Title:

Tackling food consumption inequality to fight hunger without pressuring the environment

Authors:
Tomoko Hasegawa[1,2,3,*], Petr Havlík[2], Stefan Frank[2], Amanda Palazzo[2], Hugo Valin[2]

Author Affiliations;
1. College of Science and Engineering, Ritsumeikan University, 1-1-1, Nojihigashi, Kusatsu, Shiga, 525-8577, Japan.
2. International Institute for Applied System Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria.
3. National Institute for Environmental Studies (NIES), 16–2 Onogawa, Tsukuba, Ibaraki 305–8506, Japan.

* To whom correspondence should be addressed: thase@fc.ritsumei.ac.jp

Abstract (approximately 150 words)

Ending hunger is a Sustainable Development Goal of the United Nations. However, feeding a growing world population by increasing food production without implementing more sustainable consumption will threaten the environment. We explore alternative hunger eradication scenarios that do not compromise environmental protection. We find that an economy-growth-oriented scenario, which ignores inequitable food distribution and is aimed at ending hunger by increasing overall food availability, would require about 20% more food production and 48 Mha of additional agricultural land and would increase greenhouse gas emissions by 550 Mt CO_2eq/year in 2030, compared to the business-as-usual scenario. If hunger eradication efforts are focused solely on the undernourished, food demand would increase by only 3% and the associated environmental trade-offs would be significantly reduced. Moreover, a combined scenario that targets the undernourished while also reducing over-consumption and food waste, agricultural intensification and other environmental impacts, would reduce food demand by 9% compared to the business as usual and lead to the multiple benefits of reducing hunger and contributing to environmental sustainability.

Main text (<3500 words)

The United Nations (UN) Sustainable Development Goals (SDGs), adopted in 2015, consist of 17 goals to be achieved by 2030. Ending hunger, achieving food security and improved nutrition, and promoting sustainable agriculture were raised as key aspects of SDG 2 (Zero Hunger). Through sustained economic growth and increased productivity in agriculture, the number of undernourished people has been reduced by 85 million since 2000[1]. Effective government initiatives and commitments have also contributed significantly to improvements in food security. However, globally, one in nine people in the world today (815 million) are undernourished, over 30 million children under the age of five are dangerously underweight and, in Africa, one person in every five still goes hungry[1].

Increasing food production through agricultural land intensification and extensification is one approach to meeting the dietary needs of a growing world population[2, 3]. However, agricultural production requires the use of chemical inputs and consumes natural resources, which can both negatively impact the environment. For example, agricultural activities occupy 40% of the Earth's land surface[4], and threaten more than five thousand species[5]; furthermore, these activities account for 66% of total freshwater withdrawal and 85% of water consumption[6]. Agriculture, forestry, and related land uses account for 23% of total greenhouse gas emissions, making them the largest contributors[7]. These factors point to agriculture as a major cause of exceeding planetary capacities[8]. Ending hunger while achieving other targets of global sustainability requires innovative solutions. Several recent studies have evaluated the connections between food systems and other sustainability criteria[9, 10, 11, 12, 13, 14, 15]. Most of these studies have agreed that numerous options are available for achieving sustainable global food and agricultural systems in the future. However, none of these studies directly addressed the socioeconomic and environmental challenges of ending hunger.

Hunger can be defined as a state of inability to acquire food above the minimum dietary energy requirement that lasts for at least a year[1]. According to the Food and Agriculture Organisation (FAO) of the UN[16], populations at risk of hunger can be estimated from average calorie availability, equity of food distribution, and minimum energy requirement. Since the energy requirement is a biological limit, there are only two means of reducing hunger: increasing the overall level of food availability, i.e. shifting the food distribution curve to higher levels until all people have enough to eat, as shown by the red line in Figure 1, and pursuing a more equitable food distribution by reallocating deficits and excesses of food, as shown by the red areas in Figure 1. To construct a set of scenarios, we consider alternative conceptual futures based on observations[17, 18, 19] from the literature[20]. The first alternative future, increasing the income of the entire population and thus increasing the average food availability, requires long-term focused efforts, which can be realised with sustained economic development and improvement in the living conditions of a wide range of people through policy changes such as strengthening education, health, sanitation, and nutrition, and is termed 'growth-mediated security'[20]. For example, China has experienced rapid economic growth over the last two decades and has also been one of the most successful regions in fighting hunger[17]. The second alternative future, involving more equitable food distribution, can be realised by targeted government support, such as food and nutrition programs providing food in-kind transfers, school-feeding, vouchers for food, income support programs, and safety-nets, without waiting for economic growth. This is an immediate strategy and is known as 'support-led security'[20]. For example, in the last two decades, government purchases of food from family farmers, distributed to vulnerable groups through food security interventions such as school-feeding programs, significantly contributed to improving food security in many regions including Latin America and the Caribbean[18, 19]. Additional safety nets with family farming organisations have improved the livelihoods of farmers, built capacities, and provided income support for the poor as well as helped in meeting government food demand targets. Cash transfers and access to grants for business skills training have also helped to lift people out of poverty[21].

Moreover, effective food and hunger policies in combination with land-sparing measures such as dietary changes and agricultural intensification are key for feeding a growing population while mitigating the pressures of food production on multiple sustainability goals[9, 10, 11, 12, 13]. Agricultural intensification can significantly contribute to improvements in the efficiency of land, food, and water systems, as well as compensate for restrictions on agricultural expansion and reduce the pressure on land under the given food demand for feeding a growing world population[10, 22, 23].

