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Food Surplus and Its Climate Burdens

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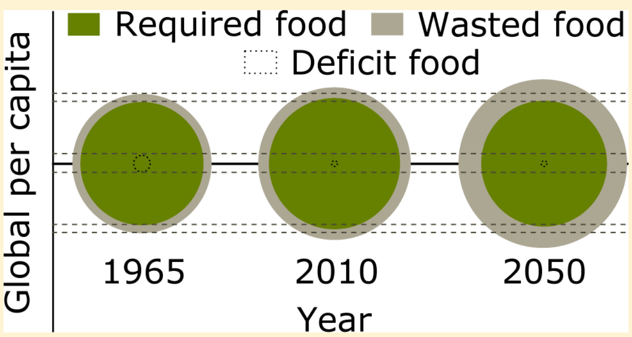
Supporting Information

ABSTRACT: Avoiding food loss and waste may counteract the increasing food demand and reduce greenhouse gas (GHG) emissions from the agricultural sector. This is crucial because of limited options available to increase food production. In the year 2010, food availability was 20% higher than was required on a global scale. Thus, a more sustainable food production and adjusted consumption would have positive environmental effects. This study provides a systematic approach to estimate consumer level food waste on a country scale and globally, based on food availability and requirements. The food requirement estimation considers demographic development, body weights, and physical activity levels. Surplus between food availability and requirements of a given country is considered as food waste. The global food requirement changed from 2,300 kcal/cap/day to 2,400 kcal/cap/day during the last 50 years, while food surplus grew from 310 kcal/cap/day to 510 kcal/cap/day. Similarly, GHG emissions related to the food surplus increased from 130 Mt CO_{2eq}/yr to 530 Mt CO_{2eq}/yr, an increase of more than 300%. Moreover, the global food surplus may increase up to 850 kcal/cap/day, while the total food requirement will increase only by 2%−20% by 2050. Consequently, GHG emissions associated with the food waste may also increase tremendously to 1.9−2.5 Gt CO_{2eq}/yr.



INTRODUCTION

The global food demand is projected to increase by 60%−110% between 2005 and 2050,[1−4] mainly due to population growth and diet shifts.[5,6] A solution to meet the increasing food demand is to reduce food loss and waste.[7] This would in parallel also dampen global warming because emissions from food production would be reduced. Currently, around one-third of global food production (about 1.3 billion tonnes per year) is lost or wasted.[8] Avoiding food loss and waste can also save resources used in food production, reduce environmental impacts of agriculture, and enhance local, regional, and global food security.[9−11] Directly and indirectly, the agricultural sector contributes to around 22%−24% of the total anthropogenic greenhouse gas (GHG) emissions and is accountable for 56% of the total non-CO_2 GHG emissions.[12] This study provides a systematic approach to tackle the food waste challenge and associated emissions.

Food loss and waste occur in various stages of the food supply chain.[8] The reduction of edible food during production, postharvest, and processing is considered as food loss, whereas food waste is referred to food discarded by the consumer.[8,13] Food losses occur mostly in developing countries due to less efficient infrastructure, while food wastes are common in developed countries.[5,13] Around 30%−40% of food is lost or wasted in both developing and developed countries.[5]

Estimating food loss and waste within the various stages of the food supply chain is a challenging task. Different methods are used to investigate food loss and waste, resulting in incompatible estimates. Methods such as surveys, measurements of plate waste, and direct examination of garbage are applied to estimate food wasted in a population sample.[14,15] On a country level, food loss and waste are often calculated by applying specific loss factors to various stages of the food supply chain.[9,16] Alternatively, Hall et al.[10] considered the food surplus of the United States, accounting for differences between food availability and modeled food energy requirements as aggregated food loss and waste.

Food energy requirements indicate the calorie expenditure needed for a person to keep his/her body functioning, which depends on age, sex, body weight, and physical activity levels.[17,18] On a country level, the energy requirements consequently depend on demographic structure. For example, a country with a large share of adults in the population requires higher food energy per person than a country with a younger population. Therefore, the average food energy requirement per person for any given country will alter with changes in its average body weight, demographic structure, and physical activity level.

For a healthy population, food consumption is equivalent to the energy requirement; food consumption above or below the energy requirement results in nutritional imbalance.[4] Therefore,

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the difference between the food availability in a country and the energy requirement of its population can be used as a standardized comparable method to estimate food waste at the consumer level.[10] However, such standardized global food waste estimation for all countries has not yet been performed.

The goal of this study is to address this missing link by calculating food waste for all countries. Further, we estimate agricultural GHG emissions associated with the food waste and present the importance of reducing food waste in terms of global warming. Specifically, we calculate country level food energy requirements accounting for past, present, and future demographic structures, different physical activity levels, and possible body weight variations with global coverage. We assemble data on average body weight according to age and sex groups for each country from various sources. Subsequently, we calculate the differences between the food availability and the estimated energy requirements of the countries to understand food waste.

