nature food

Article https://doi.org/10.1038/s43016-022-00648-y

Climate-friendly and nutrition-sensitive interventions can close the global dietary nutrient gap while reducing GHG emissions

Received: 4 April 2022

Accepted: 24 October 2022

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Sustainable food systems require malnutrition and climate change to be addressed in parallel. Here, we estimate the non-CO_2 greenhouse gas emissions resulting from closing the world's dietary nutrient gap—that between country-level nutrient supply and population requirements—for energy, protein, iron, zinc, vitamin A, vitamin B12 and folate under five climate-friendly intervention scenarios in 2030. We show that improving crop and livestock productivity and halving food loss and waste can close the nutrient gap with up to 42% lower emissions (3.03 Gt CO_2eq yr^{-1}) compared with business-as-usual supply patterns with a persistent nutrient gap (5.48 Gt CO_2eq yr^{-1}). Increased production and trade of vegetables, eggs, and roots and tubers can close the nutrient gap with the lowest emissions in most countries—with ≤23% increase in total caloric production required for 2030 relative to 2015. We conclude that the world's nutrient gap could be closed without exceeding global climate targets and without drastic changes to national food baskets.

The global syndemic—synchronous pandemics of malnutrition and climate change—poses a growing threat to humanity[1], with the COVID-19 pandemic exacerbating these effects[2]. At the same time, food systems are responsible for one-third (14–22 Gt CO_2eq yr^{-1} in 2015) of global greenhouse gas (GHG) emissions, ~33% of which are direct non-CO_2 emissions (that is, CH_4 and N_2O) occurring on-farm[3]. The critical role of food systems in limiting mean temperature increase to 1.5 °C is now well established[4,5], while nations have pledged to end all forms of malnutrition by 2030[6].

Despite a doubling of food production in caloric terms between 1995 and 2015, more than 40% of the global population continues to live in countries with inadequate micronutrient (for example, vitamins and minerals) supplies to meet population-level physiological requirements as a result of current food baskets that are largely dominated by cereals[7,8]. The shortfall between dietary nutrient (micro- and macronutrients) requirements and supply, at the country level, is termed the nutrient gap[9,10], which implies that adequate nutrition is not possible even with equal distribution within countries. Those regions with higher nutrient gaps, such as sub-Saharan Africa and Southern Asia, tend to have much larger GHG emissions intensity per kilogram of animal protein due to low productivity[11]. They are also expected to have the highest population growth[12] and may experience insufficient vegetable and fruit supply[13]. Hence, ensuring adequate nutrient supplies without exacerbating global warming requires carefully designed policies informed by appropriate indicators[14–16].

Recent assessments have largely focussed on income-driven demand[17,18] and wholesale dietary shifts (for example, towards flexitarian or vegetarian diets)[19,20] rather than physiological requirements and country-specific nutrient gaps. Some work has incorporated environmental boundaries in pursuit of optimal diets that provide recommended amounts of protein[21], fat[10] and other nutrients[22]. Production-based studies have incorporated composite productivity indicators linking nutrients to land[14,23] and water[24]. However, they have often been limited to specific regions and/or products. The 'nutritional life cycle assessment' approach has been applied to compare regional differences in environmental impacts of nutrient production,

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Table 1 | Scenario codes and brief description

Origin of supply	Scenario code	Description
Domestic	D-CP-FLW	Current productivity (CP) and food loss and waste (FLW) patterns in 2015 persist.
	D-CP-HLW	Current productivity patterns persist while food loss and waste rates are halved as per SDG 12 Target 12.3[70]. Existing production and additional production required to close the nutrient gap decrease as food loss and waste is halved (HLW) throughout.
	D-IP-FLW	Improved productivity (IP) of both crop and livestock production. Crop production is enhanced by closing the crop yield gap[71], with associated increase in fertilizer use where needed[37]. Consequently, emissions intensity of crop production changes depending on yield gap and current fertilizer use. Livestock (that is, ruminants, poultry and pigs) productivity is improved through livestock management, resulting in lower emissions intensity[44]. Food loss and waste remain unchanged. As the reduction in emissions intensity affects all production, existing emissions also decrease.
	D-IP-HLW	Improved productivity and halving food loss and waste scenarios are combined. Existing production and consequent emissions decrease as a result of scenario assumptions.
Trade	T-CP-FLW	The nutrient gap is closed via increasing imports from existing trade partners based on current trade baskets. For each country with a nutrient gap, products and trade partners are identified that close the nutrient gap at the lowest emissions. Exporting countries increase their production to meet the growing demand from their trade partners. Current productivity and food loss and waste rates remain unchanged.

Under domestic-production-based scenarios, the nutrient gap is closed via changes to domestic production of food sources that minimize the emissions based on national production baskets. No change in nutrient adequacy is imposed for countries with adequate nutrient supply (for more details, see Scenario description). In contrast, under the trade scenario, the nutrient gap is closed via imports of optimal food sources from optimal trade partners that minimize the emissions based on current import baskets.

emphasizing the importance of a nutrition angle for better-informed comparisons[25]. Analyses of nutrients and emissions embedded in household food waste have suggested that global food waste is equivalent to 15% of recommended energy and vitamin A intake, and 6.6% of the food-related non-CO_2 GHG limit to keep global warming below 2 °C[26]. Overall, there is now an urgent need to identify nutrient requirements lacking in national food supplies and to close these gaps with the lowest emissions[27].

Here, we provide detailed estimates of the non-CO_2 GHG emissions associated with closing the nutrient gap to address two dimensions of malnutrition, namely undernutrition and micronutrient deficiencies, under five climate-friendly intervention scenarios. We developed a composite indicator of emissions intensity of nutrient production to estimate non-CO_2 emissions associated with closing energy, protein, iron, zinc, vitamin A, vitamin B12 and folate gaps (that is, meeting population-adjusted nutrient requirements) of populations in 2030, following Sustainable Development Goal (SDG) 2.2—'By 2030, end all forms of malnutrition'. We used linear programming to optimize additional food production or trade to minimize the emissions from closing the nutrient gap. Given our focus on primary agricultural production and farm-level emissions, we did not consider the contribution of fortification to nutrient supplies. We optimized food supplies based on current highly disaggregated food baskets[7] that reflect national food preferences to avoid fundamental changes in diets. Our optimization covers 156 crop and 40 (terrestrial) animal products for 128 countries. Four of the five climate-friendly scenarios involve increasing domestic production coupled with halving loss and waste, and improved crop and livestock productivity, while one assumes climate-friendly international food trade (Table 1).

With a climate-friendly and nutrition-sensitive approach, we optimized food supply patterns to minimize the additional emissions while closing the nutrient gap (that is, all nutrient gaps) using linear programming. We used a range of data sources to calculate product-specific emissions. The scope of our analysis is limited to direct non-CO_2 (CH_4 and N_2O) agricultural emissions following the classification by the Intergovernmental Panel on Climate Change (IPCC)[28] due to a lack of data on product-specific emissions from land use and land-use change. Among direct agricultural emissions, we also excluded emissions from sewage applied to soils, liming and urea application, which do not have crop-specific attribution and represent less than 1% of agricultural emissions globally[3]. Our focus on non-CO_2 emissions is in line with the existing literature on climate taxes[29] and carbon footprints[30,31], as CO_2 emissions from up- and downstream activities (for example, energy use) are allocated to other sectors including energy, processing and transport as per the IPCC classification.

We first assessed scenarios based on domestic production, which included productivity and food loss and waste interventions (Table 1). Next, a trade scenario was introduced to explore the potential of exploiting comparative advantage in minimizing the emissions while closing the nutrient gap. We presented our results based on default emissions factors from the IPCC Tier 1 method[28], supplemented by lower and upper quantiles in parentheses (see Uncertainty estimates). To interpret our findings in the context of global climate targets, we compared them against what we call allowable food production emissions. The term refers to the non-CO_2 agriculture, forestry and other land use (AFOLU) emissions in 2030 compatible with the Paris Agreement[32] (see Paris Agreement and allowable food production emissions), which we downscaled according to the scope of this study (for example, population and emission sources).