Here, we explore alternative scenarios, quantitatively representing the key elements of the two alternative futures described above and three variants for each. Increasing agricultural production is the most often-discussed approach to feeding a growing population and eradicating hunger[2, 3, 10], but the amount of additional agricultural production required and the associated impacts can vary widely depending on food distribution and hunger eradication efforts. The first alternative future is referred to as the *More food for all* (MFA) scenario, which improves the living conditions of all people by increasing food production and the overall level of food availability. The second alternative future, involving more equitable food distribution, is represented by the *Food for the poor* (FFP) scenario, which targets vulnerable groups for receiving additional food. In addition to these primary scenarios, we also consider three variant sub-scenarios of the FFP scenario that may improve its environmental sustainability. The *Reduced food over-consumption* (NoOvercons) scenario represents a further improvement of food distribution to the population by not only eliminating undernourishment but also alleviating over-consumption. Second, the *Reduced food waste* (NoWaste) scenario is an alternative to the hypothetical scenario of reducing over-consumption, with a qualitatively similar effect of reduced need for food production, potentially leading to reduced negative impacts on the environment. Finally, the *Enhanced yield growth* (HigherYield) scenario avoids at least some of the negative effects on the environment, such as those related to the conversion of natural habitats to agricultural land. For this scenario, we assumed that the 2050 yield level would be achieved by 2030 in medium- and low-income regions.. To represent these scenarios in our model, average calorie and protein availability were estimated using the method developed by the FAO[16] and employed in previous studies[24, 25] (see Methods), and set food demand constraints for each scenario and region (Figure 1 and Supplementary Figure 1 for global and regional food demand constraints). We analysed the consequences of various scenarios on hunger eradication efforts with a comprehensive agricultural economic model, the Global Biosphere Management

Model (GLOBIOM)[26] using the indicators listed in Supplementary Table 1 (see Methods for model description). The same socioeconomic assumptions, aside from the hunger eradication efforts, such as future population and economic growth, were used in all scenarios. Then, the model projected per capita food demand based on per capita income, prices and preferences. Political instability and civil conflict can be dominant factors driving hunger, but were not considered in this study. We also present a *baseline* scenario that represents business-as-usual without additional hunger eradication efforts. Comparing the *baseline* with the hunger eradication scenarios allows for investigation of the impact of hunger eradication on the environment.

Results

Agricultural system response to additional food production for hunger eradication

In the *baseline* scenario, driven by economic development, the global average calorie and protein availability increase from 2770 to 2940 kcal/person/day and 76 to 82 g protein/person/day, respectively, between 2010 and 2030 (Figure 2-a,b). Accordingly, the total food demand increases from 29 to 37 EJ/year in the same period (Figure 2-c). To meet this demand, crop and livestock production increase by 1800 million tonnes and 340 million tonnes, respectively, from 2010 to 2030 (Figure 2-g,h). The global undernourished population declines from 760 million to 410 million people from 2010 to 2030, while the number of over-consuming people increases from 1.9 billion to 3.1 billion (Figure 2-d,e). See Supplementary text for comparison of our baseline estimates with FAO reports.

The additional food demands and associated responses of agricultural systems vary under the different scenarios. Under the MFA scenario, the global average per-capita calorie availability is higher than the baseline level in 2030 (Figure 2-a) by 570 kcal/person/day (650 kcal/person/day in Sub-Saharan Africa; 680 kcal/person/day in India; See Supplementary Figure 1 for regional food requirements), reaching 3500 kcal/person/day, which roughly corresponds to the current food availability in Europe and the US; per-capita protein availability increases by 21 to 100 g protein/person/day, which corresponds to almost double the required quantity. To meet this demand, food production increases to end hunger by 2030. Hunger eradication is achieved but the number of over-consuming people increases to 4.9 billion (Figure 2-e). The per-capita food demand increase translates into a large increase in total food demand of 7.2 EJ/year relative to the baseline level, which represents about 1.5 times the projected business-as-usual growth (Figure 2-c). To meet this demand, crop production increases by 580 million tonnes and livestock production decreases by 12 million tonnes from the baseline production in 2030. The livestock production decreases because the increased calorie demand in developing regions is mostly met by crop products, which are in competition with feed use, leading, therefore, to slightly lower meat consumption. This results in cereal crop yields increasing approximately 10% faster than in the *baseline* scenario, and cropland expands by additional 21 Mha while grassland increases by 27 Mha (Figure 2-f,i).

In contrast, the FFP scenario requires addition of 90 kcal/person/day (76 kcal/person/day in Sub-Saharan Africa; 110 kcal/person/day in India) in 2030 compared to the *baseline* scenario, increasing total food calorie demand by 1.1 EJ/year (3%) and protein availability by 3.7 g protein/person/day, and keeping the current over-consumption unchanged (Figure 2-a–e). The marginal additional demand would be met by almost unchanged crop yields and minor agricultural land expansion (cropland area = –1.6 million Mha, grassland expansion = +15 Mha). This results in only a marginal increase in crop production (73 Mt) and a reduction in livestock production (28 Mt) compared to the baseline levels in 2030. The decrease in livestock production results from the demand response to price increases of feed crops in regions with no hunger. This decrease in production does not necessarily lead to the same proportional reduction in grassland because highly productive livestock systems are reduced in high-income regions, where animals are grain-fed to a larger extent than in rangeland production systems.