■ MATERIALS AND METHODS

Human Energy Requirements. Humans require food and its macronutrient constituents, i.e. carbohydrates, fats, and proteins, as an energy source for maintaining body size and composition, for physical activities, and they require additional energy for growth, pregnancy, and lactation. The two major factors determining the energy requirements are basal metabolic rate (BMR) and physical activity level (PAL).[18] BMR is the minimum amount of energy required for life functioning, which depends on the body weight, age, and sex of a person.[19] The PAL value expresses a person's daily physical activity, which depends on lifestyles. For example, a population group of light, moderate, and heavy activity lifestyles have PAL values of 1.55, 1.75, and 2.4, respectively.[18]

We estimate the average per capita daily food requirement for the population of a country from 1950 to 2010 for a five years resolution by using demographic and anthropometric data. The demographic data comprises of population by age and sex groups.[20] The anthropometric data covers average body weight by age and sex groups from various sources for the most recent years (Tables S1 and S2). Body weight data is available for 71 countries, comprising 73% of the global population in 2010.[20] The data gaps are filled by calculating population-weighted average body weight for the United Nations subregions based on the available data. In the analysis, the body weight is kept constant because the data is available only for a few years.

Due to the fact that no standardized global data on PAL for countries is available, three PAL scenarios (light, moderate, and heavy) are considered to account for uncertainty (Table 1). We take the average PAL values for nonoverweight adults in the United States by age and sex groups[18] as moderate PAL. Minimum dietary energy requirements are estimated by using a PAL value of 1.55,[21] which also represents the lower bound for food requirements (light PAL). PAL values larger than 2.4 are difficult to maintain permanently.[18] Thus, this value is considered as the upper bound (heavy PAL). Because of the limited physical activity of the elderly, for age groups older than 80 years the PAL values are kept constant, at 1.28 for males and 1.19 for females for all PAL scenarios, based on observed PAL values for elderly in the United States.[18]

The energy requirements are separately calculated for four groups: (i) infants, children, and adolescents (0–19 years), (ii) adults (20–59 years), (iii) elders (60+ years), and (iv) pregnant and lactating women. The age cohort of infants, children, and adolescents is further divided into four groups (0–4, 5–9, 10–14, and 15–19 years) based on the age groups for which population data is available. We estimate the energy requirements for infants, children, and adolescents by multiplying the population data according to age and sex groups by their respective average daily energy requirement for different PALs obtained from FAO/WHO/UNU[18] (Table S3).

Table 1. Basal Metabolic Rates Slope (S) and Constant (C) by Sex and by Age Group[18] with the Three PAL Values[a]

age (year)	sex	S (kcal/kg)	C (kcal)	light PAL	moderate PAL	heavy PAL
20–29	male	15.057	692.2	1.55	1.75	2.4
30–59	male	11.472	873.1	1.55	1.74	2.4
60–79	male	11.711	587.7	1.55	1.62	2.4
80+	male	11.711	587.7	1.28	1.28	1.28
20–29	female	14.818	486.6	1.55	1.79	2.4
	female	8.126	845.6	1.55	1.83	2.4
60–79	female	9.082	658.5	1.55	1.62	2.4
80+	female	9.082	658.5	1.19	1.19	1.19

[a]The average PAL for nonoverweight adults in the United States[18] is considered as moderate PAL. The PAL value of 1.55, used to estimate minimum dietary energy requirements,[21] is taken as light PAL. For the heavy PAL, we assumed a value of 2.4 as higher values would be difficult to maintain permanently.[18] We kept the PAL value constant for the age group older than 80 years due to the limited physical activity of the elderly.

The energy requirements for adults and elderly are calculated by multiplying the population data according to age and sex groups by their respective BMR and PALs. Human BMR changes with age[18] and is represented by the Schofield equation[19]

$$\mathrm{BMR}(\mathrm{country, age, sex}) = C(\mathrm{age, sex}) + S(\mathrm{age, sex}) \times \mathrm{BW}(\mathrm{country, age, sex}) \quad (1)$$

where BMR is a linear function of body weight (BW), and where constant (C) and slope (S) depend on age and sex groups (Table 1).

In the next step, the extra energy required for a 40-week pregnancy and a 6-month lactation period is calculated. A woman requires an additional food of 280 kcal/day and 590 kcal/day of food on average during her pregnancy and lactation period, respectively.[18] The number of pregnant women (N_{preg}) in a country is estimated by

$$N_{preg} = \frac{\mathrm{BR} \times P \times \mathrm{GP}}{365.25} \quad (2)$$

where BR denotes crude birth rate; P represents population in a year (365.25 days); and GP is a mean gestation period of 280 days from Naegele's rule. We use crude birth rate data,[20] as it is widely available compared to data on pregnancy rate.

Finally, the total food requirement in a country is calculated by summing up the food requirements of the four groups. The average food requirement of a country is obtained by dividing the total food requirement by the total population of the country.

Food Surplus and Deficit. We define food surplus and deficit as the difference between available and required food calories disregarding different food types. Food Balance Sheet (FBS)[22] consists of data on the daily amount of food supply in a country from 1961 onward. The food supply data provides

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information on amount of available food in a country for consumption instead of real food intake that is mostly obtained from individual diet surveys. Hence, the food supply data is used to estimate food surplus and deficit between 1965 and 2010 in five year intervals. The analysis is performed for 169 countries that represent 97.95% of the world population in 2010[20] (Table S4).

