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Tackling food consumption inequality to fight hunger without pressuring the environment

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Ending hunger is a Sustainable Development Goal of the UN. 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, 48 Mha of additional agricultural land and would increase greenhouse gas emissions by 550 Mt of CO_2 equivalents yr^{-1} in 2030, compared with the business-as-usual scenario. If hunger eradication efforts were focused solely on the under-nourished, food demand would increase by only 3%, and the associated environmental trade-offs would be largely reduced. Moreover, a combined scenario that targets the under-nourished while also reducing over-consumption, food waste, agricultural intensification and other environmental impacts would reduce food demand by 9% compared with the business-as-usual scenario and would lead to the multiple benefits of reducing hunger and contributing to environmental sustainability.

The 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 under-nourished 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 under-nourished, over 30 million children under the age of five years 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 5,000 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 (GHG) 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[9–15]. 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 socio-economic 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 Organization (FAO) of the UN[16], populations at risk of hunger can be estimated from average calorie availability, equity of food distribution and minimum energy requirements. Since the energy requirement is a biological limit, there are only two means of reducing hunger: increasing the overall level of food availability (that is, shifting the food distribution curve to higher levels until all people have enough to eat, as shown by the red line in Fig. 1) and pursuing a more equitable food distribution by reallocating deficits and excesses of food (as shown by the red areas in Fig. 1). To construct a set of scenarios, we consider alternative conceptual futures based on observations[17–19] 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. This future can be realized by 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 past 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 realized by targeted government support, such as food and nutrition programmes providing food in-kind transfers, school feeding, vouchers for food, income support programmes 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 past two decades, government purchases of food from family farmers, distributed to vulnerable groups through food security interventions such as school-feeding programmes, significantly contributed to improving food security in many regions including Latin America and the Caribbean[18,19]. Other safety nets with family farming organizations have improved the livelihoods of farmers, built capacities and provided income support for the poor as well as helped to meet 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

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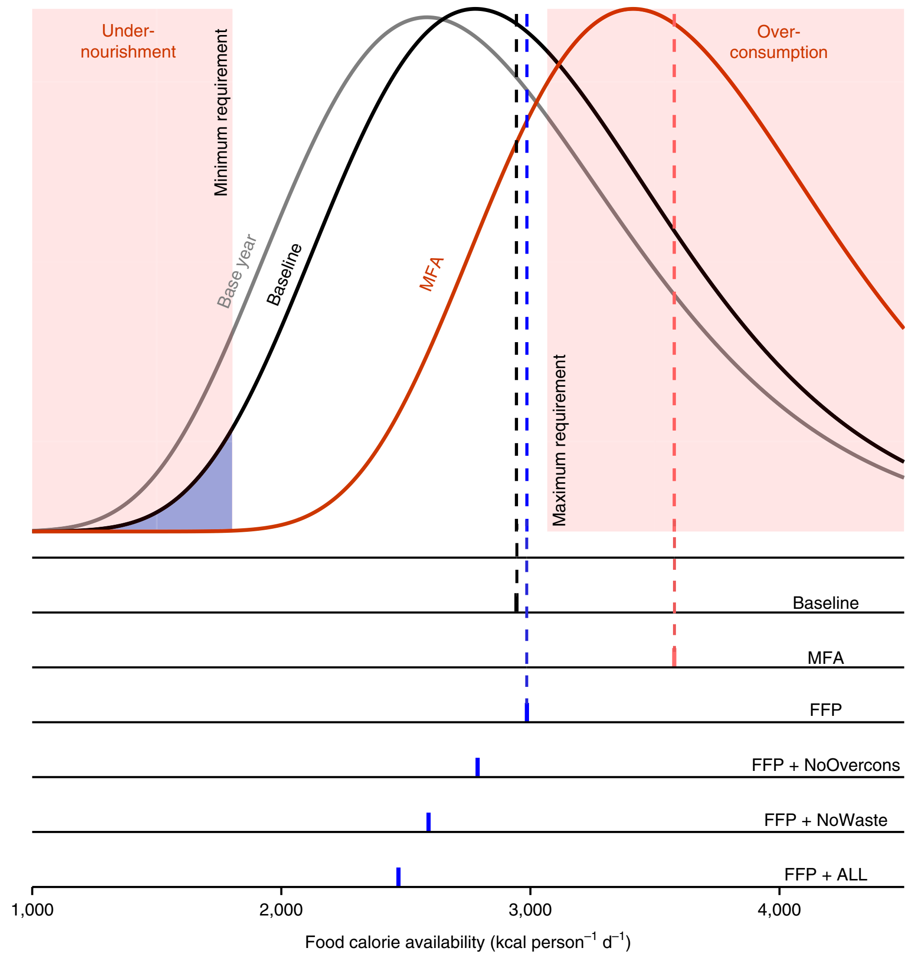