Impacts of hunger eradication on the environment

Hunger eradication scenarios result in substantially differing impacts on the environment (Figure 3). In the MFA scenario, the cropland and grassland areas expand by 48 Mha globally relative to the baseline level in 2030, which reduces forest and other natural land areas by 18 Mha (26%) and 30 Mha (15%), respectively. The increase in food production requires additional fertiliser and increased irrigation water withdrawal by 6.7 Mt (11%) and 100 km^3 (25%), respectively. The additional fertiliser use, livestock production, and deforestation increase greenhouse gas emissions by 550 Mt CO_2eq/year (8.5%) from the baseline level by 2030. In contrast, in the FFP scenario, the associated environmental trade-offs almost disappear, as targeting only the hungry requires little additional food production.

Further relaxing of the trade-offs between food security and the environment

In comparison to the *baseline* scenario, the FFP+NoOvercons and FFP+NoWaste scenarios allow for hunger eradication while improving the environment and, hence, alleviate the conflict between these objectives. The FFP+NoOvercons scenario translates into decreasing global average calorie availability by 86 kcal/person/day and decreasing average protein availability by 3.4 g protein/person/day from the baseline level in 2030. This low per-capita food demand reduces the total food calorie demand by 1.1 EJ/year (4%) from the baseline level, the cropland area by 17 Mha and an almost unchanged grassland area (–2.9 Mha). The lower demand decreases food prices, leading to lower crop yields by 0.2 t/ha. This reduces future crop and livestock production by 390 and 160 Mt, respectively, relative to their baseline levels in 2030. The low food production has positive impacts on the environment. The reduced production saves fertiliser and water withdrawal by 7.2 Mt (5.0%) and 69 km^3 (2.3%), respectively, relative to their baseline levels in 2030. Together, reductions in livestock production, fertiliser use, and deforestation reduce land-based greenhouse gas (GHG) emissions by 340 Mt CO_2eq/year (5.2%) from the baseline level.

The FFP+NoWaste scenario has substantially greater positive impacts on food systems and land requirements than the FFP+NoOvercons scenario. For example, the FFP+NoWaste scenario decreases global average food calorie availability by 120 calorie/person/day and protein availability by 4.6 g protein/person/day relative to their baseline levels, decreasing the required crop and livestock production by 490 and 190 Mt, respectively, reducing agricultural land-use by 57 Mha (Figure 2-g,h,i) and, thus, the associated side effects on the environment. The reduced production decreases fertiliser and water requirements by 10 Mt (7.0%) and 110 km^3 (3.8%), respectively, and GHG emissions are reduced by 410 Mt CO_2eq/year, relative to the 2030 baseline levels. Reducing food waste can contribute to reducing demand for food, feed, and other resources such as water and nitrogen, reducing the pressure on land and the environment while ending hunger.

The FFP+HigherYield scenario contributes to reconciling ending hunger with preserving the environment through improved crop yields, which reduce cropland expansion (Figure 2) and increase forest and other natural land areas compared to the *baseline* scenario (Figure 3). However, without other complementary policies, some negative side-effects of yield development would occur with regard to nitrogen fertiliser use (an additional 6.2–7.6 Mt) and associated GHG emissions (an additional 77–250 Mt CO_2eq/year) (Figure 3). Moreover, the land intensification contributes to decreases in food and land prices, and increases food (over-)consumption (Figure 2-e). Finally, if all three initiatives are implemented simultaneously (FFP+ALL), the side effects of yield enhancement would be offset by decreasing total food calorie demand by 3.2 EJ/year (9%) through the reduced food over-consumption and waste and, thus, the environment would be much improved.

Discussion

As hunger eradication will not be achieved by 2030 in our *baseline* scenario, projected economic development will contribute to increasing the average food availability level, but this will not be enough to end hunger by 2030. Accelerating overall economic development until all people have enough to eat is unrealistic in the short term, since the necessary average food availability of 3500 kcal/person/day in the MFA scenario would be reached at the end of the century but only with a high global GDP growth rate (3.5%/year), which would correspond to a scenario of very fast economic growth , such as SSP5[25]. This suggests that government interventions, such as targeted food support or development for the poor and agricultural investment, are necessary to achieve the SDG 2 of ending hunger by 2030. Strong governance and functioning institutions are not explicitly considered here but are the minimum preconditions for implementing the suggested policies.

An economic-growth oriented scenario, aimed at ending hunger by increasing the overall level of food availability for a wide range of people, would require 20% more food compared to the baseline level in 2030, leading to negative impacts on the environment through increased use of inputs and resources such as fertilisers, water, and land, as well as additional GHG emissions from agriculture and land-use change. In contrast, if the policy focused only on the undernourished, by means of targeted support or by establishing a right to food or a global basic income, thus guaranteeing all people a certain minimum level of access to food, associated environmental trade-offs can be significantly reduced because the additional food demand would increase by only 3%.

Our analysis shows that reducing food over-consumption and waste allows for hunger eradication while improving the environment and, hence, alleviates the conflict between the SDGs. This suggests that increasing food production to eradicate hunger is neither needed nor desirable from an environmental perspective. Regarding food over-consumption, recent studies have highlighted the potential compounding benefits of reduced consumption of livestock or unhealthy food products on both health[27] and GHG emissions[28]. These studies assessed taxation of livestock products and showed that taxing GHG-intensive food commodities could, if appropriately designed, provide health benefits in high-income countries as well as in most low- and middle-income countries[28]. Government initiatives such as taxing unhealthy foods and providing specific health guidance are expected to contribute to reduced obesity and improved health[27, 29]. Taxation of sugary products has been introduced in many jurisdictions, for example in Mexico[30], to control increasing obesity rates. Specific health guidance has been implemented in Japan. The revenue from taxation of unnecessary food consumption, or of food with substantial negative impacts on the environment, could bring a significant source of new income to support hunger eradication programs, such as the development of new income opportunities for the poor. Furthermore, in the private sector, discounts on health insurance schemes for people who are not overweight could contribute to reductions in over-consumption.

