# Confronting the double burden of malnutrition yields health and environmental benefits.

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# Abstract

Prevalence rates of overweight and obesity are increasing across the globe. Here we present a novel framework that extends the UN-FAO's methodology for assessing undernutrition to also encompass excessive calorie consumption and its association with the evolution of adult Body Mass Indexes (BMI). By incorporating these relationships into a global partial equilibrium model of the food sector (SIMPLE), we develop future trajectories of age-, sex-, and cohort-specific adult BMI across major world regions over the next three decades. This allows for an examination of the dynamics of the double burden of malnutrition between 2015 and 2050. We find that the excessive consumption of calories will play a key role in driving rising BMI levels, particularly in emerging economies. As a consequence of reaching higher levels of BMI at younger ages, future cohorts will increase their exposure to the health risks attributable to overweight and obesity, including coronary heart disease, stroke, site-specific cancers, and type 2 diabetes we use this framework to shed light on the health, food, and environmental security impacts of changing food consumption behavior. A key finding is that the environmental benefits of shifting consumption patterns are dominated by food waste reductions as opposed to changes in dietary composition.

# Teaser

Shifting towards healthier consumption habits, including reduced food waste, improves both undernutrition and obesity outcomes, while reducing pressure on environmental resources.

# Introduction

We analyze the trade-offs and synergies posed by the dynamics of the malnutrition double burden towards the mid-21st century. While the global prevalence of undernutrition is expected to decline in coming decades [1], the prevalence of overweight and obesity are expected to rise [2,3]. Trends and patterns in adults' body weight can be examined from different perspectives [4,5]. Previous authors have examined: (i) age effects [6–10], (ii) time-specific period effects, capturing events uniformly influencing age groups and cohorts [3,11–14], and (iii) cohort effects of BMI [4,15–17]. However, system-wide assessment of these nutrition challenges is needed to fully understand the trade-offs and externalities arising across sectors, agencies, and scales [18–20].

We advance the current state of knowledge by presenting a novel, holistic framework for analysis of age-cohort and genderspecific changes in BMI by extending the Food and Agriculture Organization's Prevalence of Undernourishment (PoU) methodology to consider excessive calorie consumption [21]. Previous studies have also explored the human health and environmental co-benefits of moving from current levels of food purchasing to healthier dietary intake [22–24] However, they have failed to disentangle key differences between current food purchases and food consumption under a healthy diet. Much of the literature has just looked at total calories from the Food and Agriculture Organization's (FAO) Food Balance Sheets (FBS) and concluded that reducing them to a healthy level would greatly benefit the environment. However, the FBS calories have included food waste at consumers' level. Although recently some adjustments have been made, the inaccuracy persists [25]. Therefore, the excessive consumption of food in current diets, understood as the gap between current food consumption levels (equated to food availability from FAO's FBS) and healthy dietary intake levels, includes both food waste and excessive intake components [26].

Additionally, since shifting towards healthier diets usually implies not only a reduction in food consumption, but also shifting towards more plant-based diets, there is also a third contributorthe composition of these calories–that must also be considered. We extend the existing literature on these topics by disaggregating, for the first time, these three elements of the linkage from food purchasing behavior to the environment: changes in the composition of food consumption to achieve a more balanced diet, reductions in overall food intake, and reductions in food waste. We examine the relative contribution of each subcomponent to environmental sustainability, revealing that the food waste component of what has been dubbed in the literature 'dietary changes' represents the largest contributor to the environmental benefits of shifting food purchases to a more sustainable level.

We explore how the incidence of overweight and obesity would be affected by current trends in agricultural productivity, population, and income, as well as the complexities introduced by changing diets. We then incorporate this novel statistical framework into a global, partial equilibrium model of the agriculture sector, the Simplified International Model of Crop Prices, Land Use and the Environment (SIMPLE) [27]. This approach offers several analytical advantages over prior work. Firstly, it allows for an historical validation of the methodology to assess its performance in predicting historical patterns of overweight and obesity. By looking back, before looking forward with the SIMPLE model [28], this novel methodology allows the construction of more credible baseline projections of adult BMI towards 2050. Secondly, it allows us to assess the main factors driving projected increases in adult BMI, including income growth and changes in diets and food waste and the demand side, and technological changes contributing to increasing food availability on the supply side. Thirdly, it allows us to simulate several alternative future scenarios to examine the implications of changing diets for health and environmental outcomes as well as prices and food security. Our findings shed light on some of the critical challenges of the agricultureenvironment-health trilemma posed by the rising malnutrition double burden.

# Results

## Excessive consumption of calories is driving rapid rises in adult BMI

Since the mid-20th century, the calorie gap between average availability and daily requirements has risen sharply across the world (Fig. 1). Indeed, these nutrition transitions have tipped the balance between energy intake and energy expenditure, leading to widespread increases in rates of overweight and obesity. The double burden of malnutrition, characterized by high national rates of undernutrition co-existing with simultaneous rises in obesity, continues to worsen in low- and middle-income countries. These trends present a serious threat to global health. In this context, there is a need to better understand the potential trade-offs of policies aiming to reduce hunger and their unintended consequences for overweight and obesity prevalence [24].

It is projected that the gap between the calorie availability and energy requirements is projected to increase around 58% in women and 60% in men at the global level by 2050 (Fig. 1c). Morevoer, there is also a positive correlation between the excessive availability of calories and adult BMI that has been strengthening with each successive generation over the past century (Supplementary Information). Consequently, more recent cohorts reach higher BMI levels at younger ages and therefore experience longer durations of obesity over their lifetimes. This pattern emerges consistently across regions (Figs. 1d-1f) and appears to be correlated with changes in the food environment faced by each new cohort. This is a serious concern, since higher BMI levels are associated with a series of non-communicable diseases [29,30] and loss of disease-free years [31].

# Higher adult BMI in 2050 has adverse health impacts

Under the SSP2 baseline, the increase in average calorie availability leads to a dramatic increase in the percentage of people overconsuming calories. While wealthier regions such as USA and Europe are not expected to experience large changes, middle- and low-income regions are expected to show dramatic increases in the over acquisition and consumption of calories. This is particularly true for regions that are already struggling with a growing malnutrition double burden such as South America and South Asia (**Figure S3**).

Based on the underlying relationships between the excessive calorie availability and adult BMI we project expected changes in adult BMI towards 2050 (Fig. 2). Average adult BMI is projected to increase in virtually every region and for every age range, for both, men and women. Regions at earlier stages on the nutrition transition such as South Asia (Fig. 2a) are expected to experience the larger increases. Not only will average obesity increase, but the populations will reach higher levels of BMI at younger ages. Therefore, individuals will increase the number of years that they are exposed to the health risks related to overweight and obesity. Moreover, the projected increases in BMI will also be accompanied by dramatic increases in related diseases [32,33].

