age adults, PoU would be higher in children and

adolescents. Thus, were we to include children and adolescents in our age-aggregated estimates of PoU, they might be at a similar magnitude as those of the FAO, who include individuals in these age groups. Alternatively, in the FAO's estimates of the overall population-level intake distribution, children and adolescents would likely fall towards the left tail since intake is highest in middle adulthood. As the FAO method compares this intake distribution to an overall population-level minimum energy-requirement cutoff informed in part by the higher minimum requirements in middle-aged adults, a large proportion of the individuals the FAO estimates to be undernourished may in fact be children and adolescents, purely as a artifact of their methodology. Compounded with the wide bases of population pyramids in many countries worldwide, this would lead to a higher all-age estimate of PoU than is perhaps accurate.

Limitations

Our analysis had a number of key limitations. The most significant, as mentioned above, is that our model of mean intake in the population is currently based on system-level data on availability and only accounts for food waste up to the retail level in attempting to equate availability and consumption. Ongoing work seeks to address this by developing a model for intake that can harmonize multiple types of data sources that might yield information about consumption, including the supply utilization accounts we have used in this analysis, 24-hour dietary recalls (24-hr DR), food frequency questionnaires (FFQ), and household budget surveys (HHBS). Food frequency questionnaires ask about habitual consumption of a variety of foods comprising a diet but suffer from issues of recall bias (e.g. it is more difficult for an individual to recall exactly how many times they consumed a specific item the longer the recall period) and rigidity (poorly designed questionnaires that do not explicitly ask about foods that might be

available in certain settings but not in others may miss out on large contributors to daily intake)¹⁸. Both 24-hr DRs and FFQs are also subject to underreporting of energy intake as a function of social desirability, which has been demonstrated to be further modulated by level of body-mass index^{19,20}. HHBS capture availability of food at the household level based on reported purchases, but these do not capture intra-household variability in consumption, consumption outside the household, nor intake lost due to household-level food waste. Lastly, SUAs produced by the FAO provide annual estimates of population-level food availability, accounting for commercial use and food system-level waste, while food balance sheets map the available food supply to food groups and available quantities of macronutrients. This mapping, however, requires several levels of processing from SUAs. Given the challenges in estimating consumption due to the effects of processing assumptions, food waste, instrument biases, and reporting biases that significantly affect other data sources, for this analysis we chose to exclusively use SUA data. While bias-correction methods could be developed to predict level of intake on the basis of reported availability, challenges still remain with respect to how to correct for known energy mis-reporting at the individual-level, especially given that social desirability factors at play vary widely across cultures, as well as how to capture aspects of consumption that occur both within and outside the household.

A second important limitation is that the shapes of both the intake and ensemble distributions, as well as the correlation structure in the copula, were inferred from the same group of NHANES surveys from the United States undertaken in the last decade. These surveys were the most readily available in the English language with individual-level information on energy intakes and from which energy requirements could be calculated, but a systematic review and extraction of all such sources is needed to either confirm consistency across settings or provide more

information about variation. Data contributing individually to the estimation of the shape of the distribution of intake or the distribution of the requirement (e.g from sources that only have an intake component or only have a physical activity questionnaire and anthropometry component) can and should be used as well. These efforts may be hindered in particular by the vast number of combinations of intake, anthropometric, and physical activity instruments used across surveys; a defined reference combination of instruments as well as bias adjustments would need to be developed in order to make use of all available data. A third limitation is that given the scope of current risk factors work in the GBD, this analysis focuses on adults aged 25 years and older when, relative to other age groups, the PoU is likely significant among children and adolescents and represent a large share of many populations globally. Undernourishment during childhood is extremely detrimental to growth and development and increases susceptibility to infectious diseases that form a large part of the disease burden globally^{21,22}. The long-term impacts of childhood undernourishment are also significant for population health at large, as the productive capacity of the population might limited once undernourished cohorts reach working-age given the limited reversibility of early exposure². While this analysis was intended to be a proof-of-concept for PoU estimation, true value towards SDG monitoring will require it to be extended to younger age groups.

Conclusions

Here, we have developed an improved methodology for PoU estimation that addresses issues of undercount stemming from existing methods and applied them to the global adult population.

While further validation of the method is needed, we have produced PoU estimates that provide a more realistic magnitude of the overall phenomenon as opposed to a lower bound, a significant

limiting factor to tracking progress through this indicator historically. We hope to eventually extend this analysis from the adult population to the full population in order to provide a measure more useful in gauging the overall nutrition landscape globally.

Ongoing monitoring of PoU is key to securing the ideals espoused by the SDGs, though in the coming years it is paramount to realize that the PoU alone will not be a significant enough indicator of the nutritional status of populations. As individuals worldwide are increasingly able to meet energy needs as a result of increased urbanization and mechanization of food systems driving a global nutritional transition, progress in the PoU may be masked by the substitution of insufficient calories for those that are actively unhealthy. As the global health community thinks about how to continue to improve measurement of the PoU, optimizing diet quality underlying energy intake should be a significant priority the future.

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