FBS considers seed rates, stock changes, food loss in postharvest, and types of utilization to calculate food availability, based on country level data on food production and trade.[22] Therefore, the positive differences (surplus) between food availability and requirement are attributed to consumer food waste. A negative value represents a food deficit in the country. Separately, we add food surplus and deficit of countries to understand food surplus and deficit on global and regional levels. Subsequently, the global food surplus and deficit per capita is estimated by dividing sums of food surplus and deficit on country scales by respective sums of country populations. Additionally, we attempt to understand the influence of development status on food surplus/deficit by analyzing the relation between country level food surplus/deficit and its Human Development Index (HDI).[23]

Greenhouse Gas Emissions. In order to assess the potential impact of food waste on climate, GHG emissions associated with food surplus are estimated, accounting for vegetal and animal products. This is important because the emission intensity of livestock production is larger than that of crop production.[6] It is assumed that shares of vegetal and animal products in food surplus are equal to the shares within available calories, i.e., fractions of consumed and wasted calories are equal. This is supported by a South African study that presents similar findings on the shares of vegetal and animal products in food waste.[24]

Agriculture releases a significant amount of CO_2, CH_4, and N_2O to the atmosphere; however, only non-CO_2 emissions are reported in agricultural emission inventories (e.g., FAO[22]). This is because agriculture itself is considered CO_2 neutral and CO_2 emissions from energy used for agriculture machineries, transportation, and fertilizer production are accounted for in the energy sector.[12] Therefore, we use country level data on agricultural non-CO_2 GHG emissions and food production from FAOSTAT[22] to estimate GHG emissions associated with food waste.

FAOSTAT considers the following agricultural production and management activities to estimate agricultural GHG emissions: enteric fermentation, manure management, manure applied to soils, manure left on pasture, crop residues, cultivation of organic soils, burning crop residues and savanna, rice cultivation, and synthetic fertilizer applications.[25] The conversion of total crops and livestock production from tonnes to calories is feasible by considering nutritive factors for crops and livestock items.[26] The countrywide emission intensity of crop and animal products is estimated by dividing countrywide non-CO_2 GHG emissions related to crops (manure applied to soils, crop residues, cultivation of organic soils, burning crop residues and savanna, rice cultivation, and synthetic fertilizer applications) and livestock (enteric fermentation, manure management, and manure left on pasture) by production of crop and livestock calories, respectively. Subsequently, emissions associated with food surplus are estimated by multiplying crop and animal calorie surplus with emission intensities of crop and animal products, respectively.

Scenario Analysis. The scenario analysis is conducted to understand the future food requirements, based on demographic changes and subsequent food surplus/deficit and associated GHG emissions. For future projections (2015–2050), three body weight scenarios, five demographic projections, and three PAL values are considered, resulting in 45 estimates.

The three body weight scenarios are (i) current body weight remain constant, (ii) all countries have the average body weight of Japan, and (iii) all countries have the average body weight of the United States. These two high-income countries represent global extremes in terms of body weight.[27] Hence, the body weight scenarios cover possible upper and lower bounds of future food requirements related to an increase or a decrease in human body mass. This needs to be considered because body weights are increasing globally.[28,29]

The future population development demographic projections are based on the five Shared Socioeconomic Pathways (SSPs).[30] SSPs are a set of plausible alternative future evolutions of society that would indicate a range of challenges for climate change mitigation and adaptation.[31] SSP1 depicts a future evolution toward a more sustainable path. SSP2 assumes a future that is following the historical trends and is considered as the middle of the road scenario. A fragmented world that emphasizes national security at the expense of international development is reflected by SSP3. SSP4 assumes a future world of high inequalities, both between and within countries. SSP5 refers to a future world that is based on a conventional development path where economic growth fosters rapid technological progress and development of human capital.

For the estimation of future food surplus/deficit, the food demand projection from Pradhan et al.[6] is considered. The food demand is projected based on relationships between the HDI and availability of total food and animal calories for 2010–2050 in a five year interval. However, the data on food availability is currently available only until 2011.[22] Therefore, the projected food demand is adjusted to match the food demand projection for 2010 with the food availability for ca. 2010 (2009–2011). For this, the difference between the projected food demand for 2010 and the food availability for ca. 2010 is initially calculated for each country. Afterward, the difference is added/subtracted to the projected food demand of the country from 2010 to 2050.

Subsequently, emissions associated with food surplus are estimated by following the procedure described above (see Section Greenhouse Gas Emissions). Technological progress and technology transfer that lowers emission intensities is an option to reduce emissions from the agricultural sector.[6,32] However, we keep emission intensities constant at the year 2010 level for this analysis to limit the number of scenarios. Additionally, the aim of our study is to distinguish between the future emissions reduction potential by avoiding food waste and emission reduction potential by technological advancement.

RESULTS

Food Requirements. During the last 50 years the global average daily food requirement per person has increased from 2,320 kcal to 2,370 kcal, after a decrease of 40 kcal between 1950 and 1970 (Figure 1a, moderate PAL). These changes in food requirements are mostly due to changing demographic structures. For example, youth population (0–19 years) in China grew from 44% to 51% between 1950 and 1970, while

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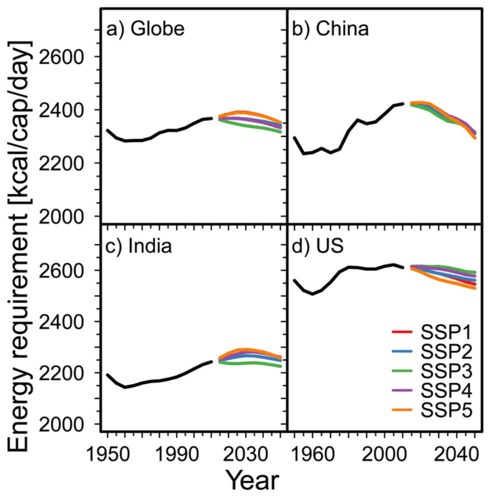