Results

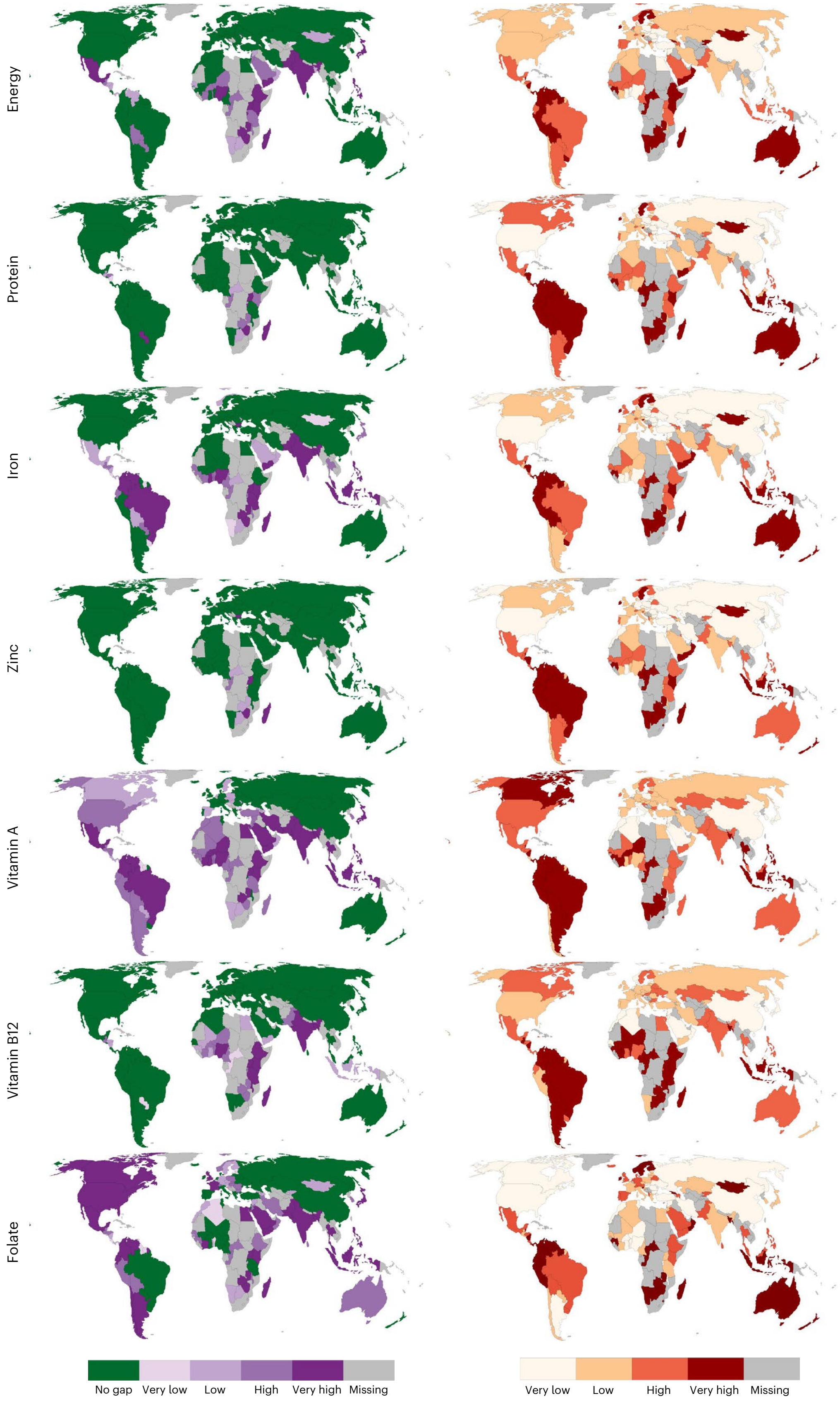
Emissions associated with closing the nutrient gap

Juxtaposition of country-level nutrient gaps and agricultural GHG emissions revealed that countries with large nutrient gaps, mainly concentrated in sub-Saharan Africa and Southern Asia, also tended to have a high emissions intensity of production (Fig. 1). Based on the United

Fig. 1 | Global maps of dietary nutrient gaps under current food loss and waste rates in 2030 compared with emissions intensity of total nutrient production in 2015. Countries are grouped into quartiles and coloured accordingly for ease of comparison. For example, light purple ('Very low') represents countries in the lowest nutrient gap quartile (see Source Data Fig. 1), while dark red ('Very high') represents countries in the highest quartile for emissions intensity of total production for a given nutrient. Higher emissions intensity of vitamin B12 production from animal sources, such as cow milk (see Source Data Fig. 1), particularly suggests low productivity in livestock production. Dominance of ruminant meat and dairy leads to high/very high emissions intensity of total nutrient production in countries such as Australia and Brazil, despite high livestock productivity in these countries, because livestock-related emissions represent the bulk of agricultural emissions and their dominance in national food baskets determines total emission volumes. Maps were drawn using the tmap R package[79].

Nations medium variant population estimates for 2030, we estimated that total nutrient requirements would increase by ~21% for energy and ~29% for protein, vitamin A, vitamin B12, and folate (Source Data Fig. 1). In contrast, iron and zinc requirements would decrease by 36% due to decreasing birth rates and associated reductions in pregnancy in countries with large populations such as China, India and Indonesia.

Total non-CO$_2$ emissions from agricultural activities in 128 countries covering 89% of the global population reached 4.62 (4.27–6.26)



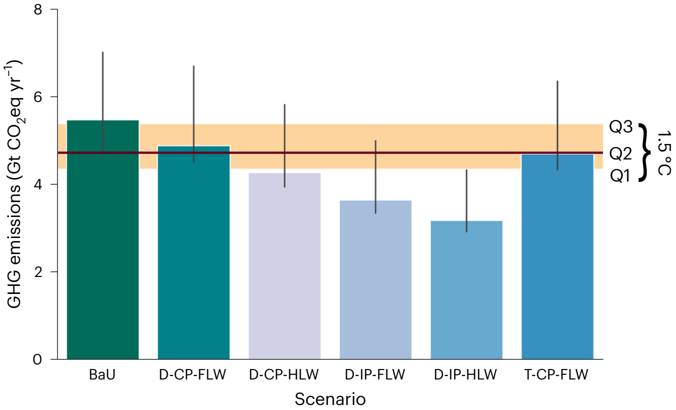


Fig. 2 | Total emissions from closing the nutrient gap against the allowable non-CO_2 emissions for food production in 2030 compatible with the Paris Agreement. Bars show the total emissions for 128 countries, that is, $n = 128$, with the top of the bar corresponding to the mode as the default measure of central tendency. Results are provided across five scenarios (Table 1) and current supply patterns extrapolated to 2030 populations (BaU). Hence, the nutrient gap persists under BaU. Error bars show the 25th and 75th percentiles and are negatively skewed (see Uncertainty estimates). The orange-shaded area represents the spread of allowable non-CO_2 emissions for food production in 2030 (25th percentile (Q1): 4.33 Gt CO_2eq yr^{-1} and 75th percentile (Q3): 5.31 Gt CO_2eq yr^{-1}). The solid red line represents the median (Q2) (4.67 Gt CO_2eq yr^{-1}). Allowable emissions are calculated based on an ensemble of models[32,77] as described in section Paris Agreement and allowable food production emissions. The values shown here are scaled based on the scope of emission sources and total population covered in this study. See Source Data Fig. 2 for full results.

Gt CO_2eq yr^{-1} in 2013–2015 (Fig. 2). This represents ~77% of total AFOLU emissions, including CO_2 emissions from drained organic soils, forest-land and net forest conversion, in 229 countries. Assuming constant production-based emissions per capita and nutrient adequacy (that is, nutrient supply/population-level requirements) into the future (business-as-usual scenario; BaU) would result in 5.48 (4.76–7.02) Gt CO_2eq yr^{-1} in 2030, exceeding 75th percentile of the allowable emission estimates compatible with the Paris Agreement. However, between-country differences in emissions intensity of nutrient production were as high as 200-fold for ruminant products such as cow's milk (Source Data Fig. 1). Such heterogeneity in emissions intensity of production determined the effectiveness of productivity and trade scenarios.

Climate-friendly and nutritionally targeted increases in production closed the nutrient gap with lower emissions compared with the BaU for 2030 (Fig. 2). Under current productivity and loss and waste patterns (D-CP-FLW), emissions decreased by 11%, compared with the BaU, to 4.89 (4.52–6.70) Gt CO_2eq yr^{-1} (Fig. 2). Closing the nutrient gap under the half loss and waste scenario (D-CP-HLW) resulted in a 22% reduction (compared with BaU) in emissions, with 4.28 (3.95–5.83) Gt CO_2eq yr^{-1}. Closing the crop yield gap increased baseline crop emissions by 6% due to increased fertilizer use, while enhancing livestock productivity decreased baseline livestock emissions by 28%. Overall, improving agricultural productivity (D-IP-FLW) reduced the emissions associated with closing the nutrient gap by 33% to 3.65 (3.35–5.00) Gt CO_2eq yr^{-1}.