We estimate the disease burden attributable to weight-related risk factors by calculating population attributable fractions (PAFs) which represent the proportions of disease cases that would be avoided when the risk exposure is changed from a baseline situation to a counterfactual situation (See Supplementary Information for the details on PAF's calculations). In our case the PAFs are based on a comparison of the relative risk exposures caused by the average adult BMI levels projected towards 2050 with the counterfactual hypothesis of BMI levels fixed at 2015 levels (Supplementary Information). Therefore, these PAFs represent the proportion of disease cases that would be avoided if average adult BMI, for men and women, did not increase as expected towards 2050. We find that the PAFs attributable to projected changes in adult BMI are substantial for many major non-communicable diseases related to overweight and obesity [34], likely impacting mortality paths towards 2050 [35]. For example, we find that the counterfactual policy scenario, in which the average adult BMI levels do over the projections period, would reduce the incidence of type 2 diabetes in the US and Canada 26%, in South Asia by 10.5%, and in China by 34%. Absent such a policy, the expected increase in major disease burdens will further stress national health care systems [36]. This will also be associated with many economic and health costs [22], which are particularly burdensome for developing countries with weak institutions and highly differentiated access to quality health systems [37].

**Multiple dividends from altering future food purchasing patterns.**

There is increasing awareness of the role that food consumption choices can play in simultaneously addressing human health and climate change challenges [38]. Following ongoing transitions in food consumption patterns [39,40], global daily per-capita food availability and consumption of animal products have increased significantly in recent decades. Consequently, the population of cattle, sheep and goats supplying livestock products for human consumption have increased by 40% and that of pigs and poultry by 60% and 370%, respectively, with attendant increases in direct and indirect global greenhouse gas (GHG) emissions [41]. Animal agriculture now accounts for 8–10.8% of GHG emissions under the IPCC framework and the contribution of livestock rises to 18% of global emissions on the basis of lifecycle analysis [42]. Consumption of these products is predicted to grow as middle and lower income regions continue to develop; livestock consumption generally increases as incomes rise [43].

Previous studies have examined how the consumption of healthy and sustainable diets presents major opportunities to reduce environmental pressure [34,36,39]. Moreover, previous studies also highlight the importance of the increase in food availability in driving trends and patterns of global diets [44]. The association between obesity and diets has been explored across countries and time, with specific attention on the role of macronutrients [45], ultra-processed foods [46,47], and fats and sweeteners [44]. Here we use our novel framework to examine the potential multiple dividends, including health and environmental co-benefits, as well reductions in undernutrition, of shifting towards healthier and more sustainable consumption levels.

We extend the previous literature by examining the specific role of changes in dietary composition, reduction in food intake and food waste on natural resource use, crop production and environmental outcomes. Figure 3 presents projected deviations from the 2050 baseline in average adult BMI, for both men and women (percentage of 2050 values). As consequence of shifting to dietary intake levels that follow the healthy dietary guidelines (HDG), we project reductions in adult BMI towards 2050, for both men and women. Results are similar when shifting towards Flexitarian Diets. (See Supplementary Information: **Figures S5**, **S6**, and **S7** for results on flexitarian diets pathway). Men's BMIs are more sensitive than women's BMIs to changes in diets. Also, those regions at earlier stages of the nutrition transition such as Central Asia, China, and South America present larger decreases in BMI with respect to the baseline scenario in 2050 (Fig. 3).

Several studies have explored the potential environmental benefits of shifting towards healthier diets [22], the role of reducing food waste [26], as well as the contribution of cutting livestock consumption in diminishing stress on natural resource use [34,48,49]. With a global decrease in food demand, as a result of the shift in diets, crop prices are lower than in the baseline scenario leading to a reduction in crop production (Fig. 4), thereby reducing rates of cropland conversion as well as growth in the use of fertilizers and other yield-increasing inputs under both the flexitarian and the healthy dietary guidelines scenarios (See Supplementary Information for a detailed description of the scenarios and the implementation).

Shifting towards healthier consumption patterns in more developed regions increases the affordability of staple foods, leading to reductions in undernutrition outcomes in key developing regions including South and Southeast Asia, Sub Saharan Africa, and North Africa. Under this scenario, we project a reduction of 16 million people experiencing caloric undernourishment in those low-income regions.

Within the regions that shift towards HDG, those that are at earlier stages of the nutrition transition such as South America and Central Asia [44,50] and/or that present higher levels of food waste such as China [26], are the ones that present the largest reductions in cropland use. Additionally, here we extend the existing literature by providing a breakout of the relative contributions within the shifts to in healthier consumption patterns (i.e., changes in the composition of the food basket, reductions in food intake, and reductions in food waste). Changes in diet composition (i.e., relative reduction in livestock consumption) plays a mild role in the observed environmental benefits as well as in food affordability. A key finding is that most of the conservation in natural resource use in food production, as well as benefits from increased food affordability are driven by reductions in food waste as these countries move to consumption at the Health Dietary Guidelines (See Supplementary Information for results related to flexitarian diets scenario).

When considering the implications of the HDG scenario for greenhouse gas emissions, results are heterogenous across regions (Fig. 5). Global greenhouse gas emissions related to crop production are predicted to decrease by about 18% compared to the 2050 baseline, while global livestock-related emissions would decrease by more than 30%. This is due to the expected shifts towards greater consumption of animal source proteins in the baseline projections (i.e., in the absence of the HDG scenario). Therefore, in the context of a shift towards healthier consumption patterns, the relative contribution of changes in diet composition (less livestock) plays a large role in the greenhouse emissions reduction. This finding is consistent with previous studies [34,39,51,52].

## Discussion And Implications

We find a positive correlation between the excessive calorie availability and adult BMI, a link that is strengthening over successive generations. As a result, more recent generations present higher BMIs and are at risk of becoming overweight and obese at an earlier age, and for larger proportions of their lifespan. Following projected increases in excessive calorie availability, adult BMIs are projected to increase towards 2050 in virtually every country and region, which leads to worsening trends in non-communicable diseases attributable to overweight and obesity. This presents an extra level of complexity for developing countries, where weak institutions and limited access to health care systems are already challenging policy makers.

By providing a novel framework that enables the simultaneous examination of both ends of the distribution of caloric purchases within populations, we are able to uncover additional synergies and trade-offs between food policies oriented toward reducing hunger by increasing food supply, on the one hand, and, on the other hand, improving overweight, obesity and health related outcomes. As the world continues to push toward increasing the supply of food to alleviate hunger there is a simultaneous need to address the importance of nutrition and diet quality, including the production, promotion, and availability of affordable healthy diets. Shifting towards healthier and more sustainable food consumption levels could synergistically address multiple health and environmental burdens.