Figure 1. Average food energy required per person between 1950 and 2050 for moderate physical activity level: (a) Globe, (b) China, (c) India, and (d) the United States. The food energy requirements are estimated using the current demographic data from the United Nations[20] for the period 1950–2010 and the future demographic conditions based on the five Shared Socio-economic Pathways (SSPs).[30] The energy requirements are varying across time, mostly reflecting change in demographic structures.

adult population (20–59 years) declined from 49% to 42%.[20] This decreased the Chinese food requirement by 60 kcal/cap/day (Figure 1b). After, the adult population grew to 60% by 2010,[20] the food requirement increased to 2,420 kcal/cap/day. Similarly, per capita food requirements in India decreased until 1960 (Figure 1c) because of youth population increase.[20] After, the growth of the adult population resulted in an increase in the Indian food requirement to 2,240 kcal/cap/day by 2010. Between 1950 and 1960, per capita food requirement of the United States also decreased (Figure 1d) due to the baby boom in the late 1950s.[20] With declining birth rates in the 1960s and constant birth rates after 1975, the food requirement increased and stabilized to around 2,600 kcal/cap/day. In 2010, the total food requirement of these three countries constituted 42% of the global total.

Globally, country scale food requirements varied between 1,800 kcal/cap/day and 2,800 kcal/cap/day in 2010 (Figure S1). Countries with heavy body weights (e.g., the United States, Australia, etc.) required larger amounts of food compared to countries with lighter body weights (e.g., China, India) [Figure 1 and Table S2]. Similarly, the light PAL provided the global minimum food requirements, while the global maximum food requirements are defined by the heavy PAL (Figure S2).

Looking into the future, the global food requirements will increase to 2,390 kcal/cap/day by 2025 under SSP1 and SSP5 scenarios (Figure 1a, moderate PAL). Afterward, the food requirements will decrease to 2,350 kcal/cap/day by 2050. Similar values of decreasing food requirements by 2050 are projected for China and India. SSP1 and SSP5 scenarios suggest low fertility and mortality rates for the non-OECD countries,[30] which implies that their aging populations will require comparatively lower amounts of food (Table 1). The aging affect can be prominent for China as its share of population above 60 years of age is projected to increase from 12% in 2010 to 37% by 2050.[30] Similarly, the food requirements will decrease after 2015 in the OECD countries, due to SSPs' medium (SSP1 and SSP2) or high (SSP5) fertility assumptions.[30] The lowest food requirements on a global scale and for the non-OECD countries is estimated under the SSP3 scenario. This is due to high fertility and mortality assumptions for the non-OECD countries, resulting in a younger global population.[30]

Additionally, the global food requirements may slightly decrease to 2,300 kcal/cap/day or increase to 2,560–2,620 kcal/cap/day by 2050 if the body weight of the global population were from Japan or the United States, respectively (Figure S3). The body weight can increase with lifestyles that simulate overeating and can result in an overweight and obese population. For populations that suffer from stunting and wasting, proper supply of nutrients helps to gain a desirable body weight and height, depending on genetic preconditions.

By 2050, the total food requirements for the global population will be in the range of 6,400 trillion kcal/yr to 12,200 trillion kcal/yr, considering three body weight scenarios, five demographic projections, and three PAL values. This corresponds to 9% less and 73% more calories compared to the 7,100 trillion kcal/yr of food available in 2010. The mid range of the food requirements is represented by the moderate PAL with constant body weight, amounting to 7,300–8,400 trillion kcal/yr (2%–20% more calories compared to food available in 2010). This mid range variation is mainly driven by the SSP population scenarios that project 8.5–10 billion people by 2050.[30] The global maximum, moderate, and minimum food requirements, as defined by the three PALs, may be in the ranges of 9,450–12,200 trillion kcal/yr, 7,150–9,300 trillion kcal/yr, and 6,400–8,300 trillion kcal/yr by 2050, respectively. A driver of these projected food requirements is human body weight. If the global body weights were the same as the Japanese body weight, the global food requirements would be 1–2% lower compared to constant body weight by 2050. However, global body weights similar to body weight of the United States would result in 10–12% higher food requirements.

Adequacy of Food Supply. Our calculations show that food surplus is increasing and food deficit is decreasing globally (Figures 2 and S4). Between 1965 and 2010, the food surplus grew from 310 kcal/cap/day to 510 kcal/cap/day, and the food deficit declined from 330 kcal/cap/day to 120 kcal/cap/day (moderate PAL). The amount of surplus food is increasing especially in most of the OECD countries, e.g., food surplus in the United States has increased from 400 kcal/cap/day to 1,050 kcal/cap/day between 1965 and 2010. Food availability has increased over the last few decades, whereas biophysical food requirements have remained almost constant.

During this period, some countries have successfully overcome a food deficit to have a food surplus. For example, available food in China and India was 440 kcal/cap/day and 220 kcal/cap/day respectively below the required amount in 1965 (Figures 2). Due to economic development, the nutritional situation in China and India improved, resulting in a food surplus of 620 kcal/cap/day and 210 kcal/cap/day in 2010, respectively. This reflects the positive relationship between country scale food availability, its per capita income,[32] and HDI.[6] Still, available food is lower than the required amount in some low-income countries (e.g., Zambia and Haiti) [Figure S4].