When we combined half loss and waste with improved productivity (D-IP-HLW), the reduction in emissions was up to 42%, with 3.19 (2.93–4.34) Gt CO_2eq yr^{-1} for 2030. Finally, closing the nutrient gap through increased imports of climate-friendly products (T-CP-FLW) showed a 14% decrease in the emissions, resulting in 4.70 (4.34–6.36) Gt CO_2eq yr^{-1}. Our findings under the domestic production (D-CP-FLW) and trade (T-CP-FLW) scenarios were similar because optimal food products were mostly plant-based sources, which had much smaller between-country differences in emissions intensity compared with livestock products. Overall, when compared against the allowable non-CO_2 emissions for food production by 2030, closing the nutrient gap through improved productivity and half loss and waste scenarios (D-CP-HLW, D-IP-FLW and D-IP-HLW) helped keep median food system emissions below the 25th percentile of the allowable emissions compatible with the Paris Agreement.

Relative performance of climate-friendly scenarios varied slightly by national income level (Fig. 3). Owing to substantial differences in the nutrient gap, low- and lower-middle-income groups required higher production increases and together accounted for more than 80% of additional emissions. Halving food loss and waste (D-CP-HLW) and improved productivity (D-IP-FLW) mitigated emissions to a larger extent in the low-income group compared with other income groups. With current productivity and loss and waste patterns, increasing imports (T-CP-FLW) showed 13% and 6% lower emissions compared with increasing domestic production (D-CP-FLW) in the low- and lower-middle-income groups, respectively. On the other hand, emissions were similar under domestic production and trade scenarios in high- and upper-middle-income groups, which can be explained by the observation that they are the major trade partners exporting to low- and lower-middle-income groups.

Climate-friendly and nutrition-sensitive supply patterns

Of the individual nutrients lacking the most in national food supplies, vegetables (for example, carrots, spinach and tomatoes) and milk are major sources of vitamin A in several low-/lower-middle-income countries of Central, Southeastern and Southern Asia, while sweet potatoes have a larger contribution in sub-Saharan Africa. For vitamin B12, for which animal products are the only food sources, milk and seafood (particularly marine-sourced fish) are the major sources. Closing the nutrient gap without an optimization approach, that is, simply increasing total production altogether, would require doubling the global production because cereals dominate existing supply baskets (Fig. 5), and those rich in missing nutrients are underrepresented food groups such as vegetables.

Minimizing GHG emissions while closing the nutrient gap resulted in different food supply priorities at the country level, depending on which nutrients were lacking and specific scenario assumptions. Under all domestic-production-based scenarios, vegetables and vitamin-A-rich roots and tubers (for example, sweet potatoes, yams and cassava) were among the optimal food options that required the largest production increases (in caloric terms). Higher dominance of plant-based products in the optimal baskets of high-income countries (Fig. 4) was a result of an abundance of animal products in their food supplies, meaning that any vitamin B12 gap was effectively very small. In contrast, non-ruminant (for example, duck, rabbit and chicken) meat also featured in optimal solutions across low-, lower-middle- and upper-middle-income groups.

In the trade scenario (T-CP-FLW), vegetables and other crops such as fruits replaced roots and tubers, and required the largest increases in a greater number of countries. This is because exporting countries in the optimal solution space were often higher-income countries with temperate climates whose production baskets did not include vitamin-A-rich roots and tubers that their partners needed, such as sweet potatoes, in their production and/or trade baskets. Therefore, other sources of such nutrients replaced roots and tubers. Additionally, non-ruminant meat, for example, chicken meat, replaced eggs in several low- and lower-middle-income countries because their exporting countries have more industrial livestock systems with much lower emissions intensities (Source Data Fig. 1).

Between 10% and 23% increase in global caloric production sufficed to close the world's nutrient gap in 2030 with optimized supply patterns. Under domestic production scenarios, optimal production baskets involved up to 260% and 200% increases in global production

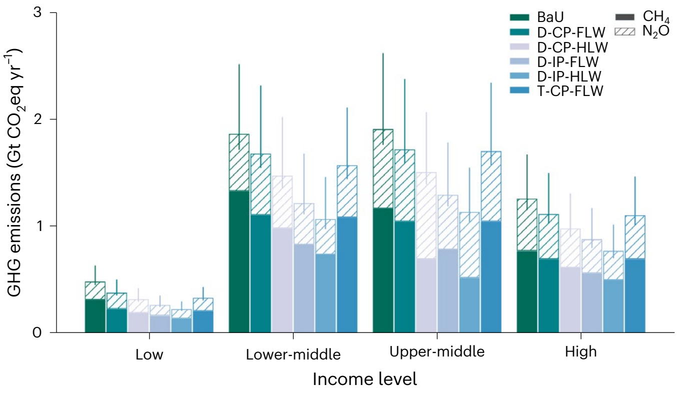


Fig. 3 | Breakdown of emissions by individual GHGs arising from closing the nutrient gap. Bars show the total emissions for 128 countries based on default emissions factors, with the top of the bar corresponding to the mode as the default measure of central tendency. Results are provided by income level and across five climate-friendly scenarios and current supply patterns extrapolated to 2030 populations (BaU). Higher shares of livestock products in their food supply baskets result in larger contributions by CH_4 to total GHG emission in the upper-middle- and high-income countries. Error bars show 25th and 75th percentiles for total GHG emissions. See Source Data Fig. 2 for full results. See Extended Data Fig. 1a for CH_4 emissions (Mt CH_4 yr^{-1}) and Extended Data Fig. 1b for N_2O emissions (Mt N_2O yr^{-1}).

of roots and tubers, and eggs, respectively (Fig. 5). Global vegetable production needed to increase by up to 116% under those scenarios. The largest production increase was observed for vegetables, by 48%, when countries resorted to increasing their imports (T-CP-FLW). Additionally, global production of non-ruminant meat showed a 37% increase under the trade scenario. Overall, all scenarios suggest some reduction (up to 17%) in the share of cereals in the global food basket.

At the country level, optimal food baskets entail production increases, which may be infeasible due to resource limitations. In these cases, it is more realistic to increase both production and imports. As vegetables and roots and tubers include several different individual products with distinct nutritional profiles, compositional change in national production baskets of these food groups can also reduce the need for large-scale increases. For instance, when the proportion of sweet potatoes, a source of vitamin A, is small compared with that of white potatoes, a high supply increase is needed to close the nutrient gap. In contrast, having a larger share of sweet potatoes would require smaller increases in the supply of roots and tubers.

Optimal food supply patterns revealed here help to explain why the climate mitigation potential of trade, compared with domestic production, was higher in the low- and lower-middle-income groups. This occurs because their trade partners included high-income countries where livestock emissions intensity is already much lower. Lastly, halving food loss and waste also performed better in the low-income group because products featuring in the optimal solutions, such as roots and tubers, vegetables and eggs, are subject to higher on-farm and post-harvest (including storage, distribution and processing/packaging) losses in those countries.

Intervention strategies and policy implications

Food loss and waste occur across food supply chains and current research emphasizes customized mitigation approaches[33,34]. Preventing household waste of vegetables and fruits could be a priority in high-income countries where vitamin A is the most commonly lacking nutrient. Even though the emissions intensity per unit of nutrient production from livestock is often lower in developed countries (for example, New Zealand, the United States and France; Fig. 1), high production volume means that absolute levels are still substantial. Therefore, addressing household waste of animal products could also reduce the emissions associated with the nutrient gap closure in their trade partners. In this regard, several low-cost interventions such as smaller portion sizes and encouraging consumers to keep a diary of their waste can be effective[34].

Targeting pre-/post-harvest (including processing and distribution) losses in fruits, vegetables, and roots and tubers could be prioritized in low/lower-middle-income countries. Similarly, low-cost and low-energy cold-chain solutions (for example, evaporative coolers) and improved preservation methods for animal products could offer remarkable contribution to closing the vitamin B12 gap. This would require investment in infrastructure, innovation, machinery, packaging and storage, as well as multi-stakeholder cooperation for awareness raising and the transfer of technology and knowledge[35]. Food shortages, extreme weather events and supply chain disruptions can force farmers to harvest too early or too late, leading to food losses. Hence, other effective measures include establishing standards, price guarantees for farmers, market information systems and public procurement schemes[33,36]. Finally, such preventative measures can be combined with end-of-pipe solutions such as redistribution and donation of surplus from retail outlets and farms via appropriate regulations and financial incentives[33,36].