Among the three variants implemented in addition to the FFP scenario, the *reduced food waste* scenario (FFP+NoWaste) would be the most effective. Most food is wasted at the consumption stage in rich countries simply because people can afford to waste food. The amount of food available in retail stores and restaurants has increased over recent decades in high-income countries[31]. In such countries, restaurants produce more food than is needed by serving buffets at fixed prices, which encourages people to take more food than they can actually eat, and by offering large package deals and "buy one get one free" offers. However, reducing waste could be more easily implemented compared to reducing over-consumption, because, in principle, it saves money without reducing the quantity consumed. To help reduce waste, the French government forbids food waste by supermarkets, while Italy has adopted a law that aims to reduce food waste and promote the donation of food to charity[32]. Moreover, education (e.g. in schools) and political initiatives could help to change consumers' attitudes, and future technology innovations such as digitalisation and smart fridges, which could automatically order food when their contents are low, could help reduce stockpiling.

The *Enhanced yield growth* scenario (FFP+HigherYield) suggests that the transfer of highly efficient production technologies, including advanced crop species, improved management for existing crop varieties, and targeted investment in agricultural research and development in the hunger regions, should contribute to meeting food demand while reducing the pressure on land. In addition, grazing intensification will probably contribute to reductions in land demand, although it is not considered in this study due to the very limited availability of data on the extent and intensity of grazing on the global scale[33]. The HigherYield scenario would result in side effects on nitrogen use in some regions and should be implemented alongside the promotion of efficient use of nitrogen and other chemicals, in addition to waste and energy improvements.

Production systems in the developing world are often less resource efficient and more GHG intensive than production systems in developed countries. For example, the developing world contributes 75% of the global GHG emissions from ruminants while it supplies only 44% of the milk and 55% of the beef[33]. Hence, the negative effects of increased food supply on the environment could be reduced by faster transfer of resource-efficient production technologies from other regions, or by supplying part of the food from more efficient production systems in other regions through international trade[26]. Implementing the *Reduced food waste* and *Enhanced yield growth* scenarios in addition to the MFA scenario shown in the Supplementary Material brings most of the environmental indicators close to the FFP scenario results. This suggests that even without food support targeted at the poor, these policies would generate almost the same effects as those of targeted food support. Finally, a combined food policy, such as food support targeting the undernourished accompanied by reducing over-consumption and food waste, agricultural intensification, and other environmental protections, would not only contribute to ending hunger (SDG 2) but also to the environmental sustainability of food production systems. These combined policies would reduce food production, demand for land, nitrogen (SDG 15) and water (SDG 6) use, and GHG emissions (SDG 13), by encouraging sustainable consumption and production practices (SDG 12).

Methods (<3000 words)

Model description

GLOBIOM is a recursive dynamic partial equilibrium model that covers the agricultural and forestry sectors. Commodity markets and international trade are represented for 30 economic regions in this study. The model is run over the period 2000–2030 at decadal intervals. Within each region, the FAOSTAT database is used to calibrate agricultural commodity prices in the year 2000 for 18 major crops and seven livestock products. The model projects endogenous demand for commodities and bilateral trade flows between regions based on estimated future population, per capita income, production costs, and equilibrium prices (including tariffs, transportation costs and capacity constraints). Food income elasticities are calibrated to food demand projections by the FAO through to 2050, and demand price elasticities are based on USDA estimates. The supply side is calculated using biophysical models on grid cells aggregated from 5 to 30 arcmin, taking into account spatial heterogeneity in agricultural and silvicultural productivities (dominant soils, climate, and topography dependent). Agricultural land area and productivity (e.g. crop yields) are endogenously determined and respond to demand and price under the given yield shift to meet the demand. Land and other resources are allocated to the different production and processing activities to maximise a social welfare function, which consists of the sum of producer and consumer surplus. Carbon prices are determined through coupling with the MESSAGE model, as well as biomass demands for energy use[34]. The model responds to carbon price by structural changes in the agricultural sector and international trade[26], implementation of various mitigation technical options[35], as well as food demand changes[23].

The interconnection between the hunger scenarios and other environmental systems serve as indicators of the global agricultural and environmental systems shown in Supplementary Table 1. We selected land-related indicators that can be quantified in our modelling framework from the list made by the UN[36]. Agricultural water withdrawals includes total agricultural water withdrawals for irrigation[37]. Nitrate fertiliser use includes total nitrate agricultural inputs from all chemical and mineral fertiliser products. Forest area includes the forest areas managed and unmanaged and can be both primary and secondary. The greenhouse gas (GHG) emissions in this study indicate the net sum of emissions from land-use, land-use change, and forestry sectors, which generate emissions from biofuels, agricultural processes, peatland, and land-use change. Energy sector emissions are excluded from the GLOBIOM model and this analysis. Although we do not cover all SDG indicators selected by the UN, such as malnutrition, access to food and land, and small-scale farmers' resilience, we covered as many variables as possible to capture an approximate picture of their changes after achieving the food distribution targets.

Scenario assumptions of dietary energy requirements for hunger eradication

First, we ran a *baseline* scenario that represents food system dynamics and responds to projected population growth and economic development. Second, we calculated the scenarios targeting food availability levels to reduce the baseline undernourished population to zero by 2030 . Third, we ran the hunger-eradication scenarios by setting the targeted food availability as a food demand constraint.

