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# Solutions to the double burden of malnutrition also generate health and environmental benefits

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Present food consumption patterns will intensify pressure on natural resources, while poor nutrition is expected to prevail at both low and high levels of calorie consumption. To better understand the interplay between food security, environment and health, we use an integrated framework that allows for the analysis of the dynamics of the double burden of malnutrition and its health and environmental impacts by 2050. We find that excessive caloric intake will be key in rising body mass index levels, particularly in emerging economies. Because higher levels of body mass index will be reached at younger ages, future cohorts will increase their exposure to health risks, including coronary heart disease, stroke, site-specific cancers and type 2 diabetes. This framework also offers insights into the health, food and environmental security impacts of changing food demand behaviour. We find that reductions in food purchasing—associated with the mitigation of food waste and excessive food intake—are more important than changes in dietary composition in increasing food affordability and reducing pressure on cropland expansion, whereas dietary composition is critical in driving greenhouse gas emissions.

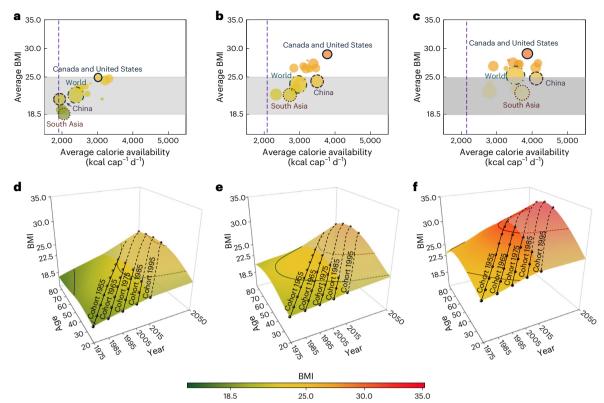
The prevalence of poor nutrition, both at low and high levels of calorie consumption, is rising in low- and middle-income countries  $^{1,2}$ . This caloric malnutrition double burden leads to the coexistence of undernutrition and overweight/obesity that constitutes an unprecedented challenge to global health  $^{3,4}$ , increasing the risk of non-communicable diseases, including cardiovascular diseases, diabetes and some types of cancer  $^{5-7}$ . Effectively responding to these health burdens requires a better understanding of the dynamics of the underlying phenomena  $^{1,8,9}$ . At the same time, reducing excess acquisition of calories is critical for improving resource efficiency and more sustainable food systems  $^{10-14}$ .

Following ongoing transitions in food demand patterns<sup>15,16</sup>, global daily per capita food availability and consumption of animal products have increased substantially in recent decades. Consequently, the global population of ruminant livestock has 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<sup>17</sup>. 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<sup>18</sup>. Demand for these products is predicted to grow as middle- and lower-income regions continue to develop; livestock demand generally increases as incomes rise<sup>19</sup>. There is increasing awareness of the role that food demand choices can play in simultaneously affecting human health and climate change burdens<sup>20</sup>. However, a system-wide assessment of these challenges is needed to fully understand the trade-offs and synergies arising across sectors, agencies and scales<sup>3,4,21</sup>. In this Article, we aim to examine health dimensions related to the dynamics of the malnutrition double burden while also considering environmental challenges posed by the food system in the long run.

We present a fully integrated framework for long-run analysis of the diets, health and environment trilemma<sup>22,23</sup>. We extend the Food and Agriculture Organization (FAO) prevalence of undernourishment

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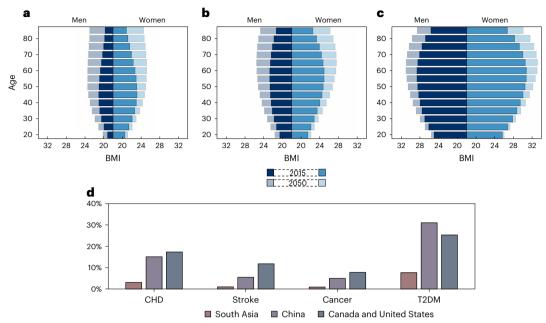
**Fig. 1**| **The excessive calorie availability and adult BMI.**  $\mathbf{a}$ - $\mathbf{c}$ , The average daily SC (kcal cap<sup>-1</sup> d<sup>-1</sup>) and average BMI in 1975 ( $\mathbf{a}$ ), 2015 ( $\mathbf{b}$ ) and 2050 projections ( $\mathbf{c}$ ) across regions. Average BMI is the population-weighted average composite of adult women and men. The grey shaded areas in the figures correspond to healthy BMI ranges. Dashed vertical lines represent the global average daily ER (kcal cap<sup>-1</sup> d<sup>-1</sup>) in reference years which are well below average calorie availability in all regions by 2050. Circle sizes in  $\mathbf{a}$ - $\mathbf{c}$  are proportional to the populations of countries.  $\mathbf{d}$ - $\mathbf{f}$ , Illustration of how BMI evolves across cohorts and over time at different income levels, for adult women in three regions (Supplementary Fig. 6, presents results for the women in the remaining regions and

Supplementary Fig. 7 for men): South Asia ( $\mathbf{d}$ ) (a low-income region), China ( $\mathbf{e}$ ) (middle income) and Canada and United States ( $\mathbf{f}$ ) (high income), present similar age and cohort patterns but at different BMI levels. 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) and 30 (red). The panels  $\mathbf{d}-\mathbf{f}$  were constructed by aggregating results from a fixed-effect, country/panel statistical model into 15 regions (Supplementary Table 1) and making projections to 2050 (Supplementary Fig. 5).