Fig. 1 | Possible food distribution transformation to achieve the eradication of hunger. Solid curves in the upper part of the figure represent the food availability distribution across the individuals in the population. The 'Base-year' represents the food availability distribution in 2010 while the 'Baseline' and 'MFA' represent the ones in 2030 in the Baseline and the More Food for All (MFA) scenarios, respectively. The left red shade represents the food consumption levels below the minimum dietary energy requirement while the right red shade represents the levels over the maximum dietary energy requirement. The shade in blue represents the population consuming less food than the minimum dietary energy requirement and facing risk of hunger in 2030 in the Baseline scenario. In the Food for the Poor (FFP) scenario, additional food supply targets only the blue part of the population. Vertical dashed lines represent the global aggregated thresholds for food calorie availability for the main scenarios (Baseline, black; MFA, red; FFP, blue). The bars in the lower part of the figure represents the thresholds for the above scenarios and their variants (FFP + NoOvercons; FFP + NoWaste; FFP + ALL). ALL combines all three policies (ALL = NoOvercons + No Waste + HigherYield).

intensification are key for feeding a growing population while mitigating the pressures of food production on multiple sustainability goals[9–13]. Agricultural intensification can substantially 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 that quantitatively represent the key elements of the two alternative futures described above and three variants for each. Increasing agricultural production is the most commonly 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 consider three variant subscenarios 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 under-nourishment but also alleviating over-consumption. 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, we estimated average calorie and protein availability 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 (see Fig. 1 and Supplementary Fig. 1 for global and regional food demand constraints). We analysed the