In 2010, 20% more food was available than required on a global scale (Figure 2a, moderate PAL). While considering the minimum and maximum food requirements, as defined by the respective light and heavy PAL, the food surplus amounts to

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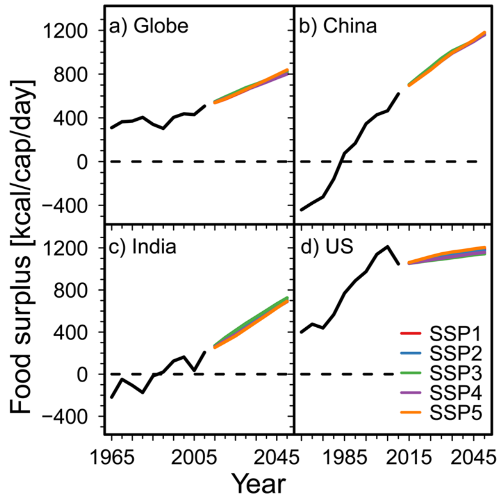

Figure 2. Estimated food surplus/deficit per person between 1965 and 2050: (a) Globe, (b) China, (c) India, and (d) the United States. We considered the differences between food availability[22] and food energy requirements as food surplus/deficit. We separately summed the food surplus and deficit of countries to estimate per capita food surplus and deficit on a global scale. Food surplus is increasing on global and national scales, mainly due to growing food availability. Some countries (e.g., China and India) evolved from suffering from food deficit conditions to a food surplus status. In the future, food surplus will further increase globally, considering the projected food demand[6] and demographic projections based on the Shared Socio-economic Pathways (SSPs).[30]

750 kcal/day and 170 kcal/day in 2010, respectively (Figure S5). On a country scale, a range between 40% less and 60% more food was available compared to the required amount in 2010 (Figure 3, moderate PAL). This represents the

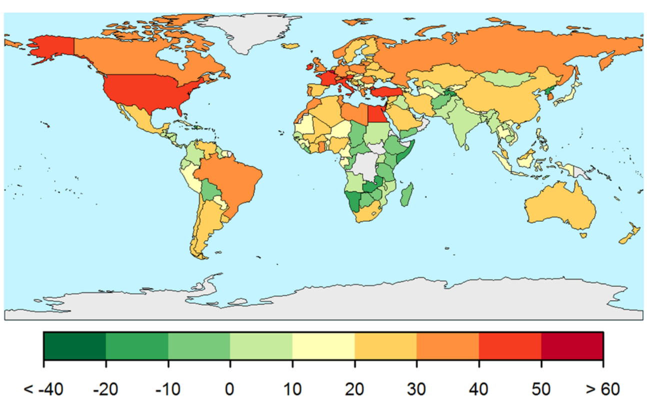

Figure 3. Share of food surplus/deficit on a country scale compared to food requirement for 2010 in percentage. The negative values represent food deficits and are depicted by greenish colors. The positive values express food surplus and are illustrated with reddish colors. Countries and regions with no data are marked by gray color. Food surplus is common in countries in the North, while food deficits are prevailing in the South.

inefficiency in food distribution systems, resulting in either too much or too little food. Food deficits are common in many developing and least developed countries, resulting in people living under hunger conditions and suffering from stunting and wasting. Currently, around 800 million people are undernourished globally.[33] In contrast, we estimated a food surplus of 20−50% of the required calories in most OECD and transition countries in 2010, resulting in a global food surplus of 1,200 trillion kcal/yr. This amount of food is enough to feed around 1.4 billion people with a daily diet of 2,370 kcal/cap (the global per capita food requirement). Food surplus, also represented by the ratio of food availability to requirement, increases with HDI (Figure 4). However, a few countries (e.g., Japan) have a relatively high HDI and have low food surplus levels, depicting the compatibility of development along with a reduced food waste.

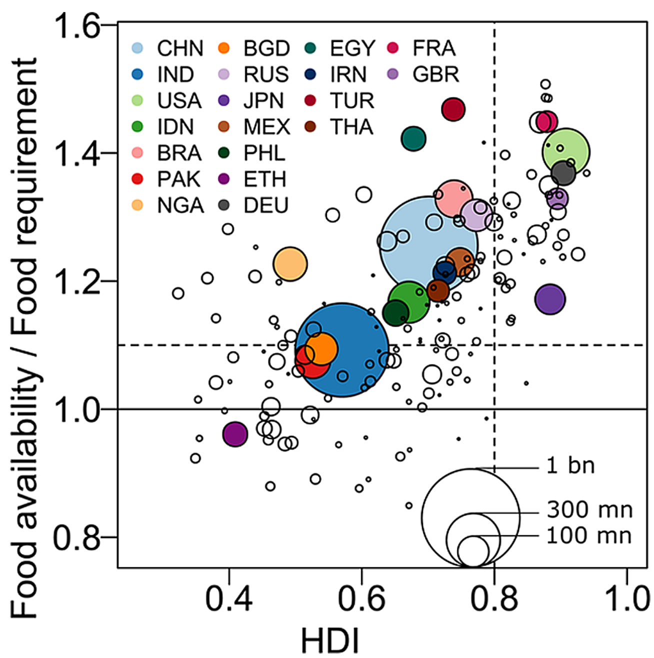

Figure 4. Plot showing the interrelation between country scale food availability and requirement ratio as a function of Human Development Index (HDI)[23] for the year 2010. The ratio below 1 represents food deficit. The country populations in billion (bn) and million (mn) are depicted by the diameter of the bubbles. The 20 largest countries in terms of population are marked in different colors. The legend list is based on their ISO codes. The threshold for development is provided by the vertical dashed line at the HDI value of 0.8.[34] For pragmatic reasons, it may not be possible to reduce food surplus to zero; hence, we considered the maximum allowable surplus as 10% of the requirement and depicted that by the horizontal dashed line. Generally, availability and requirement ratios increase with growing HDIs.