Importantly, we extend the previous literature by examining the relative contribution of the different subcomponents of shifting towards healthier and more sustainable consumption levels. By examining changes in food waste within the same framework as reductions in overall caloric intake and changes in dietary composition, we are able to assess the relative contribution of each component to reducing the pressure on natural resources. While shifting towards healthier diets and reducing caloric intake has desirable health implications for overweight and obesity health related outcomes, much of the environmental benefits, in particular reductions in land use and crop related GHG emissions, are derived from reductions in food purchasing due to mitigation of food waste rather than changes in dietary intake. A synergistic combination of measures will be needed to mitigate the projected increase in environmental pressures, while also avoiding unintended consequences on already worrisome trends in malnutrition double burden, as the global food system advances towards mid-century

## Materials And Methods

# Integrated modeling framework: overview

# Estimating the underlying relationships between calories and BMI

Despite its limitations (Supplementary Information), the FAO's Prevalence of Undernourishment[1] is widely used as the official indicator to monitor progress towards the United Nations Sustainable Development Goal 2.1 target. This indicator estimates caloric content of food commodities, allows for shifts the FAO distribution of those calories among the population across time based on incomes and prices, and utilizes an average minimum caloric requirement to produce an estimate of the share of the population that does not meet the minimum threshold of calories required for a healthy life [53]. We define, compute, and track over time and across countries the excess calorie availability (ECA) (Fig. 6, **arrow 1**). Under energy balance principle[54], the ECA is defined as the difference between the average daily supply of calories (SC) and average dietary energy requirements (ER) as follows:

$$\mathrm{ECA_{i,j,t}} = \mathrm{SC_{i,j,t}} - \mathrm{ER_{i,j,t}}$$

In this equation, subscript *i* corresponds to men and women, j indexes countries, and t corresponds to year; the average daily supply of calories (SC) in a certain population is obtained from the FAO's Food Balance Sheets; the average dietary energy requirement (ER) is defined as the calorie intake (kcal/cap/day) required to provide energy balance in a given individual of a healthy weight for their sex, age, and activity levels [55](See details in Supplementary Materials).

We then construct a pseudo-panel dataset from repeated cross-sections[56], spaced at five-year intervals for age and cohort groups. The dataset allows us to track changes in BMIs and their correlations with the ECA for 21 country-specific age-sex cohorts born between 1890 and 1995 and observed between 1975 and 2015. The dataset covers 156 countries which together represented 95% of the global population in 2015. Combining the BMI and ECA data sets, allows us to capture the long run underlying systematic relationship between the ECA and adult BMI while also dealing with potential eccentricities of individual countries and potential reporting errors to the FAO (Fig. 6, **arrow 2)** as follows:

## Model 1.

$$\mathrm{BMI_{i,j,t}} = \theta_0 + \alpha_{\mathrm{i,j,t}}\mathrm{ECA_{i,j,t}} + \beta_{\mathrm{i,j.t}}\mathrm{Age_{i,j.t}} + \gamma_{\mathrm{i,j.t}}\mathrm{Cohort_{i,j,t}} + \mathrm{R_{i,j}} + \epsilon_{\mathrm{i,j,t}}$$

## Model 2.

$$\mathrm{BMI_{i,j,t}} = \theta_0 + \alpha_{\mathrm{i,j,t}}\mathrm{ECA_{i,j,t}} + \beta_{\mathrm{i,j.t}}\mathrm{Age_{i,j.t}} + \gamma_{\mathrm{i,j.t}}\mathrm{Cohort_{i,j,t}} + \lambda_{\mathrm{i,j.t}}\mathrm{X_{i,j.t}} + \mathrm{R_{i,j}} + \epsilon$$

In these models, subscript *i* corresponds to men and women, *j* indexes countries, and *t* corresponds to year; $R$ represents region-specific fixed effects that embody relevant but unobserved historical and institutional features of a region that are highly likely to be correlated with explanatory variables in the models; and $\epsilon$ represents an error term. BMI is the age- and sex-specific body mass index (BMI). Age represents a vector of variables controlling age-related unobservable effects, Cohort is the year of birth, and ECA represents the average daily excess of calorie availability. In the model 2 we investigate more in deep the specific role of ECA as driver of adult BMI in recent years incorporating a vector of controls for the changes in the food environment (i.e., income, rural population, health expenditure, etc.). Details on data models 1 and 2 are reported in the Supplementary Material and results from these regressions are presented in **Table S1**, **Table S2**, **Table S3** and **Figure S1**.

**Incorporating ECA and BMI underlying relationships into global partial equilibrium model for the agriculture sector: an extension of the PoU**

Under a partial equilibrium framework, we equate the supply of calories (from FAO's FBS) to the demand (average daily demand of calories) **(**Fig. 6, **arrow 3)**. As a result, we define the average daily excessive consumption of calories (EC) as follows:

$$\mathrm{EC_{i,j,t}} = \mathrm{ECA_{i,j,t}} = \mathrm{SC_{i,j,t}} - \mathrm{ER_{i,j,t}}$$

In anticipation to the economic projections to be undertaken using the partial equilibrium framework, we aggregate countries into 15 major geographic regions. This particular aggregation into 15 regions has the additional advantage of matching with the Simplified International Model of Crop Prices, Land Use and the Environment (SIMPLE) [28] that we use in the economic projections towards 2050 **(**Fig. 6, **arrow 3)**. Incorporating the systematic underlying relationships between EC and adult BMI into a partial equilibrium economic framework [27], it is possible to analyze likely future scenarios based on shared socio-economic pathway (SSP) projections for the global economy.

For this work we create the Prevalence of Overconsumption (PoO) indicator. The PoO extends the FAO methodology by incorporating into the analysis the concept of excessive calorie consumption (Fig. 6), which includes both excessive calorie intake and imputed food waste [26]. The details on this PoO extension are in the Supplementary Information.

This extension of the PoU methodology allows us to simultaneously analyze both ends of the caloric distribution, thereby producing estimates of the double burden of malnutrition which is now a dominant concern in countries at earlier stages of the nutrition transition [3]. Indeed, the coexistence of undernutrition and overweight/obesity constitutes an unprecedented challenge to global health[18,19]. Effectively responding to this requires a better understanding of the dynamics of the underlying phenomena [57,58]. Moreover, reducing excess acquisition of calories is critical for improving resource efficiency towards sustainable food systems [34,59–61]. A key contribution of our study is that we split the excessive acquisition of calories (Fig. 7-b) into excessive intake and food waste. Food waste is predicted to increase with income after the average dietary energy requirements are satiated [26].

# Model validation, uncertainties, and baseline projections towards 2050

Following Baldos and Hertel (2014) and Lopez Barrera and Hertel (2020) who used the SIMPLE framework to examine the evolution of undernourishment and food waste respectively, we start our analysis by evaluating how well the model projects changes in adult BMI over an historical period: 2005–2015 (**Figure S2**). Often studies that use economic models to project future outcomes are not validated against history, yet this is a critical step. Additionally, this historical assessment provides valuable inputs for examining future changes. The model's historical projections perform best at the global level; projections are less accurate at the regional level, but still capture the broad trends. This is consistent with previous studies attempting to validate global food system models [1,26,62]. Also consistent with previous literature, there is considerable regional variation in the model uncertainties. Regions already at higher levels of excessive calorie availability and BMI (such as the US) present lower uncertainties. On the other hand, regions at earlier stages in the nutrition transition, such as South Asia, present larger uncertainties.