(PoU) methodology considering excessive calorie demand<sup>24</sup> to examine its relationships with adult body mass index (BMI)<sup>25</sup> and resource use across major world regions<sup>14</sup>. Previous studies have shed light on the human health and environmental cobenefits of moving from cur $rent \, levels \, of \, food \, purchasing \, to \, healthier \, dietary \, in take ^{12,22,26,27}. \, Several \,$ studies have explored the potential environmental benefits of shifting towards healthier diets<sup>22</sup>, the role of reducing food waste<sup>14</sup>, as well as the potential for reduced livestock demand to diminish stress on natural resource use<sup>12,28,29</sup>. However, there are few examples disentangling key differences between current food purchases and food consumption under a healthy diet<sup>15,30</sup>. Much of the literature has focused on total calorie acquisition as reported in the FAO Food Balance Sheets (FBSs) and concluded that reducing them to a healthy level would greatly benefit the environment. However, transitioning towards healthier diets implies changes in the composition of food demand bundles (more plant-based diets<sup>22,30</sup>) as well as reducing the overall demand of food<sup>12</sup>. Moreover, although recently some adjustments have been made, FBS calories have historically included consumers' food waste<sup>31</sup>. Therefore, the excessive demand for food in current diets, understood as the gap between current food demand levels (taken to be food availability from FBSs) and healthy dietary intake levels, has included both food waste and excessive intake components<sup>14</sup>.

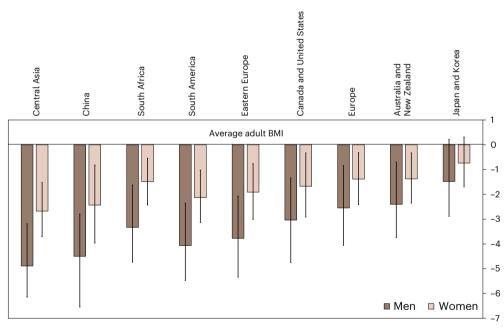
We start by exploring how the incidence of overweight people and obesity is affected by the excessive availability of calorie supply across major regions of the world<sup>25</sup>. We then incorporate these underlying

relationships into a global, partial equilibrium model of the agriculture sector, the simplified international model of crop prices, land use and the environment (SIMPLE)<sup>32</sup>. This model focuses on a few key relationships related to global agriculture while capturing the important drivers of global agricultural change. This framework presents several potential caveats for this study. For example, we omit important dimensions of the dietary-related environmental outcomes (use of water, pastureland, fertilizers and so on) in the analysis. Moreover, the high level of aggregation of food commodities within the model might also impinge on the accuracy of the projected dietary-related environmental outcomes. However, this fully integrated approach also offers several analytical complementarities with previous work on the diets-health-environment trilemma<sup>12,22,23</sup>. First, 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<sup>33</sup>, the framework allows the construction of more plausible baseline projections of adult BMI and resource use towards 2050. Second, it allows us to assess the main factors driving projected increases in adult BMI and resource use, 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. Third, it allows us to simulate, in an integrated fashion, alternative future scenarios to examine the implications of changing diets for health and environmental outcomes as well as for prices and food security.



**Fig. 2** | **Projections of the age-specific average adult BMI and PAFs. a-c**, Population pyramids for the age-specific average BMI in adult men (left side) and women (right side of each pyramid) for South Asia (**a**), China (**b**) and Canada and United States (**c**). Observed average adult BMIs in 2015 are represented in darker colours and projected average adult BMIs in 2050 are represented in lighter colours for the South Asia, China and Canada and United States regions

(Supplementary Fig. 8 present results for the remaining regions). **d**, PAFs to projected increase in BMI, the *y* axis represents the percentage of potential reduction in population diseases attributable to overweight and obesity such as CHD, stroke, some types of cancer, and T2DM, if the average adult BMI levels remained fixed at 2015 levels.



**Fig. 3** | **Projected changes in BMI for men and women.** The bars represent the mean projected percentage changes with respect to the 2050 baseline case caused by shifting towards diets following intake recommended in the HDG in each region (Extended Data Fig. 1 presents results on FLX pathway). Omitted regions are not subjected to diet changes. Error bars represent the 95%

confidence intervals resulting from n=1,000 simulations. In these simulations, the 'shocks' on key exogenous inputs are drawn from a pool of potential values generated using a triangular distribution centred around the mean of their respective expected changes (see Supplementary Section 2.2 for details of the methodology).

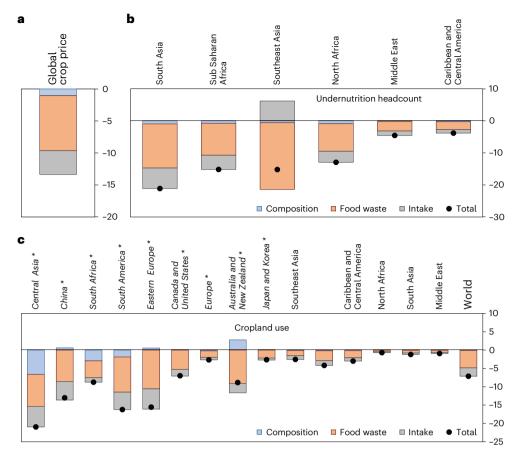
#### Results

#### Excess calories drive adult BMI to increase

Since the mid-twentieth century, the calorie gap between average availability and daily requirements has risen sharply across the world (Fig. 1). Indeed, these nutrition transitions have altered the balance between

energy intake and energy expenditure, leading to widespread increases in rates of overweight and obesity  $^{25}$ .