In the future, the food surplus will continue to grow in most countries because of increasing food demand. By 2050, the global food surplus may increase to around 850 kcal/cap/day (Figure 2, moderate PAL and constant body weight). The growth rate of available food compared to the required amount will be more prominent in the transition countries. For example, the food surplus in China and India may increase by around 500 kcal/cap/day between 2010 and 2050 when these countries follow historical trends (Figure 2). These countries are the potential food waste hot-spots mainly due to large population and increasing food surplus. In contrast, the food surplus may increase to a lesser extent in most OECD countries. For example, food surplus in the United States may only increase by 200 kcal/cap/day between 2010 and 2050, considering moderate PAL and constant body weight. Nevertheless, the food surplus in the United States will be 1,200 kcal/cap/day by 2050. On global and country scales, surplus calories

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would be higher when considering light PAL, and lower with heavy PAL, due to corresponding minimum and maximum food requirements (Figure S5).

By 2050, the global food deficit per capita may remain similar to that in 2010. However, the total food deficit will decrease from 17 trillion kcal/yr to 9−13 trillion kcal/yr between 2010 and 2050. This reflects that the nutritional situation will continue to improve in some least developed countries, while in others the situation may stagnate or get worse. For example, food availability may remain almost constant in Central African Republic and may decrease in Zambia between 2010 and 2050 (Figure S4). Extrapolation of HDI trends of both the Central African Republic and Zambia provides respectively almost constant and decreasing values.[34] Hence, rapid progress in human development conditions in such least developed countries is essential to eliminate hunger and food deficit situations.

Avoidable Emissions. Figure 5 presents the global non-CO_2 GHG emissions related to surplus crop and animal calories. Between 1965 and 2010, these global emissions increased by around 3 times, from 130 Mt CO_{2eq}/yr to 530 Mt CO_{2eq}/yr (moderate PAL), because of a growing food surplus (Figure 2a) and shifting diets. Globally, diets are changing toward a larger share of animal products that have a higher emission intensity in comparison to crops.[6] This results in a growing animal calorie surplus and increases the emissions related to total food surplus.

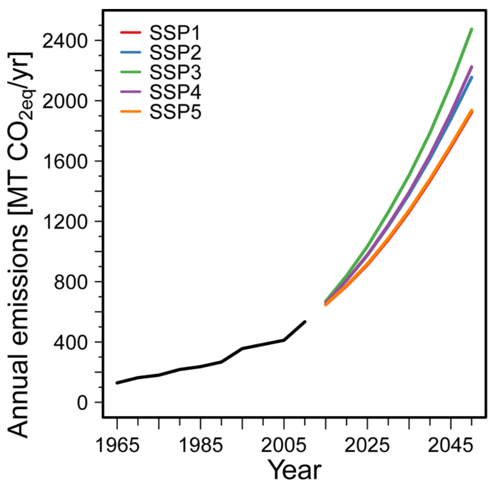

Figure 5. Estimated agricultural GHG emissions associated with food surplus between 1965 and 2050. The emissions were calculated initially for countries based on country scale emission intensity for crop and animal calorie production, which were multiplied by crop and animal calorie surplus, respectively. Globally, GHG emissions associated with food surplus have increased in the last five decades. In the future, these emissions will further increase globally considering the projected food demand[6] and demographic projections based on the Shared Socio-economic Pathways (SSPs).[30] Note, while Figures 1 and 2 show per capita quantities, here total emissions are displayed.

Regionally and in 2010, Oceania, South America, and Northern Europe have comparatively high per capita emissions related to food surplus with values of 850 g CO_{2eq}/cap/day, 680 g CO_{2eq}/cap/day, and 410 g CO_{2eq}/cap/day, respectively (Table 2, moderate PAL). Although such emissions per capita are relatively low in South and East Asia (100 and 210 g CO_{2eq}/cap/day, respectively), the regions present very high total emissions related to food surplus due to larger populations. For example, the emissions were estimated to amount to 120 Mt CO_{2eq}/yr in East Asia, of which 110 Mt CO_{2eq}/yr was contributed by China alone. Chinese food surplus emissions have grown 13 times since 1985. A reason for this is the 138% increase in the animal products share in the Chinese food supply.