Following model validation, we turn to business-as-usual (BAU) projections of adult BMI from 2015 to 2050 (Fig. 6, **arrow 4-a)**. The SIMPLE model is projected forward with exogenous shocks to population, per capita income, total factor productivity (TFP) growth in agriculture, and biofuel consumption. Growth rates for population and income were derived from the Shared Socioeconomic Pathways [63]. Our baseline follows the BAU Shared Socioeconomic Pathway (SSP2) which is widely used to evaluate climate change and environmental outcomes. This provides a natural starting point from which to explore integrated solutions for achieving societal objectives to reduce pressure on environmental resources [63]. Projected TFP growth rates are based on the historical estimates from previous studies [64,65]. Future growth in global biofuel consumption is from the IEA[66]. All of these inputs are reported in detail in the Supplementary Information. Based on the underlying relationships between the excessive calorie consumption and adult BMI we project expected changes in adult BMI towards 2050 (Fig. 2). We then use the adult BMI projections to estimate the disease burden attributable to weight-related risk factors by calculating population attributable fractions (PAFs) which represent the proportions of disease cases that would be avoided if average adult BMI, for men and women, did not increase from 2015 levels (see Supplementary Information for the details).

## Specification of the counterfactual scenarios

We adapt the counterfactual scenarios in previous studies [23] regarding shifting toward healthier and more sustainable diets (Fig. 6, **arrow 4-b)**. The counterfactual diet scenarios analyzed in this chapter include diets aligned with global dietary guidelines (HDG), and more plant-based flexitarian diets (FLX) that are reflective of present evidence on healthy eating. The HGD scenario is based on global guidelines on healthy eating issued by WHO/FAO Expert Consultations on diet, nutrition [67] and human energy requirements [55] and the FLX is a more ambitious dietary change that implies larger levels of substitution of animal source proteins for vegetable source proteins. We start by comparing the BAU projections on food consumption from Springmann et al.'s (2018) with those in this study obtained with SIMPLE, under the SSP2 scenarios. We do so by aggregating across food groups from Springmann et al. into "crop" and "livestock" categories. In order to better understand the dynamics of the malnutrition double burden, we restrict the exogenous changes in food consumption to those regions that are already at latter stages in the nutrition transition [39]. This allows us to project endogenous changes in caloric undernutrition in those regions that host most of the current and projected undernourished individuals.

Moreover, the excessive consumption of food in current diets, understood as the gap between current food consumption levels (equated to FAO FBS's) and healthy dietary intake levels, really includes both food waste and excessive intake. Additionally, since shifting towards healthier diets usually imply not only the reduction in food consumption, but also shifting towards more plant-based diets, there is also a third contributor – the composition of these calories. Here, we decompose, for the first time, these three elements (composition of diets, excessive intake, and food waste) of the linkage from food purchasing behavior and the environment to analyze their relative contribution to environmental sustainability (Fig. 6, **arrow 4b and** Fig. 7-b**)**. In order to decompose the relative environmental benefits of each of the subcomponents, we utilize a 3-step experimental design which permits us to decompose the overall environmental benefits of shifting towards healthier diets for both the HDG and FLX dietary scenarios (see details in the Supplementary Information) (Fig. 6, **arrow 5)**.
[1] Sustainable Development Goal 2.1: "By the year 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round".

## Declarations

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**Competing interests**

The authors declare no competing interests.