If the hunger target is to be reached, calorie requirements would be identical across the scenarios, but we set different average calorie requirements across different hunger eradication scenarios by adjusting the deficiency and excess of food to reduce under- and over-consumption. For the *More food for all*scenario, where hunger eradication is achieved by increasing the average food availability and keeping the current equity (variance) of food distribution, the calorie requirement to end hunger by 2030 was calculated by shifting a baseline food distribution curve (black line in Figure 1) rightwards to high food consumption levels until the dietary requirements of the entire population are met (red line in Figure 1). A difference in food availability between the baseline level (black line in Figure 1) and the level that would result in no undernourished people (red line in Figure 1) was calculated. This study assumes the 0.1 percent hunger threshold as a global goal of ending hunger. The difference of the food availability levels was added to the baseline average food availability level (Equation. 1).

For the *Food for the poor* scenario, we set the calorie constraints required to lift the undernourished from this status in regions of undernourishment, by increasing the baseline food availability by the average intensity of food deprivation of the undernourished ("depth of food deficit") (Equation 2), which represents how many calories would be needed to lift the undernourished from this status[38] (blue area in Figure 1). The intensity was estimated as the difference between the average dietary energy requirement (ADER) and the average dietary energy availability of the undernourished population, multiplied by the number of undernourished people to provide an estimate of the total food deficit in the country, which was then normalised by the total population[38] (Equation. 4).

For the *Reduced food over-consumption* (NoOvercons) scenario, we set the level of food calorie availability so as to eliminate both hunger and over-consumption. The average intensity of food deprivation of the undernourished and the average intensity of calories in excess of the maximum calorie requirements[38] were calculated. These intensities were then added to the average baseline food availability

(Equation 3). The average intensity of calorie exceedance of over-consumption was estimated for the regions of over-consumption as the difference between the average maximum dietary energy requirement (XDER) and the average dietary energy availability of the number of over-consuming people, multiplied by the number of over-consuming people to provide an estimate of the total food exceedance in the country, which was then normalised by the total population (Equation. 5).

For the *Reduced food waste* (NoWaste) scenario, we assume all food waste is avoided and set the level of food calorie availability for each scenario by decreasing the mean food calorie availability by a regional percentage ratio of food waste at the consumption stage[31].

Finally, for the *Enhanced yield growth* (HigherYield) scenario, the food constraint was not changed from the original scenarios. We assumed the 2050 level of yield would be achieved by 2030 in mid- and low-income regions by agricultural investment in, and technology transfer to, these regions. We set the target levels of average food calorie availability with the same composition among commodities, and linearly changed the food calorie consumption over time from 2020 to hit the SDG 2 target by 2030. No food demand constraints were set for the *baseline* scenario. The food availability targets can be different between countries due to different food distributions and national mean energy requirements. In high-income countries where hunger is not currently reported, food availability was not constrained for the *More food for all* and *Food for the poor* scenarios. Implementing the *Reduced food waste* and *Enhanced yield growth* scenarios in addition to the *More Food for All* scenario are shown in the Supplementary Material.

$$CALO_{s,r} = \begin{cases} CALO_{baseline',r} + FS_r & s = 'MFA',\ r = \text{med\&low-income regions} \quad \text{Equation 1} \\ CALO_{baseline',r} + FD_r & s = 'FFP',\ r = \text{med\&low-income regions} \quad \text{Equation 2} \\ CALO_{baseline',r} + FD_r - FE_r & s = 'FFP + NoOvercons', r = \text{all regions} \quad \text{Equation 3} \end{cases}$$

where,

r: region

FS: the increased level of average food availability required to eliminate the hunger (kcal/person/day)

FD: the average intensity of food deprivation (kcal/person/day)

FE: the average intensity of food exceedance (kcal/person/day)

$$FD_r = \int_0^{Ld} \left(ADER_r - x \right) fx(x) dx \qquad \text{Equation. 4}$$

$$FE_r = \int_{Le}^{L\max} \left(x - XDER_r \right) fx(x) dx \qquad \text{Equation. 5}$$

where,

x: food availability (kcal/person/day)

Ld: a cut-off point for the undernourished (= the minimum dietary energy requirement, kcal/person/day)

Le: a cut-off point for over-consumption (= the maximum dietary energy requirement, kcal/person/day)

Lmax: the maximum level of food availability (kcal/person/day)

ADER: the average dietary energy requirement (ADER) (kcal/person/day)

XDER: the average maximum dietary energy requirement (XDER) (kcal/person/day)

According to the FAO[16], the cut-off points for the requirements are based on the total energy expenditure corresponding to the minimum or maximum acceptable limits of BMI and light physical activity, while the food availability refers to food acquired by the households and includes food loss and waste rather than the actual food intake of the individual[16]. Thus, the approach in applying the cut-off point for energy needs to account for the range in food availability and is based on the idea that, due to the effect of correlation between energy intake and requirement, the individuals with food availability falling within the range of variation of requirement are likely to be close to matching their requirements although, strictly speaking, this is not always the case. In other words, the risk of food shortfall or excess is negligible if the difference is not zero. Although the assumption of light physical activity may underestimate the amount of food needed to ensure the normal life for some people, this assumption is suitable for the study estimating the amount of food and its effect on the environment to keep consistency with the SDG and earlier FAO estimation.

Protein requirements

The protein requirements originally developed by Rand et al.[39] and reported by the World Health Organisation (WHO)/FAO/United Nations University (UNU)[40] were set as lower limits of protein availability for all scenarios except for the *baseline* scenario. We used requirements based on 0.83 g/kg-weight/day of protein being the safe level, and ensured this was met by most (97.5%) of the healthy adult population. The requirements for different body weights were applied to regions in the model according to the regional average adult body weight[41] due to limited data on national or regional average weights for different age groups. No upper limit was set for protein requirement because no such limit has been identified[40].