In the future, the global emissions related to food surplus will continue to increase under all scenarios, reaching 1.9−2.5 Gt CO_{2eq}/yr by 2050 (moderate PAL and constant body weight). The projected emissions are the highest under the SSP3 scenario and the lowest under the SSP1 and SSP5 scenarios. Although the global food surplus by 2050 may range between 2.1−2.4 times that of the year 2010, the food surplus emissions by 2050 may increase by 2.6−3.6 times compared to 2010. This immense growth in the emissions can be attributed to changing diet compositions. The highest range of food surplus emissions is estimated under light PAL and the Japanese body weight scenario, 2.6−3.3 Gt CO_{2eq}/yr by 2050 (Figure S6). On the other hand, the American body weight scenario and heavy PAL provide the lowest food surplus emissions range of 70−90 Mt CO_{2eq}/yr by 2050.

By 2050, the emissions related to food surplus will be the highest in South Asia (500−680 Mt CO_{2eq}/yr), followed by East Africa (270−430 Mt CO_{2eq}/yr) and South America (220−280 Mt CO_{2eq}/yr), considering the moderate PAL and current body weights (Table 2). Between 2010 and 2050, the emissions share of South Asia to the global food surplus may increase from 12% to 25%−27%, whereas East Asia's share may decline from 23% to 11%−14%. This is mainly due to the projected increase in the South Asian population from 1.7 billion in 2010 to 2.2−2.8 billion, while the East Asian population is projected to decline from 1.6 billion to 1.4−1.5 billion. Although the East Asian food surplus per capita will be greater, the larger population size in South Asia will result in a higher total food surplus. Additionally, diet shifts and larger emission intensities will contribute to these higher food surplus emissions. For example, the emission intensity of animal calories in India (3.19 G CO_{2eq}/kcal) is three times that of China (0.96 G CO_{2eq}/kcal). Furthermore, the share of animal products in Chinese diets may increase from 25% in 2010 to 36% by 2050, while it may double in India (11% to 2 2%).

DISCUSSION

Our discussion focuses on several key findings this study presents on the interplay of food requirements, food waste, food deficits, and associated GHG emissions. First, our study highlights a small increase (100 kcal/cap/day) in the global food requirements per person compared to a large increase in the global food availability (650 kcal/cap/day) during the last five decades. This led to the global food surplus.

Our global food requirement estimates per person (2,300−2,400 kcal/day) vary slightly from that of Smil[35] (2000−2300 kcal/day) and Walpole et al.[27] (2550 kcal/day). This is because we considered additional food requirement for youths and pregnant and lactating women that was not accounted for by Walpole et al.[27] and Smil,[35] respectively. By keeping the body weight constant at the values of the most recent years, we implicitly included food requirements for generating obesity and underestimated the food surplus. It is found that increasing food availability results in both an obesity epidemic and a food waste.[29] Hence, the underestimated food surplus that accounts for increased body weight in the past can be considered as food waste.

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Table 2. Regional Overview of GHG Emissions Related to Food Surplus in 2010 and by 2050[a]

	per capita emissions 2010		total emissions 2050 (Mt CO_{2eq}/yr)				
region	(g CO_{2eq}/cap/day)	total	SSP1	SSP2	SSP3	SSP4	SSP5
Australia and New Zealand	848	8.25	18.39	17.77	13.79	16.5	22.27
Caribbean	188	2.11	6.1	6.44	7.49	5.88	5.83
Central America	265	15.06	40.18	46.6	58.57	44.99	37.93
Central Asia	284	5.58	14.02	15.77	18.5	13.67	13.46
Eastern Africa	64	2.3	274.42	338.8	432.13	429.58	269.85
Eastern Asia	214	121.02	267.17	270.99	277.45	253.01	268.02
Eastern Europe	218	23.41	31.3	31.92	31.3	29.43	32.81
Middle Africa	61	2.38	15.55	21.65	30.43	30.27	15.5
Northern Africa	212	16.24	52.48	58.26	67.82	52.5	51.23
Northern America	340	42.7	71.44	68.94	55.53	64.02	84.01
Northern Europe	407	14.7	25.45	24.45	20.05	22.32	29.33
South America	684	95.58	223.17	245.53	281.08	230.65	220.44
South-Eastern Asia	126	27.16	106.32	113.92	125.37	107.84	105.05
Southern Africa	292	5.58	8.46	9.6	10.77	7.57	8.79
Southern Asia	104	64.6	504.26	573.64	678.55	553.34	499.51
Southern Europe	291	16.47	25.31	24.26	20.71	23	28.13
Western Africa	296	32.45	157.04	196.71	250.81	247.29	153.9
Western Asia	200	14.89	47.54	54.68	64.13	59.1	48.81
Western Europe	332	22.92	34.85	33.19	27.54	30.96	39.45

[a]The estimates for 2010 are based on moderate physical activity level (PAL). Similarly, the estimates for 2050 considers moderate PAL, constant body weight, and five demographic projections based on shared-socioeconomic pathways (SSPs).