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## Figures

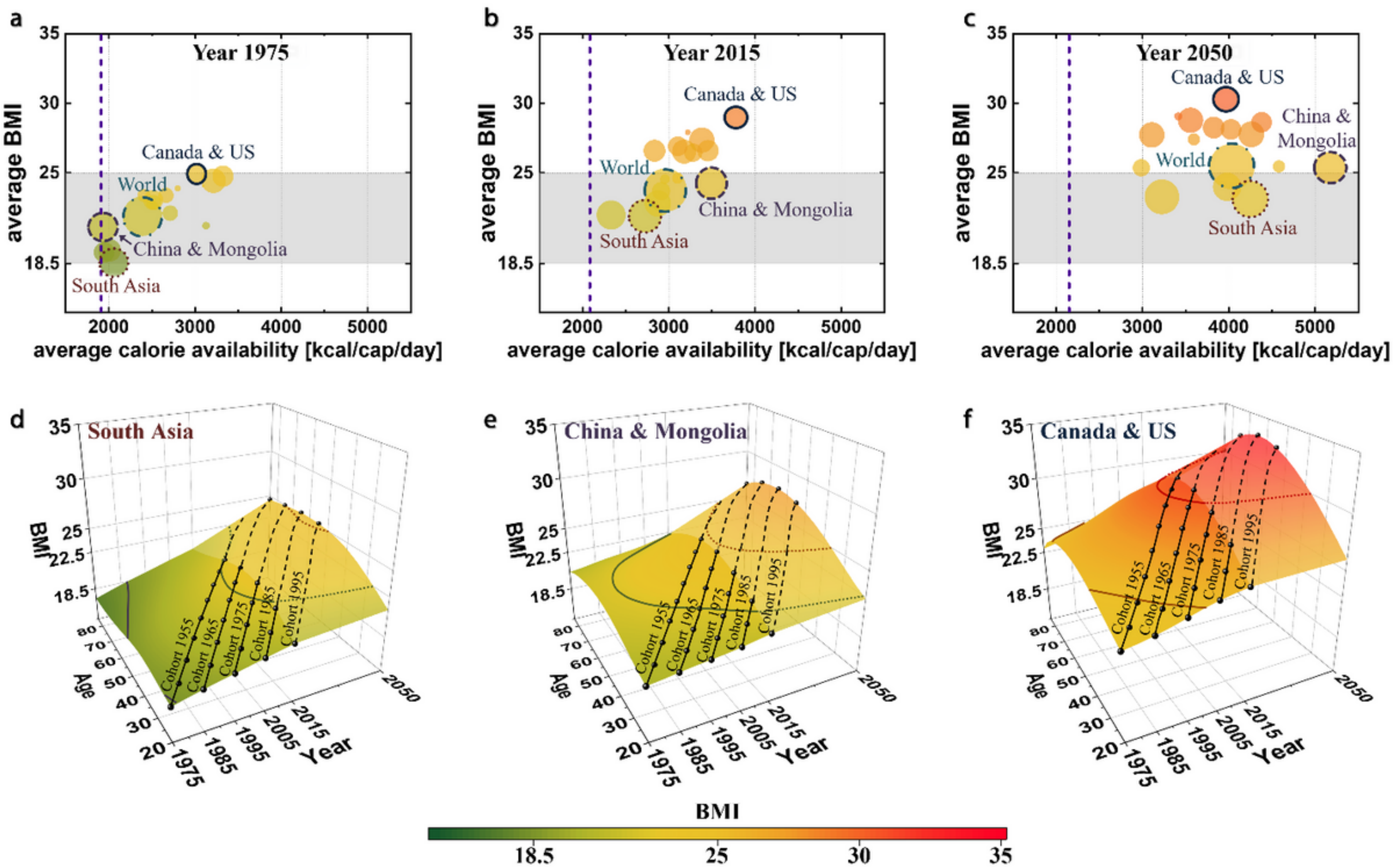


Figure 1

**The excessive calorie availability and adult BMI.** The top three panels present the average daily supply of calories (kcal/cap/day) and average BMI in 1975 (**a**), 2015 (**b**), and 2050 projections (**c**) across regions. Average BMI is the population-weighted average composite of adult women and men. The gray shaded areas in the figures correspond to healthy BMI ranges. Dashed vertical lines represent the global average daily energy requirement (kcal/cap/day) in reference years which is well below average calorie availability in all regions by 2050. Circle sizes in **a**-**c** are proportional to countries' populations. Panels **d**-**f** illustrate how BMI evolves across cohorts and over time at different income levels, for adult women in three regions (**Figure S8**, present results for the women in the remaining regions and **Figure S9** for men). Observed changes in BMI for cohorts matched by age of birth are illustrated in the solid lines, while projections towards 2050 are given by the dashed lines. The isoquants in these panels represent different BMI levels: 18.5 (purple), 22.5 (green), 25 (brown), 30 (red). South Asia (**d**) (a low-income region), China (**e**) (middle-income), and Canada & US (**f**) (high-income), present similar age and cohort patterns but at different BMI levels. These lower panels were constructed by aggregating results from a fixed-effect, country/panel statistical model into 15 regions (Supplementary Information) and making projections to 2050 (Supplementary Information).

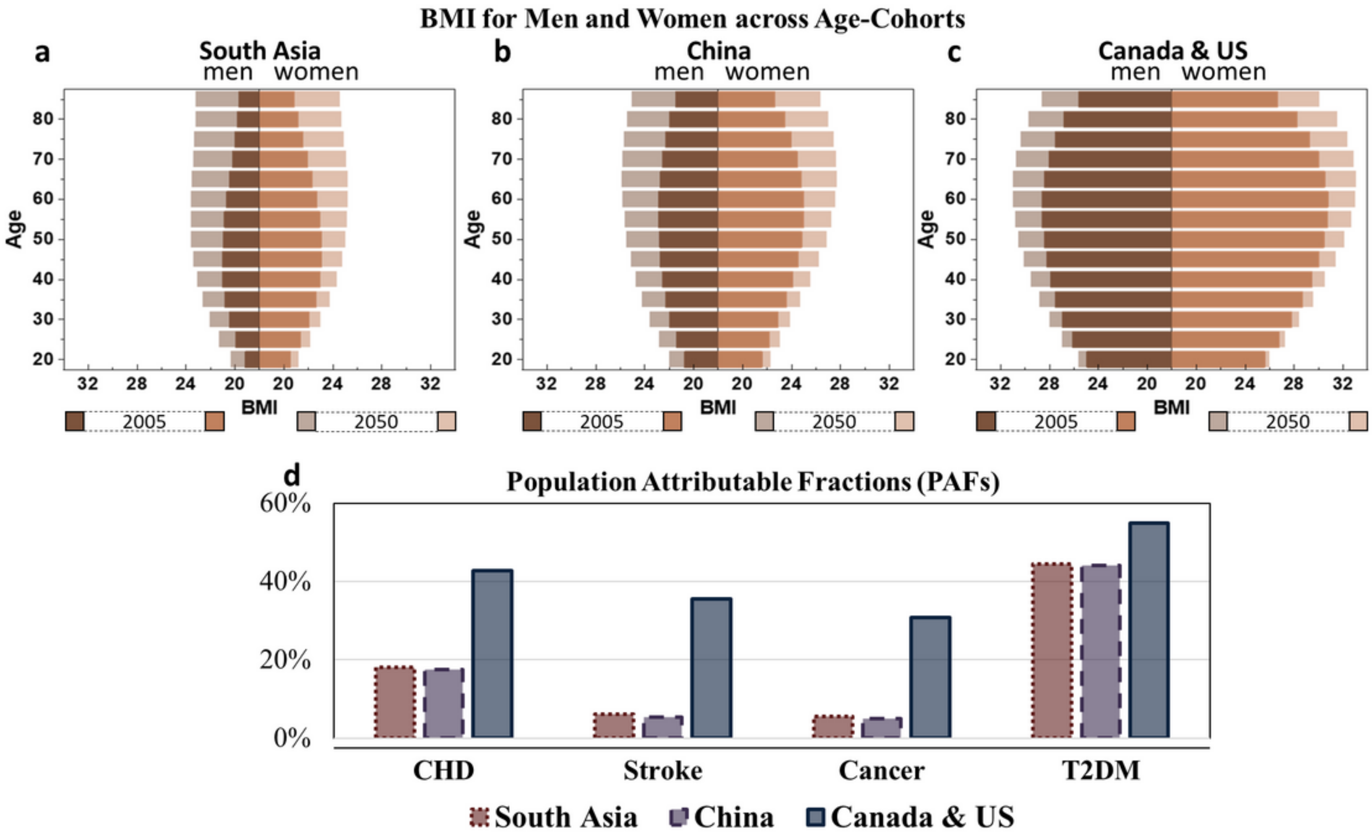


Figure 2

**Projections of the age-specific average adult BMI and PAFs.** Panels **a**, **b** and **c**, present population pyramids for the age-specific average BMI in adult men (left-side) and women (right-side of each pyramid). Observed average adult BMIs in 2015 are represented in darker colors and projected average adult BMIs in 2050 are represented in lighter colors for the South Asia, China, and Canada &US regions (**Figure S10,** present results for the remaining regions). The bar chart at the bottom (**d**) reports population attributable fractions (PAF), representing the potential reduction in population diseases attributable to overweight and obesity, coronary heart disease (CHD), Stroke, some types of cancer, and Type 2 Diabetes (T2DM), if the average adult BMI levels remained fixed at 2015 levels.