Our findings suggest that the gap between the calorie availability and energy requirements (ERs) will increase by around 50% in women and 52% in men at the global level by 2050 (Fig. 1c). Moreover, there is



**Fig. 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 HDGs in the regions marked with asterisk (\*) starting with Central Asia and ending with Japan and Korea. Demand patterns in the remaining regions are endogenously determined as a function of prices. **a**, Percentage change in global crop price. **b**, Reductions in undernutrition headcounts in those regions where diets are

endogenously determined as a function of prices. **c**, Changes in cropland use as a function of cropland returns. Coloured segments of each bar decompose the total change into three different components of the shift from current demand levels: the change within the food basket composition (the HDG scenario implies reductions in livestock demand with respect to the baseline case), reductions in food intake and reductions in food waste<sup>14</sup> (Extended Data Fig. 2 presents results on FLX pathway).

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<sup>25</sup> (Supplementary Table 1). 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 (Fig. 1d,f) and appears to be correlated with changes in the food environment faced by each new cohort<sup>25</sup>. This is a serious concern, since higher BMI levels are associated with a series of non-communicable diseases<sup>34,35</sup> and loss of disease-free years<sup>6</sup>.

#### Higher adult BMI in 2050 has adverse health impacts

Under the socioeconomic pathway SSP 2 baseline, the increase in average calorie availability leads to a dramatic increase in the percentage of people overconsuming calories. While wealthier regions such as the United States and Europe are not expected to experience large changes, middle- and low-income regions are expected to show dramatic increases in the overacquisition and excessive intake 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 (Supplementary Fig. 4).

On the basis of 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 of the nutrition transition such as South Asia (Fig. 2a) are expected to experience 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 (Supplementary Table 6). Moreover, the projected increases in BMI will be accompanied by dramatic increases in related diseases  $^{36,37}$ .

Under our baseline projections, the expected increase in major disease burdens will further stress national health care systems<sup>22</sup>. This will also be associated with many economic and health costs<sup>22</sup>, which are particularly burdensome for developing countries with weak institutions and highly differentiated access to quality health care systems<sup>38</sup>. We estimate the disease burden attributable to weight-related risk factors by calculating population attributable fractions (PAFs) (Fig. 2d). In our analysis, the PAFs are based on a comparison of the relative risk exposures caused by the projected changes in adult BMI (Supplementary Table 5). The PAFs represent the change in proportions of weight-related disease cases (coronary heart disease (CHD), stroke, some types of cancer and T2DM) attributable to expected BMI growth in our baseline projections towards 2050 (Fig. 2d). We find that the PAFs are substantial for many major non-communicable diseases related to overweight and obesity<sup>12</sup>, probably impacting mortality paths towards 2050<sup>7</sup>. For example, we find that the projected increase

in adult BMI leads to a 7.7% increase in the incidence of type 2 diabetes (T2DM) in South Asia, a 31% increase in China, and a 25% increase in the United States and Canada.

#### Multiple dividends of changing food purchasing patterns

Previous studies have examined how the consumption of healthy and sustainable diets presents major opportunities to reduce planetary environmental pressure<sup>12,15,22</sup>. We use our integrated framework to examine the potential multiple dividends, including health and environmental cobenefits, as well reductions in undernutrition, of shifting towards healthier and more sustainable food demand bundles. Figure 3 presents projected deviations from the 2050 baseline for average adult BMI, both for men and women (percentage of 2050 values). As a consequence of shifting to dietary intake levels that follow the healthy dietary guidelines (HDGs), we project reductions in adult BMI towards 2050, for both men and women. Results are similar when shifting towards flexitarian diets (FLX) (Extended Data Figs. 1, 2 and 3 give results on FLX 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).

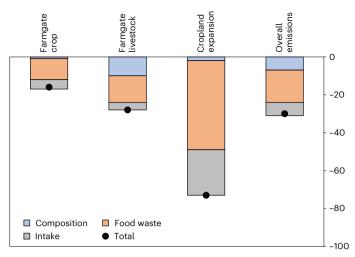
With a global decrease in food demand, as a result of the shift in diets, crop prices are lower than in the baseline scenario leading to a reduction in crop production (Fig. 4), thereby reducing rates of cropland conversion under both the FLX and the HDGs scenarios (see Supplementary Section 4.1 for a detailed description of the scenarios and the implementation).

We also highlight the effects on global malnutrition caused by such changes in consumer behaviour in the relatively wealthier regions. We do this by restricting exogenous changes in food demand to those regions that are already in the later stages of the nutrition transition, while projecting endogenous changes in caloric undernourishment for those regions that host most of the undernourished individuals. We find that shifting towards healthier demand 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 the HDGs, those that are at earlier stages of the nutrition transition such as South America and Central Asia<sup>39,40</sup> and/or that present higher levels of food waste such as China<sup>14</sup>, are the ones that show 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 healthier demand patterns (changes in the composition of the food basket, reductions in food intake and reductions in food waste) (Figs. 5 and 6, Extended Data Fig. 4 and Supplementary Tables 7 and 8). Changes in diet composition (relative reduction in livestock demand) play a mild role in the observed changes in food affordability and in cropland use. A key finding is that as these countries move to consumption at the HDGs, the greatest portion of benefits from reducing pressure on cropland expansion and food affordability is driven by the reduction in overall food demand (food waste and excessive intake) rather than by changes in the composition of diets. Results are similar for the FLX scenario (Extended Data Fig. 2).