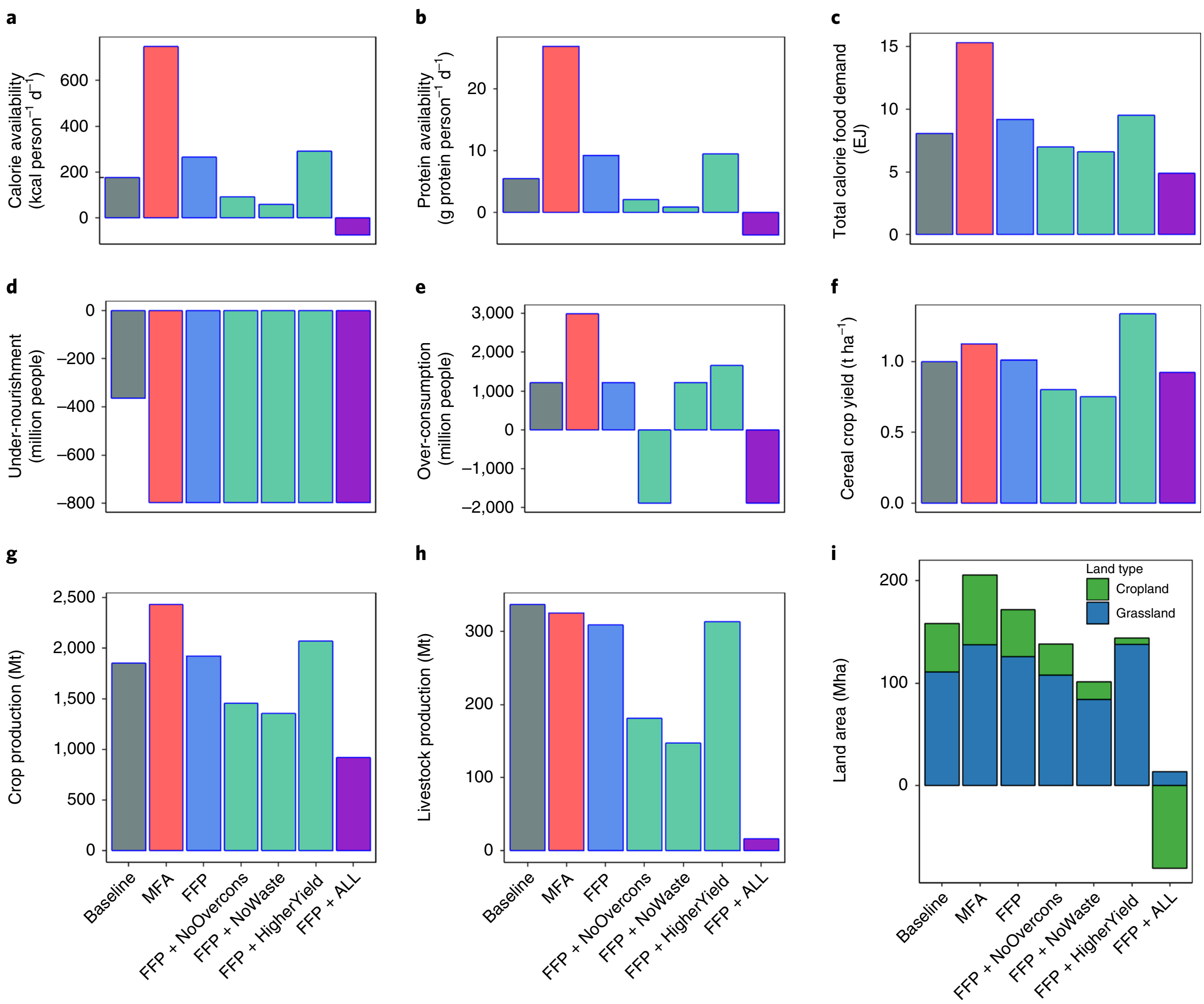

Fig. 2 | Additional food supplies and responses of agricultural systems to ending hunger under the Baseline scenario and different combinations of hunger and food security policies in 2030 relative to 2010. **a**, Calorie availability. **b**, Protein availability. **c**, Total food calorie demand. **d**, Under-nourished population. **e**, Number of over-consuming people. **f**, Cereal crop yield. **g**, Crop production. **h**, Livestock production. **i**, Cropland and grassland areas.

consequences of various scenarios for 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 the model description). The same socio-economic assumptions (aside from the hunger eradication efforts), such as future population and economic growth, were used in all scenarios. The model then 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 these factors 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 the impact of hunger eradication on the environment to be investigated.

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 availabilities increase from 2,770 to 2,940 kcal person^{-1} d^{-1} and from 76 to 82 g protein person^{-1} d^{-1} between 2010 and 2030 (Fig. 2a,b). Accordingly, the total food demand increases from 29 to 37 EJ yr^{-1} in the same period (Fig. 2c). To meet this demand, crop and livestock production increase by 1,800 Mt and 340 Mt, respectively, from 2010 to 2030 (Fig. 2g,h). The global under-nourished 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 (Fig. 2d,e). See the Supplementary Information for a 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 (Fig. 2a) by 570 kcal person^{-1} d^{-1} (650 kcal person^{-1} d^{-1} in sub-Saharan Africa; 680 kcal person^{-1} d^{-1} in India; see Supplementary Fig. 1 for regional food requirements), reaching 3,500 kcal person^{-1} d^{-1}, which roughly corresponds to the current food availability in Europe and the United States; per capita protein availability increases by 21–100 g protein person^{-1} d^{-1}, 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 (Fig. 2e). The per capita food demand increase translates into a large increase in total food demand of 7.2 EJ yr^{-1} relative to the Baseline level, which represents about 1.5× the projected business-as-usual growth (Fig. 2c). To meet this demand, crop production increases by 580 Mt, and livestock