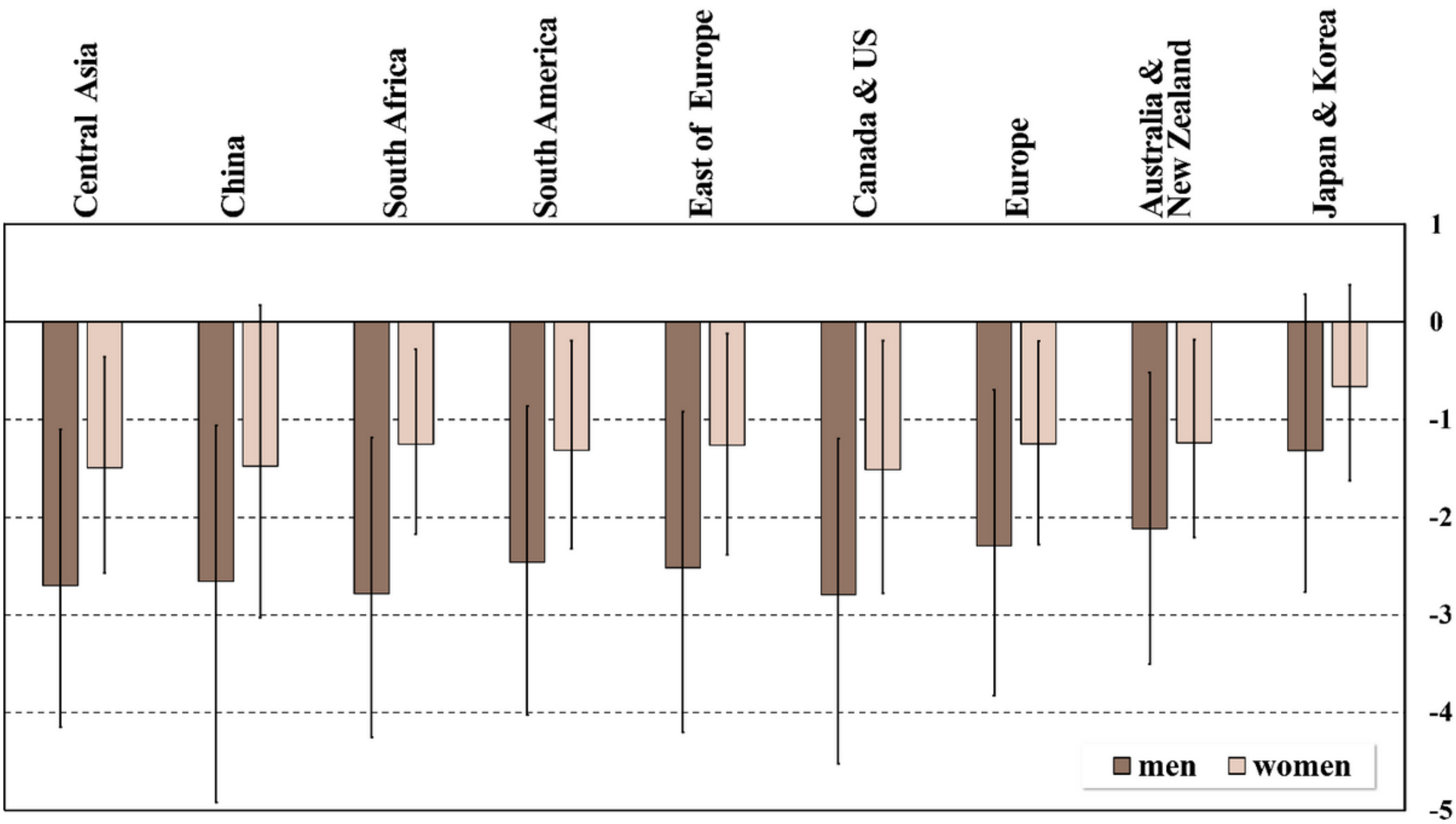


Figure 3

**Projected changes in BMI for men and women.** The bars represent the projected percentage changes with respect to the 2050 baseline case caused by shifting towards diets following intake recommended in the healthy dietary guidelines (HDG) in each region (Supplementary Information for results on flexitarian diets pathway). Omitted regions are not subjected to the diet changes. Error bars represent 95% confidence intervals. (**Figure S5** presents results on flexitarian diets pathway).