We also examine the implications of shifting diets for GHG emissions associated with agriculture production, including direct 'farmgate' emissions and those caused by cropland expansion (Fig. 5, Supplementary Table 9). When considering the HDGs scenario, results are heterogenous across regions and the global GHG emissions related to crop production are projected to decrease by about 52% compared to the 2050 baseline, while global livestock-related emissions would decrease by more than 48%. The excessive demand (food waste and excessive intake) dominates reductions in direct farmgate emissions

Avoided direct and indirect GHG emissions



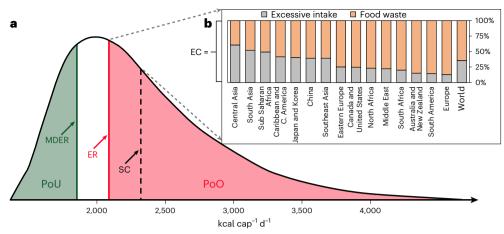
**Fig. 5 | Shifting towards healthy dietary intake levels reduces greenhouse emissions.** The GHG emissions associated with crop and livestock production include the direct farmgate emissions. Indirect emissions include emissions due to the conversion of natural lands into crop production. Bars represent percentage changes with respect to the 2050 baseline case, caused by shifting towards diets following HDGs. Results represent the breakout between three different components within the shifts in demand: the change within the food basket composition (the HDG scenario implies reductions in livestock demand with respect to the baseline case), reductions in food intake and reductions in food waste <sup>14</sup> (Extended Data Fig. 3 presents results on FLX pathway).

(due to the use of land and non-land inputs such as fertilizers, machinery and so on) and avoiding land conversion in the crop sector. On the other hand, the relative contribution of changes in diet composition (more plant-based diets) plays a large role in the projected reductions in the direct GHG emissions. These findings are consistent with previous studies <sup>12,15,23,41</sup>.

#### **Discussion and implications**

The simultaneous examination of both ends of the distribution of caloric purchases within populations allows us to uncover potential trade-offs of food policies oriented toward reducing hunger by increasing food supply. 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 increasing the risk of exposure to attributable non-communicable diseases. 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. 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 42.

Transitioning towards healthier and more sustainable food demand involves both changing the composition of diets (more plant-based diets) and reducing overall food demand (reduction in excessive intake and food waste). These could synergistically address multiple health (overweight and obesity attributable health risks) and environmental burdens (reductions in cropland use and GHG emissions). Moreover, if countries already at later stages in the nutrition transition would shift towards healthy diets, this would increase the affordability of staple foods, leading to reductions in global undernutrition.



**Fig. 6** | **Extension of the PoU methodology to encompass overacquisition of calories. a**, The solid black curve in **a** represents the probability distribution of habitual (annual average) daily energy acquisition (purchases) and is based on country-specific parameters (Supplementary Section 1.1). The dashed vertical line represents the average daily SC obtained from the FBSs (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 $^{-1}$ d $^{-1}$ ) compatible with good health and normal physical activity for an average individual; the green shaded area represents the PoU—the share of population that does not meet the MDER.

The solid vertical red line represents the average dietary ER which is defined as the calorie intake (kcal cap $^{-1}$  d $^{-1}$ ) 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 PoO—the share of the population with excessive purchasing of calories. **b**, The average daily excessive acquisition of calories (EC), understood as the difference between the average supply (SC) and average requirements (ER) (SC – ER = EC). The EC is then split into the imputed excessive calorie intake (grey share of the bars) and imputed share of food waste (orange share of the bars) using estimates from previous studies $^{14}$ .

Importantly, we extend the previous literature to assess how different subcomponents of consuming healthy diets have distinctive effects on the environmental and health burdens. We find that the move to HDGs results in reduced pressure on cropland expansion and improved food affordability, primarily due to the reductions in overall food demand (food waste and excessive intake), rather due to changes in the composition of diets. On the other hand, shifting dietary composition within the HDGs (more plant-based diets) plays a large role in the mitigation of GHG emissions from livestock production. However, a more comprehensive analysis that integrates other dimensions of dietary-related environmental outcomes (use of water, pastureland and fertilizers and so on) is needed for a better understanding of these interactions. Moreover, the high level of aggregation of commodities within our model limits the accuracy of the projected environmental implications on the counterfactual scenarios of changing diets. Exploring these issues with a higher level of resolution in the demand system (for example, disaggregating ruminant meat from other livestock commodities) would lead to more accurate projections.

In summary, our findings will help to inform future efforts aiming to find sustainable food system pathways towards mid-century. A synergistic combination of measures addressing different aspects of food purchasing behaviour will be needed to mitigate the projected increase in dietary-related health and environmental burdens. However, due to the level of aggregation in terms of regions and food commodities, the projections on food demand and the dietary-related health and environmental results should be interpreted in the context of several limitations in the data and analysis. This is of particular importance when it comes to the interpretation of results in those regions that are at relatively earlier stages in the nutrition transition but at the same time are projected to go through relatively strong growth in incomes over the coming decades (for example, South Asia).

#### Methods

We confirm that our research is in complete adherence to all applicable ethical regulations. For an overview of the integrated modelling

framework including the linkages between the dynamically applied models and associated objectives see Supplementary Fig. 9.

# $\label{thm:expectation} Estimating the underlying relationships between calories and BMI$

Despite its limitations (Supplementary Section 1.2), the PoU<sup>43</sup> is widely used as the official indicator to monitor progress towards the United Nations Sustainable Development Goal 2.1 target. The PoU is based on calorie availability and distribution of those calories among the population by country and year and offers an estimate of the share of the population that does not meet the minimum threshold of calories required for a healthy life<sup>44</sup>. We define, compute and track over time and across countries the excess calorie availability <sup>25</sup> (ECA) (Supplementary Fig. 9, arrow 1). Under the energy balance principle<sup>45</sup>, the ECA is defined as the difference between the average daily supply of calories (SC) and average dietary ER as follows:

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

In this equation, subscript i corresponds to men and women, j indexes countries and t corresponds to year; the average daily SC in a certain population is obtained from the FBSs; the average dietary ER is defined as the calorie intake (kcal cap $^{-1}$  d $^{-1}$ ) required to provide energy balance in a given individual of a healthy weight for their sex, age and activity levels $^{46}$  (Supplementary Section 1.3).