In countries with unattained potential yields, smallholder farmers may benefit from higher input use to increase yields[37,38]. Farm diversification and integrating animals (fish and livestock) into crop production creates by-product circularity so that crop residues are used as animal feed, while animal manure is used as fertilizer[38]. This would also promote diversification of farmers' incomes and avoid inflated feed costs while closing vitamin A and B12 gaps. For vegetables, access to markets and high-quality seeds are important in boosting productivity, as resource-constrained smallholders account for more than half of the global vegetable production[38,39]. Biofortification programmes may also be effective to enhance nutrient supplies from primary production[9,40]. Since the Green Revolution, staples have received most agricultural subsidies, private sector investment and agricultural research focus[41,42], promoting substantial yield growth in major energy, protein and fat sources (for example, cereals and oilseeds)[43]. This resulted in a disconnect between the emerging challenges of malnutrition and food policies[41]. For long-term impacts, investment in infrastructure, innovation, capacity building, and research and development is needed.

Reducing emissions from livestock production has a substantial mitigation potential because animal products are essential to close the vitamin B12 gap. Improved livestock management by means of better feeding practices (for example, improving feed digestibility through lipid supplementation) and veterinary services, improved forage and grassland management, community-based rangeland management, modifying the proportion of the herd dedicated for reproduction, and younger age at first calving are among the least-cost interventions available[44,45]. Access to low interest loans may facilitate such investment, but land tenure and other supporting public policies need to be secured for them to be beneficial for smallholders[46]. Nevertheless, sustainable livestock production in low-income countries needs more research that considers specific local/regional agri-environmental contexts[15,45]. Extension and support services, production safety net programmes, tenure security, access to markets and affordable loans, and insurance programmes are all promising instruments to attain nutrition-sensitive and sustainable food systems[40,46].

Market forces have the potential to promote the best use of food-related resources if policies are tailored accordingly[47]. Currently, international food trade improves nutrient availability to a much lesser extent in low- and lower-middle-income countries with inadequate production[7]. Compounding this issue, emissions intensity of nutrient production is much higher in most of these countries due to low productivity (Fig. 1). Hence, current trade patterns are not optimal for either nutrition security or climate mitigation. Additionally, resource limitations, coupled with climate change, make several

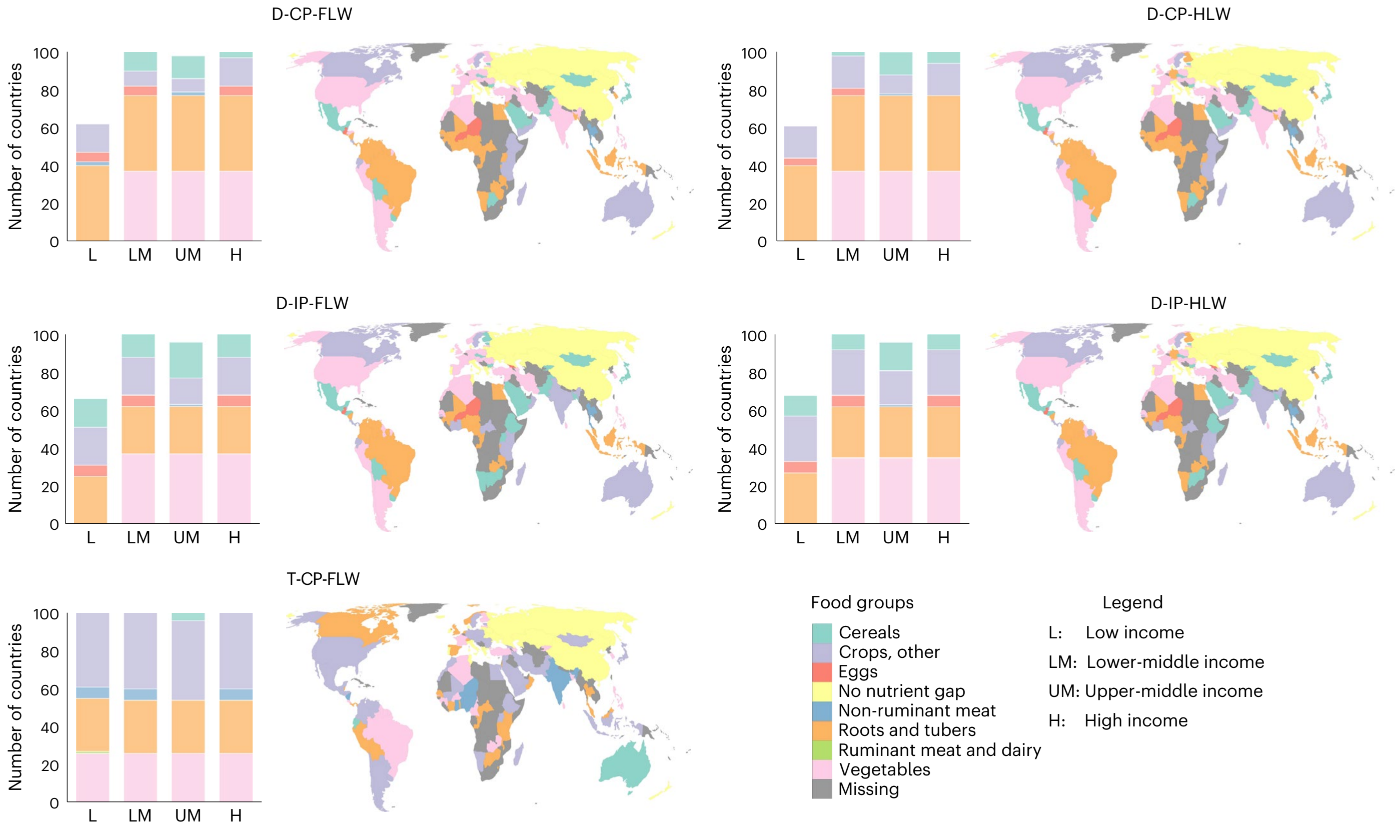


Fig. 4 | Optimal food options to close the nutrient gap with the lowest emissions. For food group compositions, please see Extended Data Table 3. The world map is coloured based on the food groups that require the largest additional supply, either domestically produced or imported, to close the nutrient gap with the lowest emissions. Grey-coloured countries are not included in the analysis. Bar graphs show the total number of countries that have the respective food group in their optimal solution, grouped by their income level. For example, under the first scenario (D-CP-FLW) and in the low-income group, there are 40 countries with roots and tubers in their optimal production baskets, while 5 countries have eggs. See Source Data Fig. 3 for full results and Table 1 for scenario descriptions. Maps were drawn using the tmap R package[79].

low-income countries increasingly dependent on imports[48]. Therefore, promoting trade between countries with production surpluses and lower emissions intensities and countries with production deficits and higher emissions intensity could help close nutrient gaps at lower emissions. Average tariffs applied on dairy, meat and seafood—high in most low-income countries[7]—could be selectively lowered to close vitamin B12 gaps[49]. In addition, internalizing the emissions of food (for example, border tax adjustments and climate measures in regional trade agreements) could facilitate trade patterns where nutrients flow from countries with lower emissions intensities to those with higher emissions intensities[29]. This would reverse the situation where less than half of the flows occurred from countries with lower emissions intensity to those with higher intensity, rendering the global nutrient trade ineffective as a mitigation mechanism[50].

Discussion

There is growing consensus on the importance of food systems transformation, involving production- and consumption-based interventions, to tackle climate change and malnutrition simultaneously[1,18]. Targeted metrics, underpinned by comprehensive datasets and rigorous modelling, are crucial for effective policies[16,51]. Here, we developed a multi-dimensional, high-product resolution, country-level dataset that combines dietary nutrient requirements, production, trade and resulting non-CO_2 GHG emissions. With an optimization model, we evaluated the minimum emissions associated with closing the nutrient gap (for energy and six nutrients) across five climate-friendly intervention scenarios, 196 agri-food products and 128 countries. In contrast to wholesale dietary changes, a common approach in the literature[8,31], we identified country-specific priority food sources that close the nutrient gap with the lowest emissions.

Interventions to address inefficiencies at home, for example, reducing loss and waste and livestock emissions, had a higher potential to mitigate the emissions compared with importing from the least emissions-intensive partner. Moreover, when emissions from transportation are incorporated, which may be up to 3 Gt CO_2 yr^{-1} globally[52], closing the nutrient gap via trade may offer lower mitigation potentials. Our results indicate that halving food loss and waste and improving agricultural productivity together can reduce the emissions by up to 42% while closing the nutrient gap at the same time. At-home interventions are also likely to be pro-poor because, otherwise, import substitution may harm producers in the lower-income countries[18].