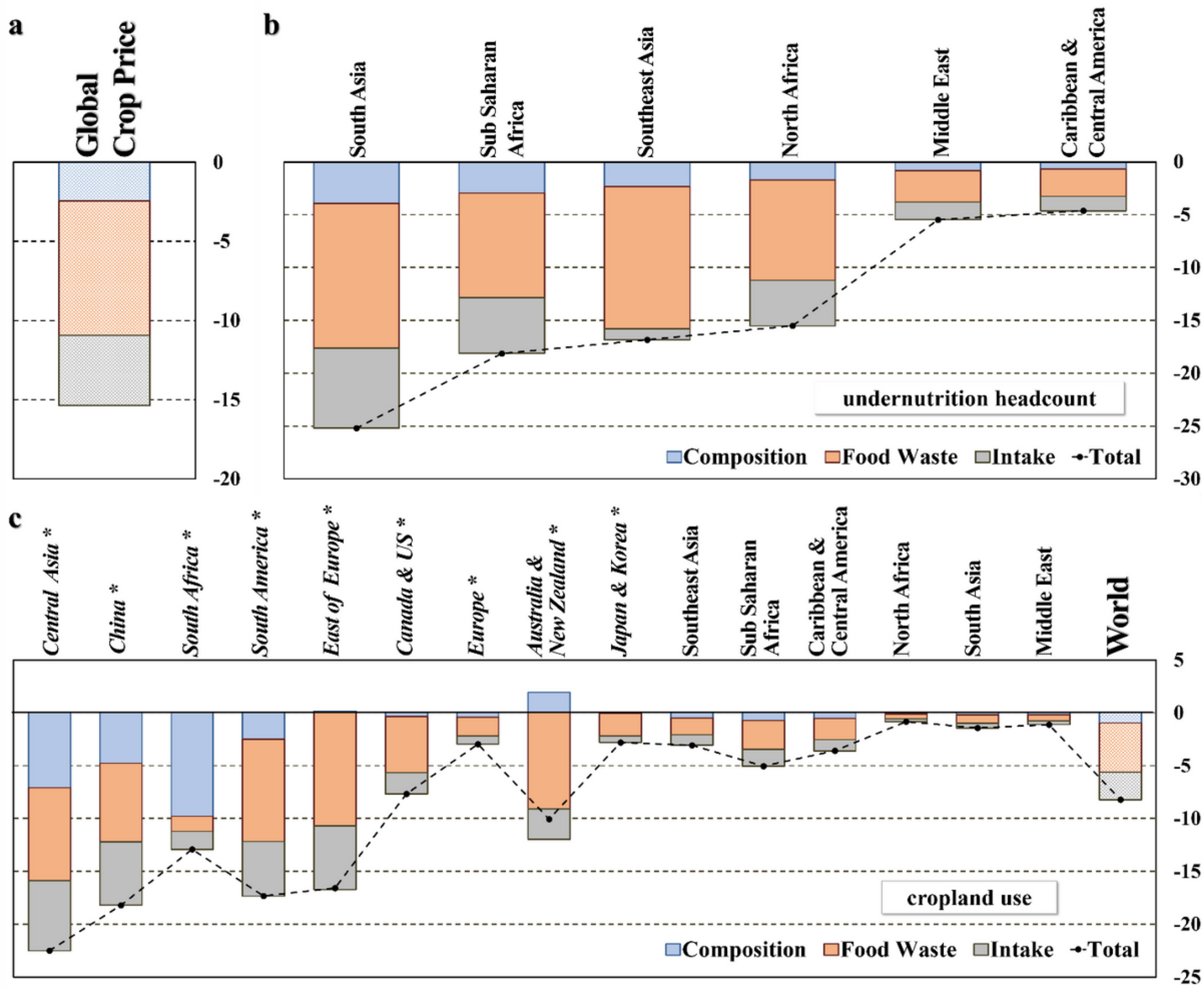


Figure 4

**Shifting towards healthy dietary intake levels reduces caloric undernutrition and land use**. Bars represent percentage changes in 2050 baseline outcomes caused by shifting towards diets following healthy dietary guidelines (HDG) in the *regions in italics* and marked with asterisk (*) starting with Central Asia and ending with Japan and Korea. Consumption patterns in the remaining regions are endogenously determined. Panel **a** represents the percentage change in global crop price, panel **b** represents reductions in undernutrition headcounts in those regions where diets are endogenously determined as a function of prices, and panel **c** represents changes in cropland use. Colored segments of each bar decompose the total change into three different components of the shift from current consumption levels: the change within the food basket composition (i.e., the HDG scenario implies reductions in livestock consumption with respect to the baseline case), reductions in food intake, and reductions in food waste [26]. (**Figure S6** presents results on flexitarian diets pathway).

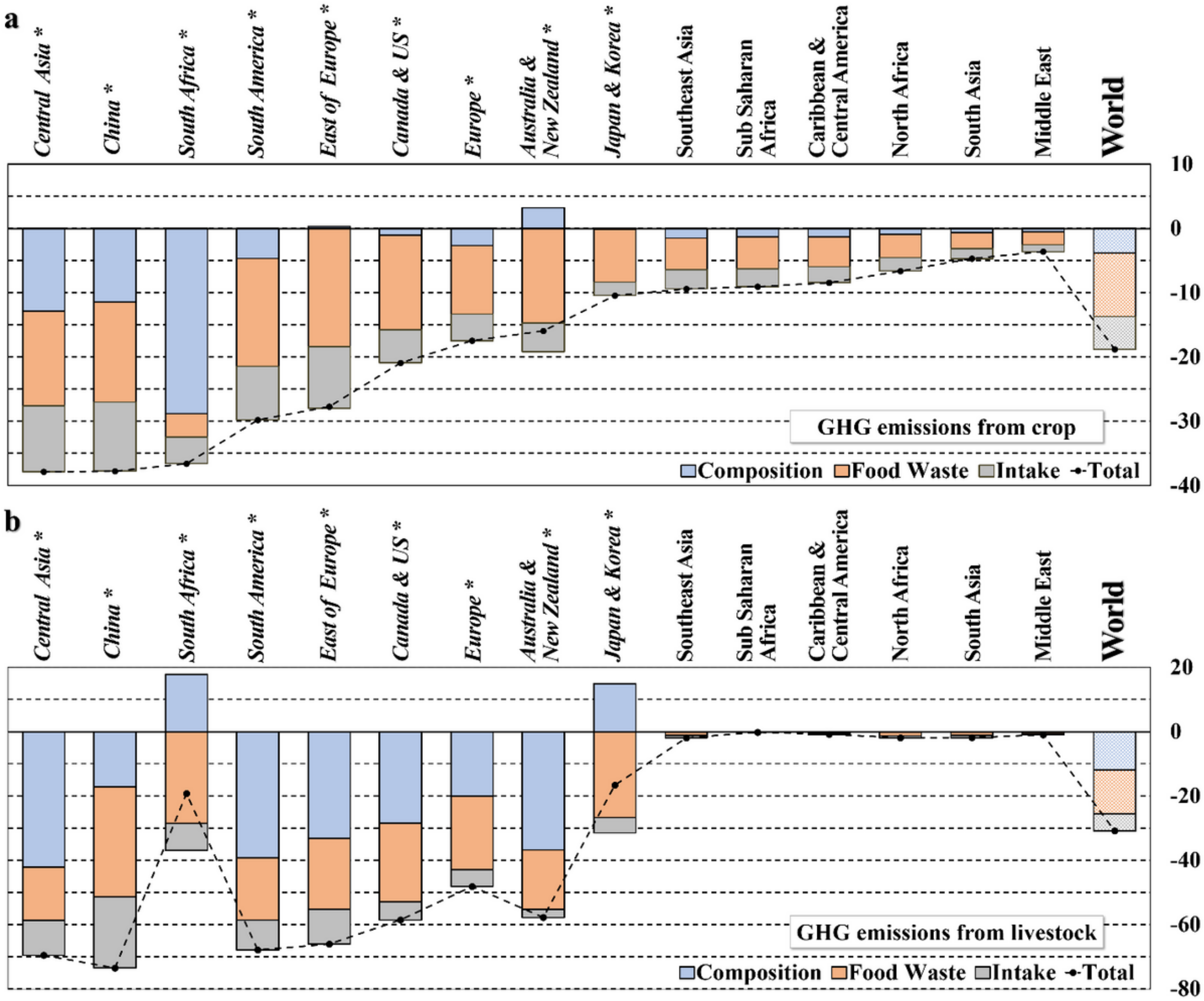


Figure 5

**Shifting towards healthy dietary intake levels reduces Green House Emissions.** Bars represent percentage changes with respect to the 2050 baseline case, caused by shifting towards diets following healthy dietary guidelines (HDG) *in the regions in italics* and marked with an asterisk (*). Results represent the breakout between three different components within the shifts in consumption: the change within the food basket composition (i.e., the HDG scenario implies reductions in livestock consumption with respect to the baseline case), reductions in food intake, and reductions in food waste [26]. (**Figure S7** presents results on flexitarian diets pathway).