Estimation of population at risk of hunger and over-consumption

The definition of undernourishment or hunger is a state of energy (calorie) deprivation lasting over one year; this does not include the short-lived effects of temporary crises nor inadequate intake of other essential nutrients[1]. The undernourished population is a multiple of the prevalence of undernourishment (PoU) and the total population. According to the FAO, the PoU is calculated using three key factors: the mean dietary energy availability (kcal/person/day), the mean minimum dietary energy requirement (MDER), and the coefficient of variation (CV) of the domestic distribution of dietary energy availability in a country. The food distribution within a country is assumed to obey a lognormal distribution, which is determined by the mean food calorie availability (mean) and the equity of the food distribution (variance). The proportion of the population under the cut-off point (MDER) is then defined as the PoU. The over-consumption population is calculated in an analogous manner. The over-consumption population is a multiple of the prevalence of food over-consumption (PoO) and the total population. The proportion of the population over the maximum dietary energy requirement (XDER) is then defined as the PoO.

The calorie-based food consumption (kcal/person/day) output from the model was used for the mean food calorie availability. The future mean MDER (XDER) was calculated for each year and country using the mean MDER (XDER) in the base year at the country level[38], adjusted for the MDER in different age and sex groups[42] and future population demographics[43] to reflect differences in the MDER (XDER) across age and sex. The future equity of food distribution was estimated by applying the historical trend of income growth and the improved CV of the food distribution to the future, such that the equity is improved along with income growth in future at historical rates up to the present best value (0.2) (See Supplementary Figure 2 for the future equity of food distribution). We assumed no risk of hunger for high-income countries where hunger is not currently reported.

Data availability

The data repository, including scenario data, is stored on Harvard Dataverse (https://doi.org/10.7910/DVN/RQZELX).

Code availability

The authors declare that the program code used to generate results in this study are available from the corresponding author upon request.

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Correspondence and requests for materials should be addressed to T.H.

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Author Contributions

T.H. and P.H. designed the research and carried out the analysis of the modelling results. T.H. created figures and led the writing of the paper. All authors contributed to the discussion and interpretation of the results, and writing the paper.

Competing interests

The authors have declared that no competing interests exist.