We then construct a pseudo-panel dataset from repeated cross-sections<sup>47</sup>, spaced at 5-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 datasets, 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 (Supplementary Fig. 9, arrow 2) as follows:

Model 1. 
$$BMI_{i,j,t} = \theta_0 + \alpha_{i,j,t}ECA_{i,j,t} + \beta_{i,j,t}Age_{i,j,t} + \gamma_{i,j,t}Cohort_{i,j,t} + R_{i,j} + \epsilon_{i,j,t}$$

$$\begin{aligned} \text{Model 2. BMI}_{i,j,t} &= \theta_0 + \alpha_{i,j,t} \text{ECA}_{i,j,t} + \beta_{i,j,t} \text{Age}_{i,j,t} \\ &+ \gamma_{i,j,t} \text{Cohort}_{i,j,t} + \lambda_{i,j,t} \chi_{i,j,t} + R_{i,j} + \epsilon_{i,j,t} \end{aligned}$$

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 represents an error term. BMI is the age- and sex-specific 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 model 2, we investigate in greater depth 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 (income, rural population, health expenditure and so on). Details of data models 1 and 2 are reported in the Supplementary Section 1.3 and results from these regressions are presented in Supplementary Tables 1, 2 and 3 and Supplementary Fig. 1.

# 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 FBS) to the demand (average daily demand of calories) (Supplementary Fig. 9, arrow 3). As a result, we define the average daily excessive acquisition of calories (EC) as follows:

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

In anticipation of 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 SIMPLE<sup>33</sup> that we use in the economic projections towards 2050 (Supplementary Fig. 9, arrow 3). Incorporating the systematic underlying relationships between excessive consumption (EC) and adult BMI into a partial equilibrium economic framework<sup>32</sup>, it is possible to analyse probable future scenarios on the basis of shared socioeconomic pathway (SSP) projections for the global economy.

For this work we develop the prevalence of overacquisition (PoO) indicator. The PoO extends the FAO methodology by incorporating into the analysis the concept of excessive acquisition of calories (Fig. 6), which includes both excessive calorie intake and imputed food waste<sup>14</sup>. The details of this PoO extension are in Supplementary Section 1.1.

This extension of the PoU methodology allows us to simultaneously analyse both tails of the caloric distribution <sup>48</sup>, thereby producing estimates of the double burden of malnutrition which is now a dominant concern in countries at early stages of the nutrition transition<sup>1</sup>. A key contribution of our study is that we split the excessive acquisition of calories (Fig. 6b) into excessive intake and food waste. Food waste is predicted to increase with income after the average dietary ERs are satiated <sup>14</sup>.

# Model validation, uncertainties and baseline projections towards 2050

Following refs. 14,43 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 (Supplementary Fig. 3). A critical step in studies that use economic models to project

future outcomes is to validate them against past periods. This historical assessment provides valuable input for examining future changes. The historical projections of the model perform best at the global level; projections are less accurate at the regional level but still capture broad trends. This is consistent with previous studies attempting to validate global food system models 14,43,49. 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 United States) present lower uncertainties. On the other hand, regions at earlier stages in the nutrition transition, such as South Asia and China, present larger uncertainties. China's income is projected to triple from US\$8,016 to US\$23,446 (constant 2015), resulting in a per capita (cap) food acquisition of 4,172 kcal cap<sup>-1</sup> d<sup>-1</sup> in 2050. However, recent developments indicate that the baseline income projections may be overly optimistic. Lower income growth would dampen demand and slow down dietary transitions.

Following model validation, we turn to business-as-usual (BAU) projections of adult BMI from 2015 to 2050 (Supplementary Fig. 9, arrow 4a). 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 SSPs<sup>50</sup>. Our baseline follows the BAU SSP 2 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<sup>50</sup>. Projected TFP growth rates are based on the historical estimates from previous studies<sup>51,52</sup>. Future growth in global biofuel consumption is from the IEA<sup>53</sup>. All of these inputs are reported in detail in Supplementary Section 2.1. On the basis of the underlying relationships between the excessive calorie acquisition 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 PAFs which represent the proportions of disease cases that would be avoided if adult BMI, for men and women, did not increase from 2015 levels (Supplementary Section 3.3).

#### Specification of the counterfactual scenarios

We adapt the counterfactual scenarios in previous studies<sup>12</sup> regarding shifting toward healthier and more sustainable diets (Fig. 6, arrow 4b). We start by comparing the BAU projections of food demand from ref. 12 with those in this study obtained with SIMPLE, under the SSP 2 scenarios. We do so by aggregating across food groups from ref. 12 into the categories within SIMPLE (crops, livestock and processed food). We then shift to analyse counterfactual scenarios of shifting towards healthier food consumption bundles. The counterfactual diet scenarios analysed in this study include freezing adult BMIs at 2015 levels, shifting to diets aligned with global HDG and also more plant-based FLX that are reflective of present evidence on healthy eating. The freezing of adult BMI is a simplistic scenario, developed to provide a contrast to the projected-2050 adult BMI levels, allowing for estimated PAFs based on the changes in relative risk exposures to BMI-related diseases. The HDG scenario is based on global guidelines for healthy eating issued by WHO/FAO Expert Consultations on diet, nutrition<sup>54</sup> and human ERs<sup>46</sup>. The FLX diet is a more ambitious dietary change that implies larger levels of substitution of animal source proteins for vegetable source proteins. To better understand the dynamics of the malnutrition double burden, we restrict the exogenous changes in food demand to those regions that are already at later stages in the nutrition transition<sup>15</sup>. This allows us to estimate the likely changes in caloric undernutrition in the poorer regions due to the ensuing price changes following implementation of the HDG and FLX diets in the wealthier economies.