We estimated the global food requirements to increase by 2%−20% by 2050 compared to the food available in 2010 (under a moderate PAL and constant body weight scenario). Compared to food demand that is projected to increase by 60%−110% between 2005 and 2050,[1,2,4] our future food requirement estimates are lower. The projected food demands are based on the food availability data that includes both food requirements and food waste. Hence, the food demand projections to a large extent reflect growing food waste rather than food requirements. Therefore, reducing food loss and waste that lowers overall food demand can be an option to feed the growing population. Dampening the food demand is crucial due to restricted options to increase food production because of limited land availability for agriculture expansion[36] and constraints related to conventional intensification approaches.[37]

Second, this study emphasizes growing food waste across the globe by applying a consistent method to estimate food waste from 1965 to 2050. So far, food loss and waste are estimated by using waste factors in each step of the food supply chain.[8] However, we calculated food waste based on available and required calories. Our global food waste estimate of 510 kcal/cap/day in 2010 that is larger than the consumer level food waste of 214 kcal/cap/day estimated by Kummu et al.[9] FAOSTAT accounts for postharvest food loss while calculating food availability.[22,26] However, Kummu et al.[9] used the food availability data from FAOSTAT and additionally considered the postharvest food loss while estimating food loss and waste. This resulted in a lower value. On a country scale, our estimates for the United States and China are comparable to the food waste values provided in the literature.[10,16]

Third, our study highlights climate burdens associated with food waste by estimating GHG emissions generated while producing the wasted food. Our global emission estimate related to food waste in 2005 of 410 Mt CO_{2eq}/yr is lower than the estimation of 560 Mt CO_{2eq}/yr in 2007 by FAO.[38] To be precise, FAO[38] calculated GHG emissions associated with both food loss and waste considering on-farm energy use and nonenergy-related emissions from crop and livestock. While we assessed non-CO_2 GHG emissions related to food waste only. By comparing these estimates, it is clear that a larger share of emissions is associated with food waste and non-CO_2 GHGs. Hence, reducing food waste is an important climate change mitigation option within the food system.[39]

Fourth, this study highlights that there are the regions of the world where food waste is prevalent and others where food deficit is the mainstay. Food waste and deficit on a country scale is also related to the development stage (HDI) of the country. However, undernourishment may prevail in a country with food surplus due to income inequality and poverty, resulting in disparity in food security within the country. For example, although our analysis shows that India currently has a food surplus of 210 kcal/cap/day, it also has the second-highest number of undernourished people in the world.[33] Hence, the problem of undernourishment and hidden hunger around the globe is a distribution problem rather than a production one.[40] In order to eliminate hunger, countries with food deficits at first need to increase their food availability, while other countries need to improve their food distribution systems. One of the Sustainable Development Goals (SDGs)[41] is to eliminate hunger of any kind by 2030, globally.

Similarly, another SDG targets halving per capita global consumer level food waste by 2030.[41] However, we find that country level food waste increases with its HDI, which is a trend opposite to the SDGs. Hence, this trend needs to be reversed like CO_2 emissions[42] which follow a weak environmental Kuznets curve,[43] making development and reduced food waste compatible.

Although our study provides clear findings, interpretation of our results also requires a discussion on its limitations that implied from the data sources and chosen methodology. On the data side, FAOSTAT is criticized because of consistency, completeness, and reliability issues. The national data that UN population estimates rely upon suffer from errors due to under- and overestimations. Yet, both data sets are the only global

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databases available. Additionally, these data are periodically updated with revised methodologies to enhance data quality and are widely used by the scientific community.

From a methodological perspective, our food requirement calculations may include overestimates and underestimates because we did not consider physiology and environmental conditions that may additionally affect food requirements. After all, it was not possible to account for these factors due to data scarcity and methodological limitation. Most studies[10,27,29] investigating food requirements accounted for body weight, age, gender, and PAL as our study did. Additionally, our analysis did not consider if and how the future food requirement would be fulfilled.

We considered food surplus as a proxy for food waste. However, food surplus may additionally contribute to overeating, resulting in an overweight and obese population. Nevertheless, we compiled global body weight data for the most recent years and, hence, accounted for overeating in the past. Additionally, part of the food surplus may be used as livestock feed, investigation of which is beyond the scope of our current study. After all, the share of food waste on feed is relatively low compared to the 40% of the total crop calories that are currently fed to livestock.[3] In addition, some regions, e.g., European Union, prohibit the feeding of food waste to livestock.[44] Nonetheless, to use discarded food as feed could be an option to tap into parts of wasted calories. Other options of using the food waste would be to downcycle into biogas and composting.

Last, our emission estimates include only non-CO_2 GHGs emitted during the food production. This study did not cover CO_2 emissions from on-farm and off-farm energy use (e.g., machinery, fertilizer production, transportation, etc.). Thus, we underestimated the total GHG emissions mitigation potential of food waste reduction. However, agriculture is a major source of non-CO_2 GHG emissions which is captured by our approach. We did not consider different food commodities while estimating the emissions because of challenges in assigning food surplus to the food commodities. Additionally, we are not aware of data on GHG emissions by food commodities for a large number of countries. Nevertheless, our study distinguished emission intensities based on crop and animal products that have large variations in GHG emissions.[12]

Summing up, our study highlights the important challenge of reducing food waste and its associated climate burdens. Although physical food consumption has metabolic limits, food availability across the globe is increasing with growing incomes and advancing development. This is the case for many countries, where the food supply chain does not reflect the physical limits of calorie requirements, providing excess food that results in waste and overconsumption. Hence, this inefficiency in the food supply chain needs to be addressed[45] to reduce agricultural related environmental consequences and climate burdens. Addressing this challenge will also lower the future food demand. Therefore, to feed around 9 billion people by 2050, in addition to increasing food production (e.g., by closing crop yield gaps[46]), the key underlying questions that remain to be answered are how can we make the food supply chain smarter and more efficient, and how can consumers be convinced to reduce food waste.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b05088.

Details on Materials and Methods and additional figures and tables (PDF)

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Notes

The authors declare no competing financial interest.

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