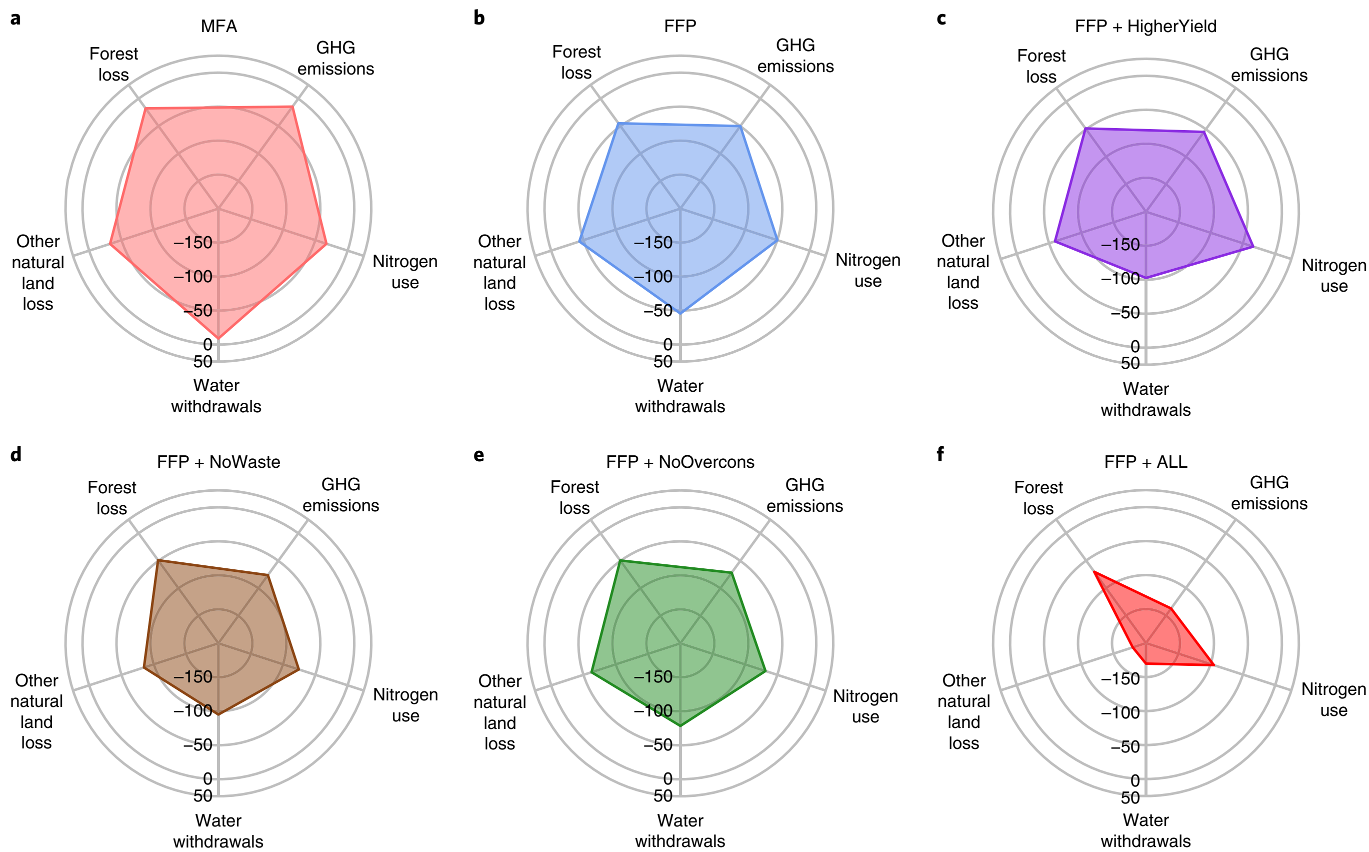

Fig. 3 | Global agricultural impacts on the environment under different hunger eradication policies in 2030. **a**, MFA. **b**, FFP. **c**, FFP + HigherYield. **d**, FFP + NoWaste. **e**, FFP + NoOvercons. **f**, FFP + ALL. Indicators show agricultural irrigation water withdrawals, nitrogen fertilizer use, GHG emissions from agriculture and land use, forest area loss and other natural land loss. The rings indicate the difference (%) between the changes for each indicator in 2030 relative to 2010 and the ones in the Baseline scenario with no hunger policy.

production decreases by 12 Mt from the Baseline production in 2030. 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 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 (Fig. 2f,i).