We complement previous work on dietary changes by decomposing, in our counterfactual scenarios, three key elements of the food purchasing behaviour (composition of diets, excessive intake and food waste) to analyse their relative contribution to environmental sustainability (Fig. 6b and Supplementary Figs. 9 (arrow 4b) and 13). Transitioning towards healthy dietary bundles implies both changing the composition of diets (more plant-based diets) and reducing the overall food demand. We use a three-step experimental design. First. we isolate the composition effect by changing the relative shares of food commodities (crops, livestock and processed food) to a composition of food demand that follows a healthy diets bundle (HDG and FLX diets) but maintains the projected-2050 levels of overall calorie acquisition. In the second and third steps, we analyse the environmental effects of reducing excessive food acquisition. We do so by maintaining the relative shares of calories of the food commodities under healthy diets bundles but reducing the overall acquisition. We decompose the excessive acquisition into food waste and excessive intake capitalizing on previous work that establishes a relationship between per capita income growth and food waste<sup>14</sup> and between excessive calorie availability and adult BMI<sup>25</sup> (Supplementary Section 4.1.3 and Supplementary Figs. 9 (arrow 5) and 13). In future work, we recommend estimating and incorporating commodity-specific food waste estimates. These allow for more detailed environmental analyses, due to the differences in the environmental footprints of commodities.

#### **Reporting summary**

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

#### **Data availability**

Correspondence and requests for materials should be addressed to E.L.B. All data needed to replicate results from econometric model 1, model 2 and the weight-related factors calculations are available at https://doi.org/10.18738/T8/GFT756 (Replication Data for: Solutions to the double burden of malnutrition also generate health and environmental benefits). The bulk of input data used for calorie availability are derived from the statistics of FAO, available at http://www.fao.org/faostat/en/#data. The bulk of input data used for adult BMI are derived from the statistics of the NCD Risk Factor Collaboration available at https://ncdrisc.org/data-downloads.html. The remaining data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Information or upon request to the authors.

#### Code availability

The code developed in the study is available from the corresponding author upon reasonable request.

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#### **Author contributions**

E.L.B. and T.H. contributed to conceptualization, methodology, formal analysis, investigation, writing the original draft and reviewing and editing the final paper, visualization, supervision and funding acquisition.

#### **Competing interests**

The authors declare no competing interests.

#### **Additional information**

Extended data is available for this paper at https://doi.org/10.1038/s43016-023-00798-7.

**Supplementary information** The online version contains supplementary material available at https://doi.org/10.1038/s43016-023-00798-7.

**Correspondence and requests for materials** should be addressed to Emiliano Lopez Barrera.

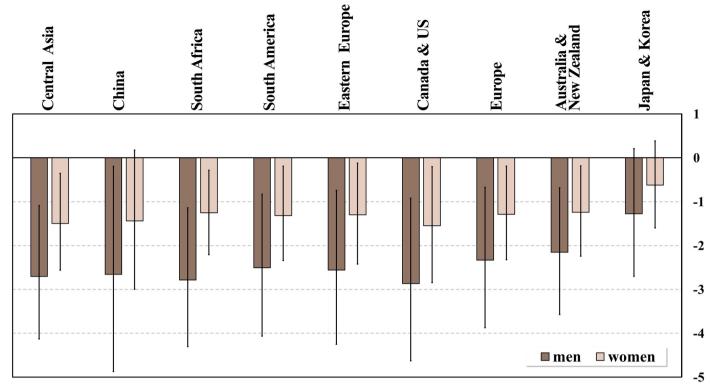
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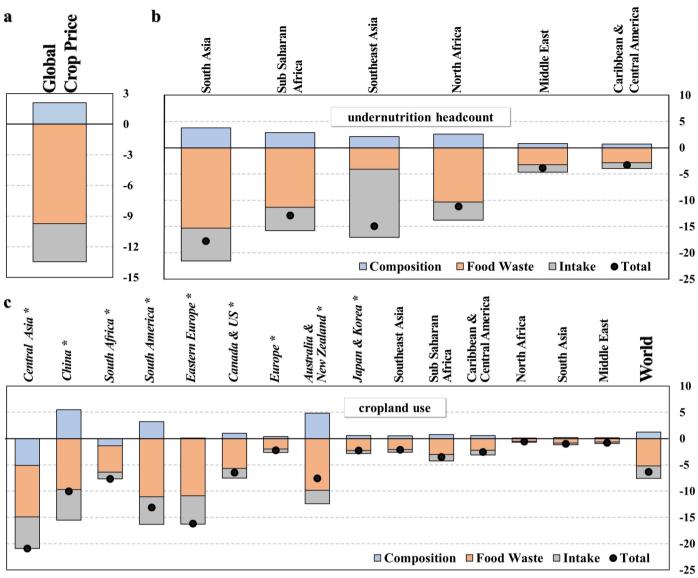
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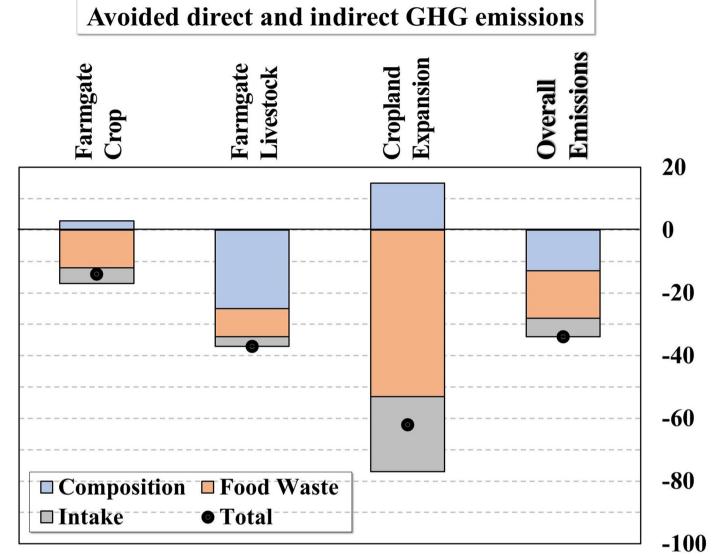
**Extended Data Fig. 1** | **Projected changes in BMI for men and women.** The bars represent the mean projected percentage changes with respect to the 2050 baseline case caused by shifting towards diets following intake recommended in the flexitarian diets pathway (FLX) in those regions. Omitted regions are not subjected to diet changes. Error bars represent the 95% confidence intervals