In terms of food sources, our high-product resolution, as opposed to the oft-cited[8] aggregate food balance sheets, offers a more nuanced evaluation of not only the nutrient gap but also priority food sources by country. Increasing production of vegetables, roots and tubers, and non-ruminant meat would help close the world's nutrient gap with the smallest emissions and result in 10–23% increase in global caloric production by 2030. This translates into a reduction in the share of cereals in food production/supply baskets, as is also suggested in the literature[8,18,31,39,53]. Our findings confirm the importance of addressing losses in and productivity of vegetable and fruit production[13,18,54].

Our model assumes that any increase in production is associated with an increase in total factor productivity and excludes emissions from land-use change due to a lack of high-resolution

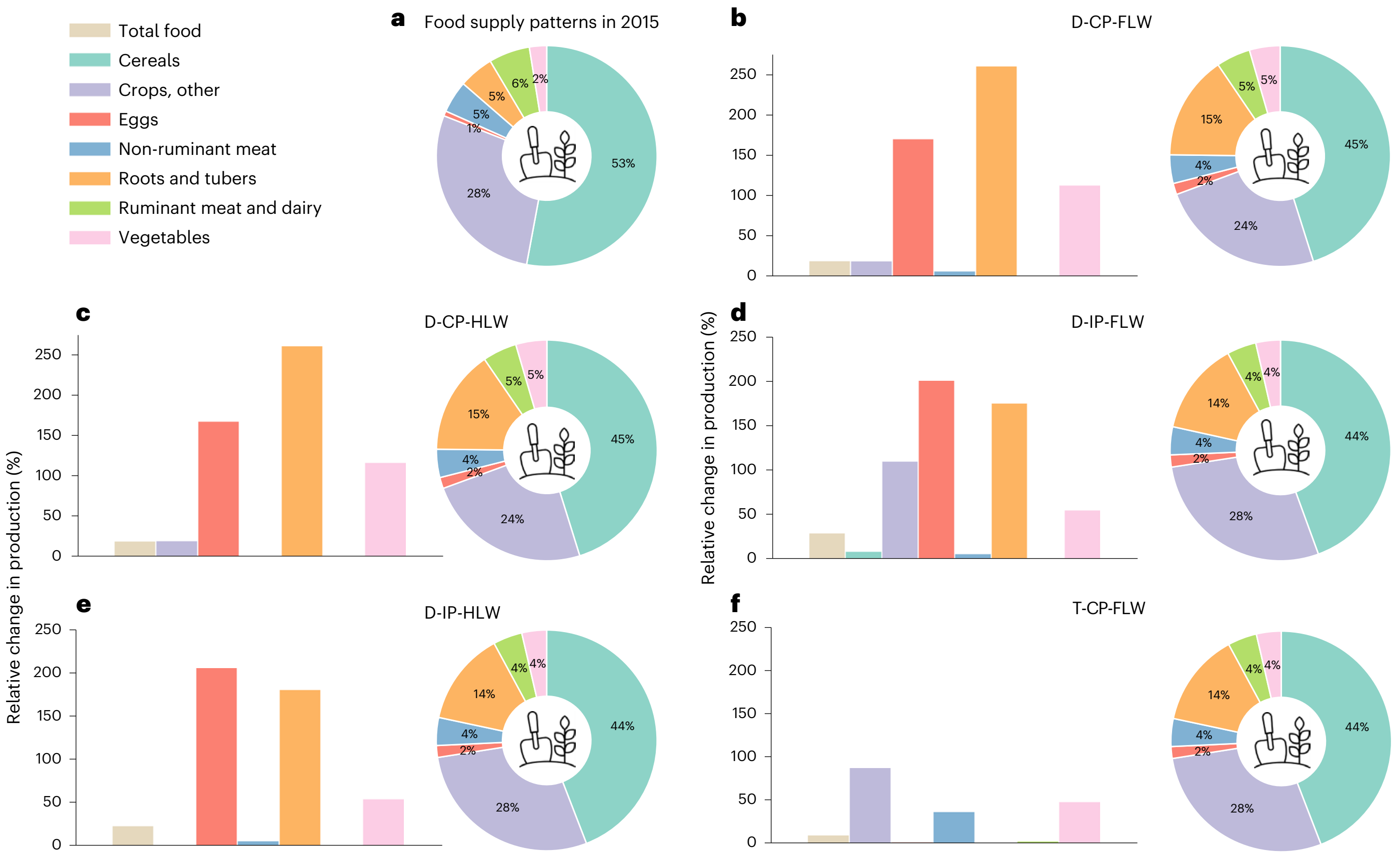


Fig. 5 | Agricultural production increase for closing the global nutrient gap in 2030 under five scenarios. a–f, The percentage change is compared to baseline production levels in 2015 (**a**). Bar graphs show that global production of eggs, vegetables, and roots and tubers needed to increase by more than 100% under domestic-production-based scenarios (**b**–**e**), while the increase is between 10% and 23% for total calorie production from all food sources (including oilseeds and sugar crops in 2015) combined. Pie charts illustrate the relative contribution of each food group to global calorie production in 2015 (**a**) and under five climate-friendly scenarios (**b**–**f**). See Table 1 for scenario descriptions. Tool and crop icons from Flaticon.com.

commodity-specific datasets that allow prospective mapping of different products with cropland and pasture change and associated changes in biomass—as is common practice in dynamic modelling approaches[19,31]. Hence, the consequent emissions are potentially underestimated, particularly in regions nearing attainable yields. Nevertheless, abandoned farmland could also be re-cultivated in regions such as North America, Europe, Eastern and Central Asia, and Oceania. Our results can also be integrated with crop models to map where climate- and nutrition-sensitive cropping patterns are suitable.

Our model can be extended to include other environmental and nutritional constraints[14–16]. Given our focus on the double burden of malnutrition, that is, undernutrition and micronutrient deficiencies, we neither set an upper limit on nor aimed to reduce calories to address overconsumption. However, we excluded energy-rich and micronutrient-poor sources, based on the way they are currently consumed, for example, sugar and oilseed crops, from optimization input because we aimed to address the double burden of malnutrition simultaneously and such food sources tend to encourage caloric overconsumption. This is similar to the ‘no sugar’ scenario in the literature[8]. Consequently, the required increase in global caloric production was between 10% and 23% due to selection of nutrient-rich foods such as vegetables by the optimization model. On the other hand, tackling overconsumption, particularly of animal products, in higher-income countries is paramount to address the global syndemic[1,8,31,55], with a caveat for low-income countries where undernutrition and micronutrient deficiencies necessitate increased consumption of animal products[21,31]. Lastly, our scope is limited to availability, one of the four pillars (that is, availability, accessibility, utilization and stability) of nutrition security, and that adequate supply does not necessarily equate to adequate intake[8]. Nonetheless, without adequate supply, equal distribution alone does not suffice, with the caveat that complementary measures, for example, fortification, are also important to enhance nutrient supplies, such as iron and vitamin A, particularly from cereals and vegetable oils.

Climate change creates further challenges for nutrient availability and economic access to nutritious food, especially in low-income countries[55]. Economic responses and potential shifts in price, supply, demand and access should therefore be considered for integrated policies. For instance, productivity gains are found to encourage land expansion in non-food sectors[18], which necessitates complementary instruments such as taxation[18,44]. Despite the limitations regarding rebound effects in static models like ours, value-based economic models lack other dimensions such as biophysical limits and preservation of mass and energy balances[56]. By incorporating livestock production and crop models, our scenarios can directly inform the sustainable food systems debate. For instance, given the urgency of the global syndemic and the difficulties in achieving large-scale dietary shifts, which food supplies need to be scaled up to contribute to the food system transformation?

Without imposing drastic changes in the current food baskets (and hence, diets), increasing production of less emissions-intensive products that provide the set of nutrients lacking in the national supplies could close nutrient gaps and achieve substantial climate mitigation. This implies a different picture compared with that suggested by most global food demand models. While the literature suggests up to 30% increase in income-driven total food (calories) demand between 2010 and 2030[17], we offer an approach based on physiological needs[47]. Our findings suggest that less than 24% production increase from 2015 would suffice in closing the world's nutrient gap by 2030, with 42% less GHG emissions compared with the BaU scenario, in which the nutrient gap remains.

Methods

Dietary nutrient production, supply and gap

Many countries do not produce and/or import enough nutrients to meet the recommended nutrient intake, an estimation of daily intake needed to provide the requirements of 97.5% of healthy individuals in a population group differentiated by age and sex, for their populations[7]. We obtained the dataset for country-level total nutrient production, trade, and supply from ref. [7] and methodology to estimate population-level nutrient requirements from ref. [57]. These cover nutrient supply (energy, protein, iron, zinc, vitamin A, folate and vitamin B12) from crops, livestock and seafood. Nutrient supply estimates account for the share of crops that are fed to animals (see ref. [57] for more details). For better representation of nutrient supplies, we converted oilseeds into vegetable oils based on the share of oilseeds processed over their national supply by respective product (Extended Data Table 4). Finally, we subtracted the share of non-food uses, by using food balance sheets[58], due to the use of large volumes of oilseeds and their oil derivatives (for example, linseed, soybean oil and rapeseed oil) for fuel purposes (that is, biodiesel).