In contrast, the FFP scenario requires the addition of 90 kcal person^{-1} d^{-1} (76 kcal person^{-1} d^{-1} in sub-Saharan Africa; 110 kcal person^{-1} d^{-1} in India) in 2030 compared with the Baseline scenario, increasing total food calorie demand by 1.1 EJ yr^{-1} (3%) and protein availability by 3.7 g protein person^{-1} d^{-1}, and keeping the current over-consumption unchanged (Fig. 2a–e). The marginal extra demand would be met by almost unchanged crop yields and minor agricultural land expansion (cropland area = −1.6 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 with 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 (Fig. 3). In the MFA scenario, the cropland and grassland areas expand by 21 Mha and 27 Mha respectively in global relative to the Baseline level in 2030, which reduces forest and other natural land areas by 18 Mha and 30 Mha, respectively. The increase in food production requires more fertilizer and increased irrigation water withdrawal by 6.7 Mt and 100 km^3, respectively. The additional fertilizer use, livestock production and deforestation increase GHG emissions by 550 Mt of CO_2 equivalents yr^{-1} (MtCO_2e yr^{-1}) from the Baseline level in 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^{-1} d^{-1} and decreasing average protein availability by 3.4 g protein person^{-1} d^{-1} from the Baseline level in 2030. This low per capita food demand reduces the total food calorie demand by 1.1 EJ yr^{-1} (4%) from the Baseline level, reduces the cropland area by 17 Mha and leaves the grassland area almost unchanged (−2.9 Mha). The lower demand decreases food prices, leading to lower crop yields by 0.2 t ha^{-1}. 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 fertilizer and water withdrawal by 7.2 Mt and 69 km^3, respectively, relative to their Baseline levels in 2030. Together, reductions in livestock production, fertilizer use and deforestation reduce land-based GHG emissions by 340 $MtCO_2e\,yr^{-1}$ 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 $kcal\,person^{-1}\,d^{-1}$ and protein availability by 4.6 $g\,protein\,person^{-1}\,d^{-1}$ relative to their Baseline levels, decreasing the required crop and livestock production by 490 and 190 Mt, respectively. This decreased production reduces agricultural land use by 57 Mha (Fig. 2g–i) and thus lowers the associated side effects on the environment. The reduced production also decreases fertilizer and water requirements by 10 Mt and 110 km^3, respectively, and GHG emissions are reduced by 410 $MtCO_2e\,yr^{-1}$ 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 (Fig. 2) and increase forest and other natural land areas compared with the Baseline scenario (Fig. 3). However, without other complementary policies, some negative side effects of yield development would occur with regard to nitrogen fertilizer use (an additional 6.2–7.6 Mt) and associated GHG emissions (an additional 77–250 $MtCO_2e\,yr^{-1}$) (Fig. 3). Moreover, the land intensification contributes to decreases in food and land prices and increases food (over-)consumption (Fig. 2e). Finally, if all three initiatives are implemented simultaneously (FFP + ALL), the side effects of yield enhancement are offset by decreasing total food calorie demand by 3.2 $EJ\,yr^{-1}$ (9%) from the Baseline level through the reduced food over-consumption and waste. The reduced demand decreases crop and livestock production by 930 Mt and 320 Mt respectively from the Baseline production in 2030, decreasing the cropland and grassland areas by 130 Mha and 100 Mha globally and increasing forest and other natural land areas by 12 Mha and 210 Mha, respectively relative to the Baseline level in 2030. The decrease in food production reduces fertilizer and irrigation water withdrawal by 17.6 Mt and 290 km^3, respectively from the Baseline level in 2030. The reduced fertilizer use, livestock production and deforestation decrease GHG emissions by 1,360 $MtCO_2e\,yr^{-1}$ from the Baseline level in 2030.

Discussion

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 3,500 $kcal\,person^{-1}\,d^{-1}$ in the MFA scenario would be reached at the end of the century but only with a high global gross domestic productgrowth rate (3.5% yr^{-1}), 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 SDG 2, Zero Hunger. 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 with the Baseline level in 2030, leading to negative impacts on the environment through increased use of inputs and resources such as fertilizers, water and land, as well as higher GHG emissions from agriculture and land-use change. In contrast, if the policy focused only on the under-nourished, by means of targeted support or by establishing a right to food or a global basic income and thus guaranteeing all people a certain minimum level of access to food, associated environmental trade-offs could 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 for 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 an important source of new income to support hunger eradication programmes, 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, 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 than 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 (in schools, for example) and political initiatives could help change consumers' attitudes, and future technology innovations such as digitization and smart fridges, which could automatically order food when their contents are low, could help reduce stockpiling.

The FFP + HigherYield scenario suggests that the transfer of highly efficient production technologies, including advanced crop species, improved management of existing crop varieties and targeted investment in agricultural research and development in the regions experiencing greater hunger, 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 this factor 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 an 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 NoWaste and HigherYield scenarios in addition to the MFA scenario shown in the Supplementary Information 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 for targeted food support. Finally, a combined food policy, such as food support targeting the under-nourished accompanied by reducing over-consumption and food waste, agricultural intensification and other environmental protections, would contribute not only 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

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 7 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 2050, and demand price elasticities are based on US Department of Agriculture 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 (for example 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 maximize 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] and changes in food demand[23].