resulting from n = 1000 simulations. In these simulations, the "shocks" on key exogenous inputs are drawn from a pool of potential values generated using a triangular distribution centered around the mean of their respective expected changes (See Supplementary Section 2.2 for details in the methodology).



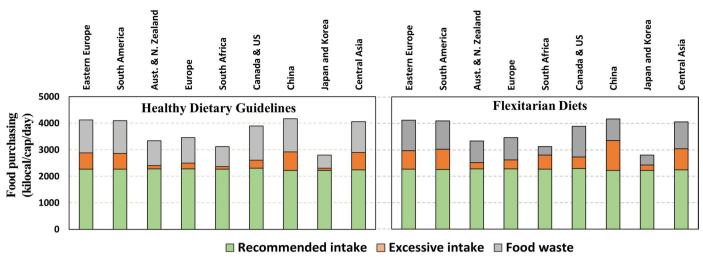
**Extended Data Fig. 2** | **Shifting towards healthy dietary intake levels reduce caloric undernutrition and land use.** Bars represent percentage changes in 2050 baseline outcomes caused by shifting towards diets following flexitarian diets pathway (FLX) in the regions in italic and marked with asterisk starting with Central Asia and ending with Japan and Korea. Regions exogenously shifted to the FLX are in italic and marked with an asterisk, food demand patterns in the remaining regions are endogenous. 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. Coloured segments of each bar decompose the total change into three different components of the shift from current food demand levels: the change within the food basket composition (that is, the FLX scenario implies reductions in livestock demand with respect to the baseline case), reductions in food intake, and reductions in food waste<sup>3</sup>.



**Extended Data Fig. 3 | Shifting towards healthy dietary intake levels reduces Green House Emissions.** The GHG emissions associated with crop and livestock production include the direct "farmgate" emissions. Indirect emissions include emissions due to the conversion of natural lands into crop production (See Supplementary Information for details). Bars represent percentage changes with respect to the 2050 baseline case, caused by shifting towards diets following

healthy dietary guidelines (HDG). Results represent the breakout between three different components within the shifts in food demand: the change within the food basket composition (that is, the HDG scenario implies reductions in livestock demand with respect to the baseline case), reductions in food intake, and reductions in food waste  $^{59}$ . (Fig. 5 presents results on flexitarian diets pathway).



Extended Data Fig. 4 | Shifting towards Healthy Dietary Guidelines and Flexitarian Diets levels reduce food waste and excessive intake. We developed counterfactual dietary scenarios based on the Healthy Dietary Guidelines (HDG) and the Flexitarian Diet scenario (FLX) proposed by Springmann et al. in 2018. These scenarios involved exogenous shifts in the average consumer's behaviour, moving from 2015 consumption levels towards a projected scenario for 2050. The bars in the chart represent the mean of overall calorie purchases projected

for 2050. The green portions of the bars represent the quantity of calories recommended under a healthy (flexitarian) intake level. The orange portion of the bars represents the reduction in excessive intake necessary to transition from current projections to a healthy (flexitarian) diet. Finally, the grey portion of the bars represents the reduction in food waste at the consumer level necessary to transition from current projections to a healthy (flexitarian) diet.

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#### Software and code

Policy information about availability of computer code

Data collection

No software was used for the collection of data. Data analysis of the long-run relationships between ECA and adult BMI was carried out with StataCorp. 2019. Stata Statistical Software: Release 16. College Station, TX: StataCorp LLC. Baseline forecasting and counter factual scenarios on the global partial equilibrium framework were obtained using the GEMPACK 12.0 economic modeling software [Harrison and Pearson (1996)].

Data analysis

This study relies on two main blocks of methodology, an econometric analysis and a modeling simulation analysis. For the econometric block of the study, publicly available data assembled from a range of sources including documents and reports from the NCD Risk Factor Collaboration (NCD-RisC), the Food and Agriculture Organization of the United Nations (FAO), and the DataBank of the World Bank. For the modeling block of the study, For the modeling part of the study, we construct separate base data for the years 2001 and 2006. Data from external sources include income, population, consumption expenditures and crop production and their sources are as follows. Information on GDP in constant 2000 USD and population are obtained from the World Development Indicators (2011) and from the World Population Prospects (2013), respectively. Data on cropland cover and production, utilization and prices of crops are derived from FAOSTAT (2011). We further converted the crop quantities into corn- equivalent quantities using weights constructed from world crop prices and the world price of corn. We then combined the data above with additional information on industry cost and sales shares in order to construct the rest of the database. The amount of crop feedstock used by the global biofuel sector is constructed using the sales shares by the global crop sector taken from GTAPBIO V.6 (Taheripour et al. 2007). Shares constructed from the crop utilization data were then used to split the remaining cornequivalent crop quantities across 15 geographic regions and across different uses (i.e. food, feed and raw materials for processed food). We then calculated the global crop price from the value and corn-equivalent quantity data of crop production. Using the global price and the allocated corn-equivalent crop quantities, we then derived the value of crop input use in the livestock and processed food industries. Under the assumption of zero profits, we calculated the total value of land and non-land input costs in the regional crop sect