We estimated future population-level nutrient requirements based on median variant population forecasts for 2030[12] and following an established nutrient adequacy approach that compares country-level nutrient supplies against age- and sex-adjusted requirements[57]. Because the requirements for zinc and iron almost double for zinc and quadruple for iron during pregnancy, lower fertility rates decreased the aggregate requirements for these nutrients.

The difference between nutrient supplies (that is, supply = domestic production + net trade − food loss and waste) and requirements provided country-level supply gaps for each nutrient, as shown in equation (1). We quantified the nutrient supply in 2015 under current food loss and waste patterns (that is, FLW) using regional and food group specific loss and waste rates provided by ref. [59] where p represent nutrients, a represents countries and c represents food products (C being the total number of food products). In equation (1), nutrient production, that is, $\mathrm{NP}^{p}_{a,c}$, refers to the weight before farm losses minus exports, which we adjusted by adding on values reported as excluding harvesting losses by the Food and Agriculture Organization of the United Nations (FAOSTAT).

$$
\begin{aligned}
&\text{Nutrient gap}^{p}_{a} = \text{Population requirements}^{p}_{a} - \text{Nutrient supply}^{p}_{a}\\
&\text{where}\\
&\text{Nutrient supply}^{p}_{a} = \textstyle\sum_{c=1}^{C}\Big[\mathrm{NP}^{p}_{a,c} \times \mathrm{LW}^{\mathrm{FL}}_{a,c} \times \mathrm{LW}^{\mathrm{PHL}}_{a,c} \times \mathrm{LW}^{\mathrm{PPL}}_{a,c} \times \mathrm{LW}^{\mathrm{DL}}_{a,c} \times \mathrm{LW}^{\mathrm{HW}}_{a,c}\\
&- \text{Exports}^{p}_{a,c} \times \mathrm{LW}^{\mathrm{PHL}}_{a,c} \times \mathrm{LW}^{\mathrm{PPL}}_{a,c}\\
&+ \text{Imports}^{p}_{a,c} \times \mathrm{LW}^{\mathrm{DL}}_{a,c} \times \mathrm{LW}^{\mathrm{HW}}_{a,c}\Big]
\end{aligned}
\qquad (1)
$$

Equation (1) considers the five different types of loss and waste (LW) as proportional values. For example, if farm loss is 5% of the production, then the LW for farm loss, $\mathrm{LW}^{\mathrm{FL}}_{a,c}$, becomes 0.95. Types of loss and waste include: farm loss (FL), post-harvest loss (PHL), processing and packaging loss (PPL), distribution loss (DL) and household waste (HW). We assumed constant supply, hence supply gaps, for each scenario. Consequently, the emissions associated with closing the nutrient gap varied by (1) how much production increase is needed to meet these gaps and/or (2) emissions intensity of production.

GHG emissions components

We developed a composite indicator to quantify farm-gate non-CO_2 emissions intensity of national agricultural production to be used as input for optimization (equation (5)). Ref. [60] provides a comprehensive dataset of life cycle emissions for 188 commodities from 119 countries. However, most crops (excluding maize) and livestock products in that dataset originate from major producing countries, which does not allow reveal differences across countries from different income levels. Therefore, we chose to use process-based emissions estimates following the IPCC (2006)[28] Tier I approach and account for the heterogeneity in emissions factors across different agro-ecological regions.

We obtained the data from FAOSTAT database (2020 revision)[61]. FAOSTAT emissions estimates follow the Tier I approach of the IPCC guidelines for national GHG inventories[28]. We focused on non-CO_2 GHG emissions from agriculture, excluding emissions from land-use change (for example, forest conversion to cropland/grassland) due to the lack of product-specific attribution that would allow us to link production growth (for example, increase in vegetable production) with corresponding land-use change. In contrast, emissions from crop residues and fertilizer use are directly attributable to source products.

We included 128 countries (Extended Data Table 1) with comparable data for production, product-level bilateral trade and GHG emissions. We used the average GHG emissions values for the 2013–2015 period to smooth out yearly fluctuations[61]. We used the most widely used metric, 100-year global warming potential (GWP100), from the IPCC Sixth Assessment Report (AR6) in our calculations (CH_4-non-fossil origin: 27; N_2O: 273)[62].

Our emissions scope covered rice cultivation (CH_4 from decomposition of organic matter in paddy fields), synthetic fertilizers (direct emissions of N_2O from nitrification and de-nitrification, and indirect emissions from volatilization/re-deposition and leaching processes), crop residues (N_2O from decomposition of residue left on soils), burning crop residues (CH_4 and N_2O from the combustion of crop residues), enteric fermentation (CH_4 from rumination in the digestive track), manure management (CH_4 and N_2O from manure decomposition), manure applied to soils (direct emissions of N_2O from nitrification and de-nitrification, indirect emissions from volatilization/re-deposition and leaching processes from manure applied to cropland) and manure left on pasture (direct emissions of N_2O from nitrification and de-nitrification, and indirect emissions from volatilization/re-deposition and leaching processes from manure left on pasture by grazing animals)[61]. Manure applied to soils is regarded as organic fertilizer and allocated to emissions from crop production.

Although recent assessments show that the share of total global food system emissions related to energy use is growing[3,63], we excluded emissions from energy use in this study because product-specific global data were lacking. Interventions to mitigate emissions from energy use are similar to other economic sectors like industry and transport such that their emissions intensities are primarily determined by energy mix, which can be decarbonized via increasing the amount of renewable energy and technological innovation such as the electrification of transport.

Crops

Crop emissions cover the non-feed portion used for direct human consumption and are differentiated by product and country. The share of crops fed to livestock was obtained from food balance sheets of the FAOSTAT (see ref. [57] for more details). We also subtracted the quantity of crops used as feed in aquaculture (that is, aquafeed). As not all aquaculture is fed, we used several different sources to ensure reliable and comprehensive emissions accounting. Ref. [64] provides the share of aquaculture that is fed for 11 fish species: carps, tilapia, shrimp, catfishes, marine fish, salmon, freshwater crustaceans, other diadromous fishes, milkfish, trout and eel. The study also provides data on the share of fish sources (fishmeal and fish oil) in their compound feeds in addition to fish-in-fish-out ratios. Based on this information, we calculated the share coming from non-fish sources because we are interested in GHG emissions from growing crops used as feed. Ref. [65] estimated the share of individual crop sources (maize, soybeans, wheat, pulses and other oil crops) in aquafeed at the regional level. However, aquafeed does not entirely consist of these plant sources. To correct for this, we combined ratios[65] of this regional crop-based feed with the share of plant sources in aquafeed[64]. Extended Data Table 8 shows the consequent aquafeed use ratios for products from maize, soybeans, wheat, pulses and other oil crops for fed aquaculture.

Finally, we estimated the primary crop equivalent of aquafeed sources from soybeans and other oil crops often used as by-products (for example, flour and oil cake) in aquafeed[66]. Extended Data Table 9 shows the conversion factors that are used in these calculations[67]. We used the weighted average of top producers (whose cumulative production accounts for ≥80% of global production). We assumed that other aquafeed uses of oil crops were largely rapeseed and sunflower seed. Consequently, we derived aquafeed-to-supply ratios per crop and country ($\beta_{c,a}$), which we used in estimating the nutrient gap.