The interconnections 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 include total agricultural water withdrawals for irrigation[37]. Nitrate fertilizer use includes total nitrate agricultural inputs from all chemical and mineral fertilizer products. Forest area includes the forest areas managed and unmanaged and can be both primary and secondary. The GHG emissions in this study indicate the net sum of emissions from the 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. Then we calculated the scenarios targeting food availability levels to reduce the Baseline under-nourished population to zero by 2030. Finally, 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 MFA 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 Fig. 1) towards high food consumption levels until the dietary requirements of the entire population are met (red line in Fig. 1). A difference in food availability between the Baseline level (black line in Fig. 1) and the level that would result in no under-nourished people (red line in Fig. 1) was calculated. This study assumes the 0.1% 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 FFP scenario, we set the calorie constraints required to lift the under-nourished from this status in regions of under-nourishment by increasing the Baseline food availability by the average intensity of food deprivation of the under-nourished ('depth of food deficit') (equation 2), which represents how many calories would be needed to lift the under-nourished from this status[38] (blue area in Fig. 1). The intensity was estimated as the difference between the average dietary energy requirement and the average dietary energy availability of the under-nourished population, multiplied by the number of under-nourished people to provide an estimate of the total food deficit in the country, which was then normalized by the total population[38] (equation (4)).

For the 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 under-nourished 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 in kcal person^{-1} d^{-1} (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 normalized by the total population (equation (5)).

For the 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 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 MFA and FFP scenarios. This Article focuses on the variants implemented in addition to the FFP scenario while results for implementing the NoWaste and HigherYield scenarios in addition to the MFA scenario are shown in the Supplementary Information.

$$\mathrm{CALO}_{s,r} = \begin{cases} \mathrm{CALO}_{\mathrm{baseline},r} + \mathrm{FS}_r & s = \mathrm{MFA},\ r = \text{medium- and low-income regions} \quad (1) \\ \mathrm{CALO}_{\mathrm{baseline},r} + \mathrm{FD}_r & s = \mathrm{FFP},\ r = \text{medium- and low-income regions} \quad (2) \\ \mathrm{CALO}_{\mathrm{baseline},r} + \mathrm{FD}_r - \mathrm{FE}_r & s = \mathrm{FFP} + \mathrm{NoOvercons},\ r = \text{all regions} \quad (3) \end{cases}$$

where CALO is the per-capita calorie availability, s is the scenario, r is the region, FS is the increased level of average food availability required to eliminate the hunger (kcal person^{-1} d^{-1}), FD is the average intensity of food deprivation (kcal person^{-1} d^{-1}) and FE is the average intensity of food exceedance (kcal person^{-1} d^{-1}).

$$\mathrm{FD}_r = \int_0^{\mathrm{Ld}} (\mathrm{ADER}_r - x) fx(x)\mathrm{d}x \quad (4)$$

$$\mathrm{FE}_r = \int_{\mathrm{Le}}^{\mathrm{Lmax}} (x - \mathrm{XDER}_r) fx(x)\mathrm{d}x \quad (5)$$

where x is the food availability (kcal person^{-1} d^{-1}), Ld is a cut-off point for the under-nourished (the minimum dietary energy requirement, kcal person^{-1} d^{-1}), Le is a cut-off point for over-consumption (the maximum dietary energy requirement, kcal person^{-1} d^{-1}), Lmax is the maximum level of food availability (kcal person^{-1} d^{-1}) and ADER is the average dietary energy requirement (kcal person^{-1} d^{-1}).

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 body mass index 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 to 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 energy 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 a 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 Organization/FAO/UN University[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 per kg of body weight per day of protein being the safe level, and ensured this level 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 requirements because no such limit has been identified[40].

Estimation of population at risk of hunger and over-consumption. The definition of under-nourishment or hunger is a state of energy (calorie) deprivation lasting over 1 yr; this does not include the short-lived effects of temporary crises or inadequate intake of other essential nutrients[1]. The under-nourished population is a multiple of the prevalence of under-nourishment and the total population. According to the FAO, the prevalence of under-nourishment is calculated using three key factors: the mean dietary energy availability (kcal $person^{-1} d^{-1}$), the mean minimum dietary energy requirement (MDER) and the coefficient of variation of the domestic distribution of dietary energy availability in a country. The food distribution in a country is assumed to obey a log-normal 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 prevalence of under-nourishment. The over-consumption population is calculated in an analogous manner. The over-consumption population is a multiple of the prevalence of food over-consumption and the total population. The proportion of the population over the XDER is then defined as the prevalence of food over-consumption.

The calorie-based food consumption (kcal $person^{-1} d^{-1}$) 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 coefficient of variation 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 Fig. 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 is available from the corresponding author on request.

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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 to writing the paper.

Competing interests
The authors declare no competing interests.

Additional information
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