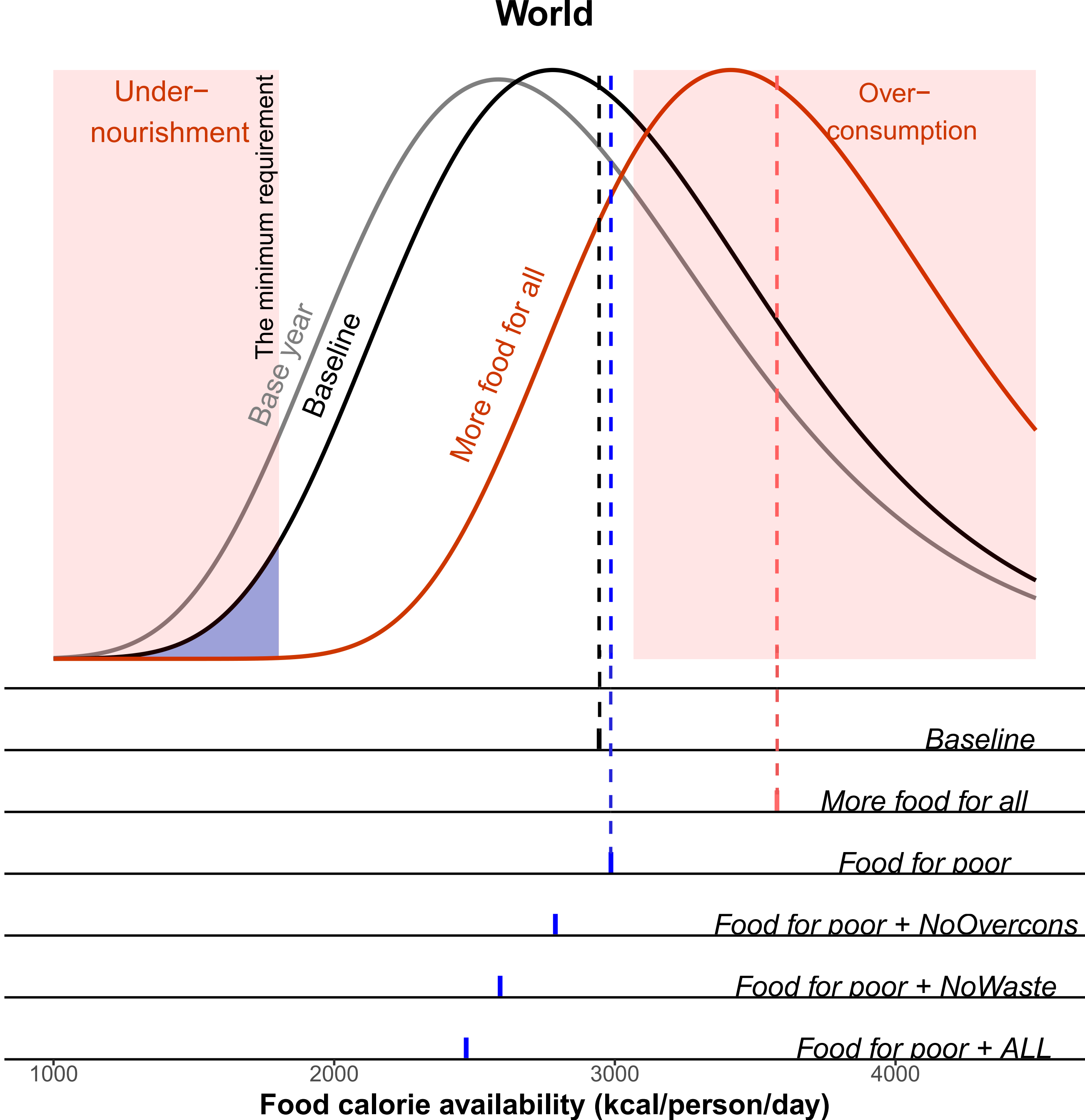
Figure Legends and Tables

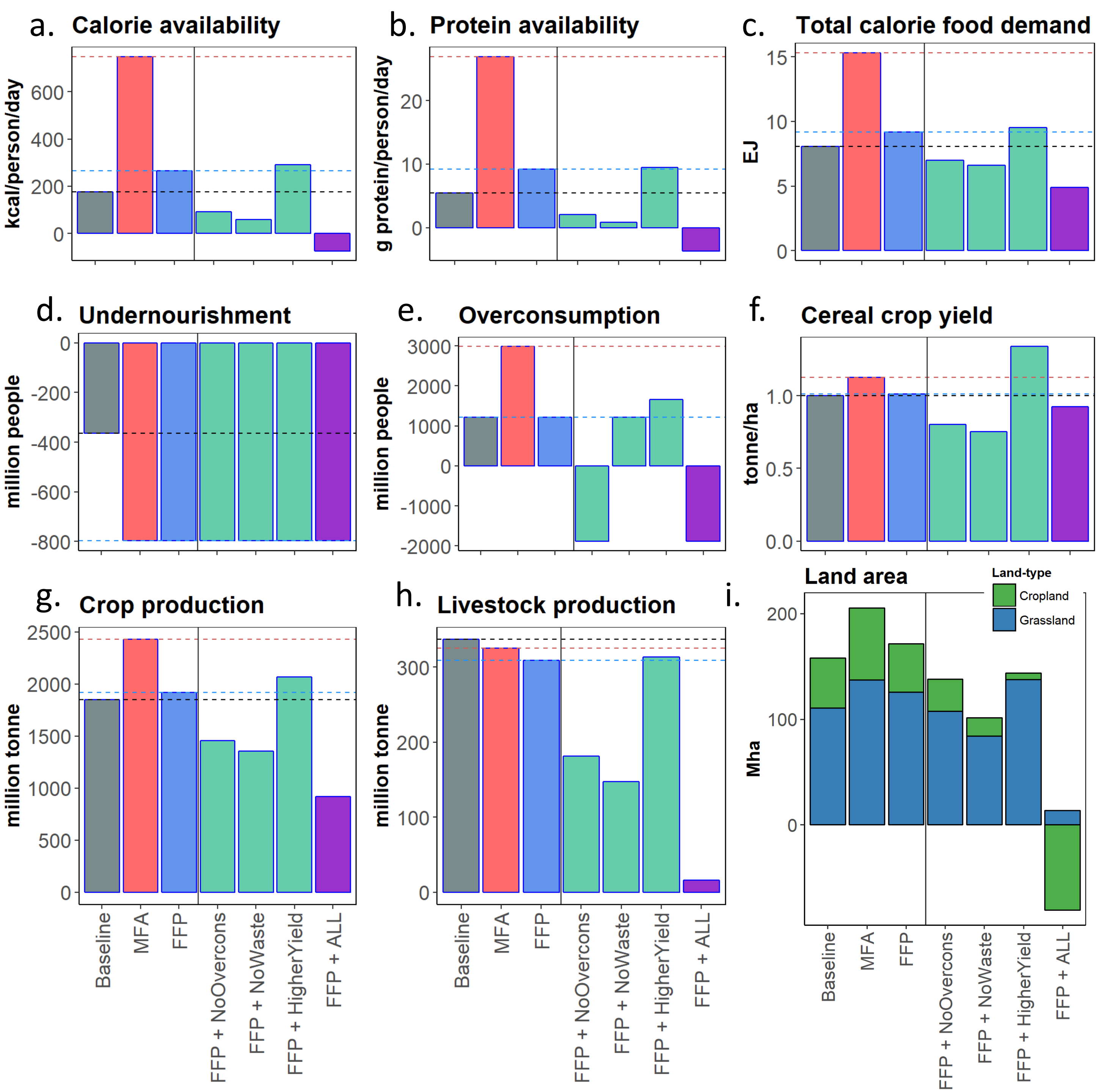
Figure 1 Possible food distribution transformation to achieve the eradication of hunger. Solid-line curves in the upper part represent the food availability distribution across the individuals in the population. Vertical dashed lines represent the global aggregated thresholds for food calorie availability for the main scenarios (*Baseline* – black, *More food for all* – red, *Food for poor* – blue). The lower part of the Figure represents the thresholds for the above scenarios and their variants (*Food for poor + NoOvercons, Food for poor + NoWaste, Food for poor + ALL*).