Total GHG emissions from crop residues ($\mathrm{GHG}_{s,a,c}^{\text{Crop residues}}$), burning crop residues ($\mathrm{GHG}_{s,a,c}^{\text{Crop residues, burning}}$) and rice cultivation ($\mathrm{GHG}_{s,a,c}^{\text{Paddy rice}}$) were calculated for each crop product (c), country (a) and intervention scenario (s). We attributed emissions from synthetic ($\mathrm{GHG}_{s,a,c}^{\text{Synthetic fertilizer}}$) and organic ($\mathrm{GHG}_{s,a,c}^{\text{Organic fertilizer}}$) fertilizers to respective food sources based on data on fertilizer use by crops[68] as detailed in Extended Data Table 2. Country-level total crop emissions were calculated as per equation (2) where $\theta_{c,a}$ represents livestock feed-to-supply ratio for a given country and product (calculated based on food balance sheets[58] and $\beta_{c,a}$ shows aquafeed (that is, feed for aquaculture)-to-supply ratio (see Extended Data Table 7) for a given country and product[64,65]. The ratio of crops that are not diverted to livestock or aquaculture is given by γ.

$$\begin{aligned}
\mathrm{GHG}_{s,a}^{\text{Crops}} &= \textstyle\sum_{c=1}^{C} \mathrm{GHG}_{s,a,c} \text{ and} \\
\mathrm{GHG}_{s,a,c} &= \gamma_{c,a} \times \Big(\mathrm{GHG}_{s,a,c}^{\text{Crop residues}} \\
&\quad + \mathrm{GHG}_{s,a,c}^{\text{Crop residues, burning}} \\
&\quad + \mathrm{GHG}_{s,a,c}^{\text{Synthetic fertilizer}} \\
&\quad + \mathrm{GHG}_{s,a,c}^{\text{Organic fertilizer}} \\
&\quad + \mathrm{GHG}_{s,a,c}^{\text{Paddy rice}}\Big) \\
\text{where } \gamma_{c,a} &= 1 - (\theta_{c,a} + \beta_{c,a})
\end{aligned} \tag{2}$$

Livestock

Livestock emissions included those from enteric fermentation ($\mathrm{GHG}_{s,a,c}^{\text{Enteric fermentation}}$), manure management $\left(\mathrm{GHG}_{s,a,c}^{\text{Manure management}}\right)$ manure left on pasture $\left(\mathrm{GHG}_{s,a,c}^{\text{Manure left on pasture}}\right)$, fertilizers applied to grassland ($\mathrm{GHG}_{s,a,c}^{\text{Synthetic fertilizer}}$ and $\mathrm{GHG}_{s,a,c}^{\text{Organic fertilizer}}$) and feed crops ($\theta_{c,a} \times \mathrm{GHG}_{s,a,c}^{\text{Crops}}$) that are grown domestically (see Extended Data Table 6 for feed crop consumption by livestock group). We allocated the emissions from crops fed to livestock (that is, share of crops used as livestock and poultry feed according to food balance sheets of the FAOSTAT (see ref. [57]) from crop emissions to the respective livestock type based on the relative amount of food crops estimated to be consumed by ruminants, pigs and poultry[69] (consumption share by animal given in Extended Data Table 5). Fertilizer use by crops (Extended Data Table 2)[68] also includes fertilizers applied to grassland. Hence, we linked the relevant share of emissions from synthetic ($\mathrm{GHG}_{s,a,c}^{\text{Synthetic fertilizer}}$) fertilizers to respective animals based on the share of grass-fed animals by animal type, for example, ruminants, pigs and poultry[69]. Total country-level livestock emissions were calculated as per equation (3) for each livestock product (c), country (a) and intervention scenario (s):

$$\begin{aligned}
\mathrm{GHG}_{s,a}^{\text{Livestock}} &= \textstyle\sum_{c=1}^{C} \mathrm{GHG}_{s,a,c}, \\
\mathrm{GHG}_{s,a,c} &= \mathrm{GHG}_{s,a,c}^{\text{Enteric fermentation}} \\
&\quad + \mathrm{GHG}_{s,a,c}^{\text{Manure management}} \\
&\quad + \mathrm{GHG}_{s,a,c}^{\text{Manure left on pasture}} \\
&\quad + \mathrm{GHG}_{s,a,c}^{\text{Synthetic fertilizer}} \\
&\quad + \theta_{c,a} \times \mathrm{GHG}_{s,a,c}^{\text{Crops}}
\end{aligned} \tag{3}$$

Emissions intensity of nutrient production

Emissions intensity of nutrient production, for visualization purposes in Fig. 1, is calculated by simply dividing total GHG emissions ($\mathrm{GHG}_{s,a,c}$) by individual nutrient (for example, protein) production (see Dietary nutrient production, supply and gap). In order to construct our optimization model, we calculated GHG emissions intensity (that is, $I_{s,a,c}^{p=\text{energy}}$) of unit caloric availability (that is, domestic production minus food loss and waste[59]):

$$I_{s,a,c}^{p=\text{energy}} = \mathrm{GHG}_{s,a,c} / \text{Nutrient availability}_{s,a,c}^{p=\text{energy}} \tag{4}$$

Scenario description

We introduced five climate-friendly intervention scenarios related to crop and livestock productivity, food loss and waste, and trade. Based on the assumptions imposed by each scenario, emissions intensity of energy availability (represented by $I_{s,a,c}^{p=\text{energy}}$) changed and we calculated the agricultural production required to meet or exceed population-level requirements for energy, protein, iron, zinc, vitamin A, vitamin B12 and folate (see Dietary nutrient production, supply and gap) with the minimum emissions accordingly.

Current food loss and waste and productivity patterns

Under the current food loss and waste and productivity patterns (D-CP-FLW), emissions intensity ($I_{s,a,c}^{p=\text{energy}}$ where s = D-CP-FLW) was calculated based on current emissions, $\mathrm{GHG}_{s,a,c}$, and 2015 productivity patterns.

Halving food loss and waste

Losses arise before and after harvest, and during processing, packaging and distribution, while waste occurs at the household and retail level. Because there is no systematic evaluation of the extent of abatable food loss and waste in different regions (as there is for productivity), we assumed a 50% reduction in the half loss and waste scenario (HLW) in line with SDG 12 Target 12.3, which aims to halve food waste at retail and consumer levels[70]. For sugar crops, we assumed the same loss and waste rate as oil crops and pulses.

Depending on the stage at which loss/waste occurred as per the description in ref. [59], nutrient supply was calculated by halving loss and waste rates (equation (1)). As a result, for example, if farm loss is originally 5%, halving farm loss would result in $\mathrm{LW}_{a,c}^{\mathrm{FL}} = 0.975$. Because we assumed constant nutrient supply and gaps, halving loss and waste resulted in a reduction of baseline emissions and additional emissions through lower emissions intensity of energy availability $\left(I_{s,a,c}^{p=\text{energy}}\right)$.

Improved productivity

Under current productivity patterns (CP), we assumed the current (2013–2015) emissions intensity of production (that is, nutrient content of a given product/production-based GHG emissions) for every country (a). For increased productivity scenarios (D-IP-FLW and D-IP-HLW), we followed slightly different approaches for crops and livestock. For crops, we considered yield gap closure. We used the Global Agro-Ecological Zones (GAEZv3) model outputs, which include spatially resolved estimates of potential yields for dozens of individual crops under specific agro-climatic, soil, terrain and management conditions[71]. To quantify yield gaps, we compared historical crop yields with potential yields under high-input use. We then estimated the additional nitrogen (N) fertilizer requirement to achieve these high-input yields estimated at the regional level[37]. We assumed that yield increases were achieved by the increased use of synthetic fertilizers only and estimated the resulting emissions. Potential yields and fertilizer requirements were estimated at the regional level and downscaled to derive country-level estimates (see Supplementary Tables 1 and 2). Quantification of fertilizer GHG emissions followed the Tier 1 approach[28], which assumes a default emissions factor of 0.01 kg N_2O–N (kg N)$^{-1}$.

For livestock productivity, we used potential mitigation in emissions intensities estimated by the Global Livestock Environmental Assessment Model (GLEAM)[44]. The model quantifies the environmental impacts of livestock production over its life cycle and draws on adaptation and mitigation scenarios for a more sustainable livestock sector. It provides the scope for mitigation in the livestock sector globally across five animal species and as case studies for five world regions that are applicable in the medium term (for example, up to two decades) (Extended Data Table 5). Beyond cattle, pigs and poultry covered by the GLEAM model, camelids are also a good source of nutrients in certain regions. They mostly occur in marginal lands of arid countries in Africa (for example, camels in North Africa and Sahelian countries), Asia (camels in West and Central Asia) and South America (alpacas and llamas in the Andean region), and are often kept for draught power. In this regard, any food product, such as milk and meat, provides additional income rather than being the main source of income for the farm. Hence, we did not treat them as regular farm animals and assumed no increase in their emissions intensity. The mitigation potentials were quantified based on constant output in the GLEAM model.

Feed quality and animal health and husbandry are critical factors for improving livestock productivity in low-/lower-middle-income countries[72]. We chose this approach to avoid imposing the same productivity patterns on developing countries as industrialized countries (that is, intensive production systems). The model also gives a breakdown of impacts from different intervention scenarios at the animal, herd, production unit and supply chain levels. These include optimized feed digestibility, animal health and mortality, genetics, grassland management, and manure management for ruminants and monogastrics, in addition to energy efficiency and anaerobic digestors for pig production[44]. We only considered interventions in feed quality (for example, digestibility), grazing management, manure management and reduced mortality. Feed conversion ratios are assumed to be constant and emissions from feed crops changed in accordance with crop-based emissions under the combined productivity scenarios.