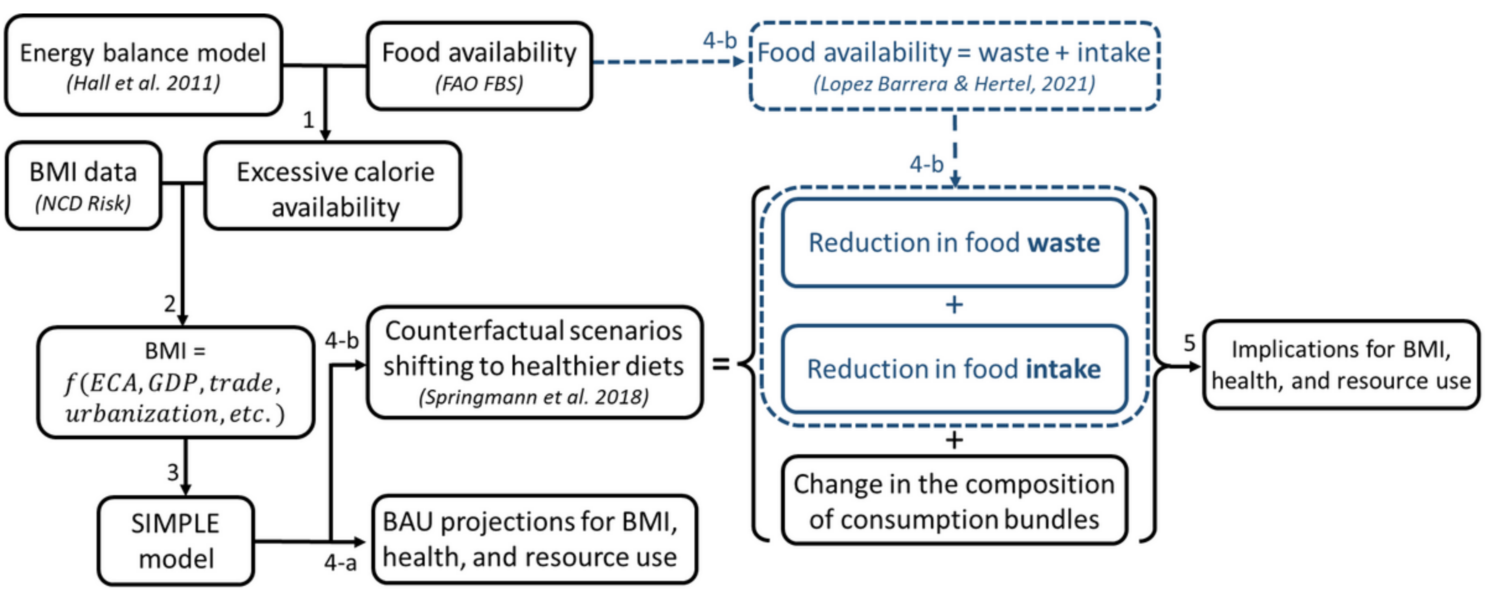

Figure 6

**Linkages between the dynamically applied models and associated objectives.** Boxes correspond to models and data sets employed in this analysis and numbers correspond to individual steps as discussed in the text.

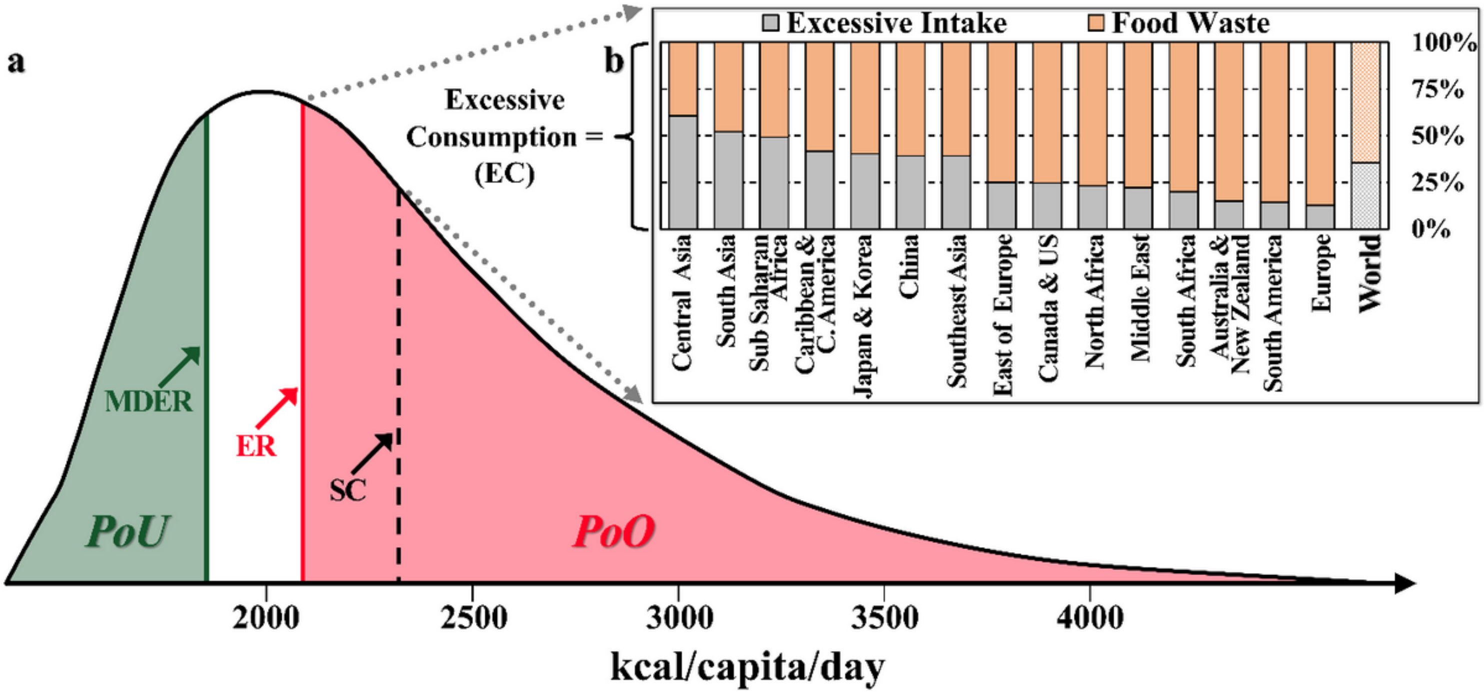


Figure 7

**Extension of the FAO's Prevalence of Undernourishment methodology to Overconsumption.** The solid black curve in panel **a** represents the probability distribution of habitual (i.e., annual average) daily energy consumption (purchases) and is based on country-specific parameters (Supplementary Information). The dashed vertical line represents the Average Daily Supply of Calories (SC) obtained from the FAO's Food Balance Sheets (food acquisition) of an individual in the population. At the lower end of the calorie distribution, the solid green vertical line represents the Minimum Dietary Energy Requirements (MDER), which is the calorie intake (kcal/cap/day) compatible with good health and normal physical activity for an average individual; the green shaded area represents the Prevalence of Undernourishment (PoU) –the share of population that does not meet the MDER. The solid vertical red line represents the Average Dietary Energy Requirement (ER) which is defined as the calorie intake (kcal/cap/day) required to provide energy balance in a given individual of a healthy weight for their sex, age, and activity levels; the solid red area represents the Prevalence of Overconsumption (PoO) –the share of the population with excessive consumption of calories. Panel **b** presents the average daily excessive consumption (EC) of calories, understood as the difference between the average supply (SC) and average requirements (ER) (i.e., SC-ER= EC). The EC is then split into the imputed excessive calorie intake (gray share of the bars) and imputed share of food waste (orange share of the bars) using estimates from previous studies [26].

## Supplementary Files

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