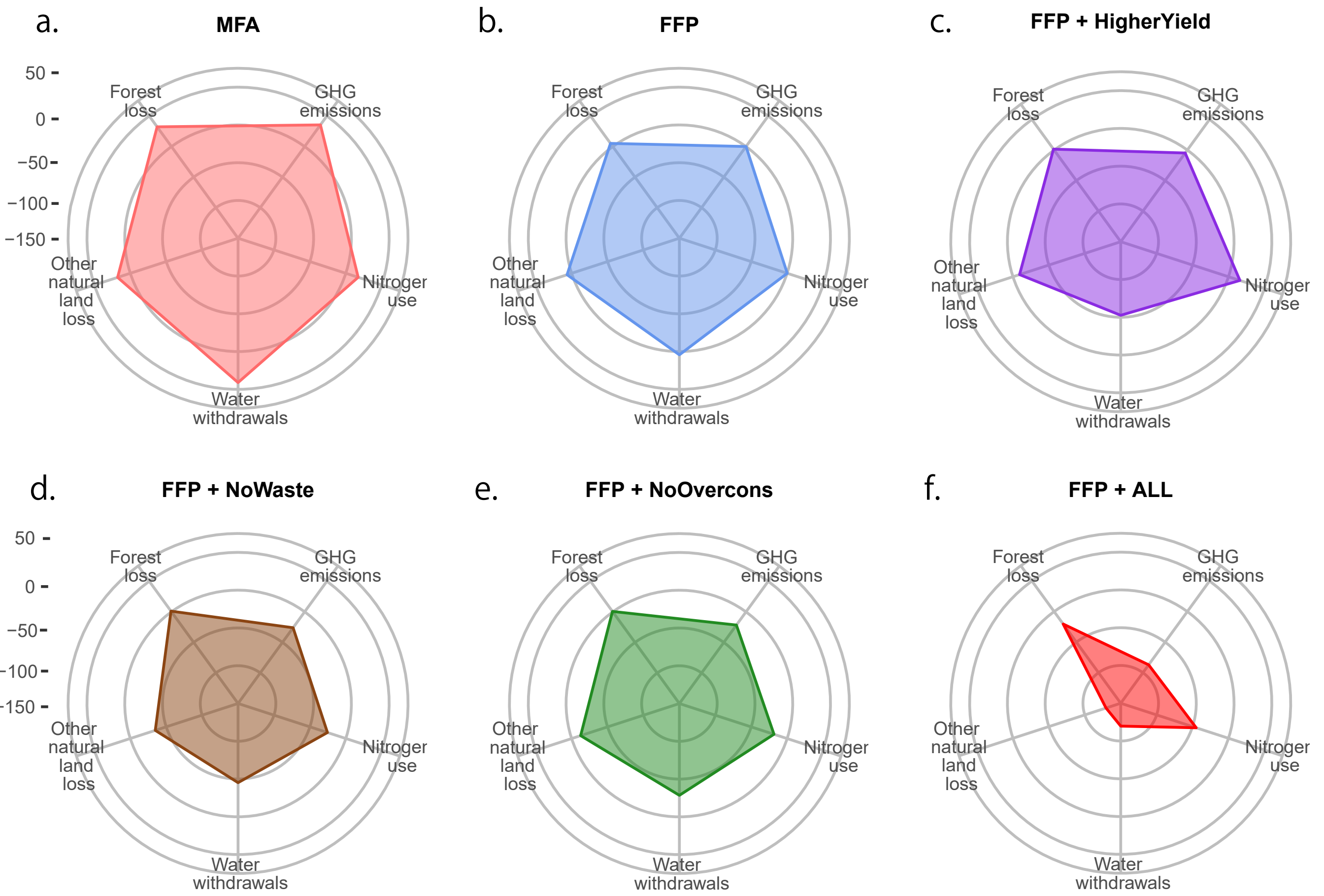
Figure 2 Additional food supplies and responses of agricultural systems to ending hunger under the *baseline* scenario and different combinations of hunger and food security policies. Changes in a. per-capita calorie availability, b. per-capita protein availability, c. total food calorie demand, d. undernourished population, e. the number of over-consuming people, f. cereal crop yield, g. crop production, h. livestock production, and i. cropland and grassland area, in 2030 relative to the 2010

level. MFA: More Food for All; FFP: Food for Poor; NoOvercons: no food over-consumption; NoWaste: no food waste; HigherYield: yield developments; ALL combines all three policies (ALL = NoOvercons + No Waste + HigherYield).

Figure 3 Global agricultural impacts on the environment under different hunger eradication policies in 2030. Indicators show i) agricultural irrigation water withdrawals, ii) greenhouse gas emissions from agriculture and land-use, iii) nitrogen fertiliser use, iv) forest area and v) other natural land loss. Values show difference in the percentage changes in 2030 relative to the 2010 level from the baseline levels with no hunger policy. Policy codes are the same as Figure 2.


World
Under–
nourishment
The minimum requirement
Base year
Baseline
More food for all
Over–
consumption
Baseline
More food for all
Food for poor
Food for poor + NoOvercons
Food for poor + NoWaste
Food for poor + ALL
1000
2000
3000
4000
Food calorie availability (kcal/person/day)


a. Calorie availability
kcal/person/day
b. Protein availability
g protein/person/day
c. Total calorie food demand
EJ
d. Undernourishment
million people
e. Overconsumption
million people
f. Cereal crop yield
tonne/ha
g. Crop production
million tonne
h. Livestock production
million tonne
i. Land area
Mha
Land-type
Cropland
Grassland
Baseline
MFA
FFP
FFP + NoOvercons
FFP + NoWaste
FFP + HigherYield
FFP + ALL



a.
MFA
50
0
−50
−100
−150
Forest loss
GHG emissions
Nitrogen use
Water withdrawals
Other natural land loss
b.
FFP
c.
FFP + HigherYield
d.
FFP + NoWaste
e.
FFP + NoOvercons
f.
FFP + ALL