shares as our guide. We again used GTAP v.6 cost shares and the value of crop input usage in the livestock and process food industries to impute the value of non-crop inputs used in these sectors. Under the assumption of zero profits, we then derive consumer expenditures and price indices for livestock and processed food commodities. Land rents and crop yields for each geographic region were derived using the value of land inputs, corn-equivalent crop production and cropland areas.

We then start by simulating the model over the historical period 2005 to 2015 (10-years) and then projecting towards 2050. For this experiment, we implement shocks in population, per capita incomes, total factor productivity (TFP) growth, and biofuel consumption. We then compare the simulated changes for the period 2005 to 2015 with the actual changes from our data base on average adult BMI for men and women. Growth rates for population and income were derived from the Shared Socioeconomic Pathway 2 (Fricko et al. 2017). TFP growth were based on the historical estimates (Ludena et al. 2007) and by (Fuglie 2012). The growth in global biofuel consumption from the "Current policies" scenario published in the World Energy Outlook (International Energy Agency 2019). These forecasts are based on the results of a detailed world energy model given exogenous growths in GDP and population as well as assumptions on future energy prices and technology. We also calculate the growth in global biofuel consumption from the "Current policies" scenario published in the World Energy Outlook (International Energy Agency 2019). These forecasts are based on the results of a detailed world energy model given exogenous growths in GDP and population as well as assumptions on future energy prices and technology. TFP growth rates for the crop and the livestock sectors are based on the projections from (Ludena et al. 2007) which are generated under the assumption of gradual convergence in productivity across regions. Growth rates of each driver for the period 2005 to 2015 (2050) are listed in the SI materials.

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Correspondence and requests for materials should be addressed to Emiliano Lopez Barrera. All data needed to replicate results from Model 1, Model 2, and the weight related factors calculations are available at Replication Data for: Solutions to the double burden of malnutrition also generate health and environmental benefits. The bulk of input data used for calorie availability are derived from the statistics of the United Nations Food and Agriculture Organization (FAO), available at: http://www.fao.org/faostat/en/#data. The bulk of input data used for adult BMI are derived from the statistics of the NCD Risk Factor Collaboration (NCD-RisC), available at: https://ncdrisc.org/data-downloads.html. The remaining data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials or upon request to the authors.

### Human research participants

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Study description

Here we present a novel framework that extends the UN-FAO's methodology for assessing undernutrition to also encompass excessive calorie consumption and its quantitative association with the evolution of adult Body Mass Indexes (BMI). We examine these relationships for 156 countries over the past century using an age-, sex-, and cohort-specific approach. We measure the association between increases in food energy supply and changes in BMI across countries and time based on a purposely constructed

	panel data base from repeated cross-sectional data, accounting for fixed effects and clustering effects in the sample. 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.	
Research sample	This study relies on publicly available data assembled from a range of sources including documents and reports from the NCD Risk Factor Collaboration (NCD-RisC), the Food and Agriculture Organization of the United Nations (FAO), and the DataBank of the World Bank, GTAP, International Energy Agency, as well as related previous literature.	
Sampling strategy	The sample strategy was based on convenience and availability of data for the relevant variables defined in the study to ensure the maximum representativeness of the sample. Data used in this study encompass all available data for the relevant variables at the country level over the past century. The final version of the developed data based for the study covers 156 countries which together represented 95% of the global population in 2015.	
Data collection	At the moment of collecting the Data, the researchers were blinding to the study hypothesis. Data used in this study encompass all available data for the relevant variables at the country level over the past century. Data were extracted from multiple public sources including: CD Risk Factor Collaboration (NCD-RisC), the Food and Agriculture Organization of the United Nations (FAO), and the DataBank of the World Bank, Global Trade Analysis Project (GTAP), International Energy Agency, as well as related previous literature. After collected, data is stored at the authors' personal computers and devices (i.e., pen drives).	
Timing	Data was collected during 2018-2021.	
Data ovelusions	No exclusions were made, rather than publicly availability of the data for the relevant variables on the study	

Data exclusions

Non-participation

No participants were involved in the study

Randomization

Since the purpose of the data sampling was to ensure the representativeness of the sample as well as gain insights on the contextual country and region-specific characteristics affecting the underlying relationships among the variables of interest in the study, the authors did not use randomization. When conducting a data collection process involving variables at the country level, it is important to consider the potential drawbacks of using randomization when researchers desire a larger number of data points. For example, randomization presents trade-offs with representativeness. Each country has its unique characteristics, such as size, population, socio-economic conditions, and cultural factors. By relying solely on random selection, there is a risk of excluding important countries or including too many countries that are not truly representative of the population being studied. This can lead to biased or skewed results, limiting the generalizability of findings.

Moreover, randomization may affect contextual understanding. When studying variables at the country level, it is crucial to consider the contextual factors and their influence on the research question. Randomly selecting countries might overlook specific conditions or circumstances that are critical to understanding the variables being studied. By purposefully selecting countries based on relevant criteria or expert knowledge, researchers can ensure that the data collected aligns with the research objectives and provides a more nuanced understanding of the phenomena under investigation.

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