The emissions intensity ($I^{p=\text{energy}}_{s,a,c}$, where s = D-IP-FLW) was calculated based on changes in crop- and livestock-related GHG emissions ($\text{GHG}_{s,a,c}$) and changes in crop production per unit emissions associated with crop yield gap closure.

Improved productivity and half food loss and waste

Under D-IP-HLW scenario, emissions intensity ($I^{p=\text{energy}}_{s,a,c}$, where s = D-IP-HLW) involved changes in crop- and livestock-related GHG emissions and lower production needs due to larger shares of production being available for consumption.

Domestic production versus imports

In contrast to the scenarios based on domestic production, the objective function included emissions intensity of production in the partners exporting to the given country a under T-CP-FLW. We constructed the objective function with the existing bilateral trade partnerships and baskets based on data provided by the FAO under the detailed trade matrix domain[73]. Any increase in the export volume of their trading partners was assumed to be met by corresponding increases in production. Hence, apparent consumption (for example, supply) in exporting countries remained unchanged. $I^{p=\text{energy}}_{s,a,c}$, where s = T-CP-FLW, was equal to $I^{p=\text{energy}}_{s,a,c}$, where s = D-CP-FLW, for all countries and products.

Optimization of food supply patterns to close the nutrient gap

We applied linear programming to identify the additional production (measured in caloric terms) required for a given country (a) and product (c) under a certain intervention scenario (s) to close the nutrient gap while minimizing food system non-CO_2 GHG emissions. The objective function minimized GHG emissions from additional production such that the supply of all nutrients was adequate to meet national dietary requirements based on the existing production and bilateral trade baskets for each country. Therefore, additional production refers to domestic production of a given country a under domestic-production-based scenarios (D-CP-FLW, D-CP-HLW, D-IP-FLW and D-IP-HLW). In contrast, under the trade scenario (T-CP-FLW), it refers to additional production in partners that country a imports from. Similarly, $I^{p=\text{energy}}_{s,a,c}$ represents domestic emissions intensity under domestic-production-based scenarios, whereas it represents the vector of emissions intensity in partners exporting to the given country a. Composition of production and trade baskets (that is, the number of individual products) remained the same, although relative contribution by food source changed, with the assumption that diets do not observe radical changes in their composition (for example, complete elimination of certain food groups from diets and introduction of novel food products that are absent from current food baskets).

$$\begin{aligned}
&\text{GHG}^{\text{Min}}_{s,a} = \\
&\text{minimize}\ :\ \textstyle\sum_{c=1}^{C} I^{p=\text{energy}}_{s,a,c} \times \Delta\text{NP}^{p=\text{energy}}_{s,a,c} \\
&\text{subject to the constraints}\ : \\
&\text{NER}^{p}_{s,a,c} \times \Delta\text{NP}^{p=\text{energy}}_{s,a,c} \geq \text{NG}^{p}_{a} \text{ for all nutrients } p \\
&\text{and} \\
&\Delta\text{NP}^{p=\text{energy}}_{s,a,c} \geq 0
\end{aligned} \tag{5}$$

where $\text{NP}^{p=\text{energy}}_{s,a,c}$ is the nutrient production of dietary energy (that is, calories). $I^{p=\text{energy}}_{s,a,c}$ was calculated as described in equation (4). $\text{NER}^{p}_{s,a,c}$ is the nutrient-to-energy ratio for each nutrient p (that is, energy, protein, iron, zinc, vitamin A, vitamin B12 and folate), each country a and food product c, and $\text{NER}^{p}_{s,a,c} = 1$ for p = energy. NG^{p}_{a} is the nutrient gap for each nutrient p and country a. The general form of equation (5) was applied to each country for every scenario. We used the HiGHS solver from the linprog package from the SciPy library of Python[74], which implements the interior-point method and features parallel programming.

Following equations (1)–(5), the emissions associated with closing the nutrient gap globally are the sum of baseline emissions in 2015 and additional emissions from the production increase required to close the nutrient gap (where A is the total number of countries):

$$\text{GHG}^{\text{Total}}_{s} = \textstyle\sum_{a=1}^{A} \text{GHG}^{\text{Crops}}_{s,a} + \sum_{a=1}^{A} \text{GHG}^{\text{Livestock}}_{s,a} + \sum_{a=1}^{A} \text{GHG}^{\text{Min}}_{s,a} \tag{6}$$

Uncertainty estimates

There are inherent uncertainties with our underlying data and approach. Uncertainty ranges are unknown for production/trade data that originate from FAOSTAT[75], but the Tier 1 approach to estimate GHG emissions have known uncertainty ranges related to default emissions factors[28]. Therefore, in addition to the default factors, we included lower and upper bounds for emissions factors used in the Tier 1 approach (that is, Emissions = Activity data × Emissions Factor) to estimate GHG emissions[28]. The IPCC (2006)[28] provides lower and upper bounds either as a percentage of deviation from the default value for some emissions sources (for example, enteric fermentation) or as an absolute value for others (for example, rice cultivation). Additionally, some emissions sources (for example, N_2O from managed soils) have direct and indirect emissions. In that case, there is also uncertainty associated with the fraction of leaching and volatilization. The IPCC methodology suggests leaching only in regions where runoff occurs. However, the FAOSTAT assumes that leaching occurs in all regions due to absence of region-specific information[61]. Our estimates encompass uncertainty associated with both factors and converted absolute values to percentage change for ease of calculation (for example, percent deviation from the default value). Specific emissions factor ranges for each emission source are presented in Extended Data Table 9.

To construct uncertainty ranges, we assumed that our three-point estimates (results based on the default, lower and upper bound emissions factors) follow a program evaluation and review technique distribution. This distribution is defined by the most likely (that is, mode) and extreme (the minimum and the maximum) values a variable can take. We used the qpert function in the mc2d package in the R software to estimate the 25th and 75th percentiles[76].

Paris Agreement and allowable food production emissions

To interpret our findings, we compared our results against the allowable emissions range of pathways compliant with the Paris Agreement[32]. Paris Agreement-compatible allowable emissions are estimated by selecting the Paris-compliant pathways from the full ensemble of pathways underlying the IPCC AR6[77]. The ensemble was filtered by criteria for efforts to limit global warming to 1.5 °C (for example, <66% chance to overshoot of 1.5 °C), holding global warming well below 2 °C (for example, 90% chance) and achieving net zero emissions in the second half of the twenty-first century, in order to remain consistent with the Paris Agreement[32].

In line with our scope, we considered only the CH_4 and N_2O emissions from the AFOLU sector in 2030. To derive the CO_2eq emissions, we used the updated GWP100 factors from the IPCC AR6[62]. To further ensure compatibility with our study scope, we adjusted the allowable AFOLU emissions based on the global population covered in this study (89% of the global population) under the assumption of fair-share GHG per capita. Furthermore, as we did not include N_2O emissions from drained organic soils, which represents 2% of the global non-CO_2 emissions, we rationalized the allowable non-CO_2 emissions accordingly. In addition, our focus on food crops (that is, excluding fibre crops) corresponds to 99% of total agricultural production by weight[75]. Given that around 20% of agricultural non-CO_2 emissions arose from crop production in 2013–2015, this amounted to ~0.3% downscaling in boundaries. Consequently, we scaled down the 25th (5.03 Gt CO_2eq yr^{-1}), 50th (5.43 Gt CO_2eq yr^{-1}) and 75th (6.17 Gt CO_2eq yr^{-1}) percentile values by 14% for comparison with our findings. The consequent allowable non-CO_2 emissions range was 4.33–5.31 Gt CO_2eq yr^{-1}.

Assumptions and limitations

Recent research suggests that CO_2 warming equivalents (CO_2we), following the newly established GWP* model, may better account for the behaviour of the short-lived climate pollutants, such as CH_4, in projecting temperature effects[78]. Given that the increase in CH_4 emissions was smaller when optimization was introduced (Extended Data Fig. 1), compared with BaU, due to relatively smaller gaps in vitamin B12 supplies and associated increase in livestock production (the only source of vitamin B12 as an input to optimization), future research could enhance the understanding of temperature effects of decreasing growth in CH_4 emissions by using GWP*. To provide an illustrative figure, we presented our optimization results based on CO_2 warming equivalents using the GWP* model in the Supplementary Information. It suggests that despite smaller warming potentials suggested by GWP* because CH_4 emissions either decrease (for example, with productivity improvements) or nearly stabilize (for example, with optimization only) compared with 2015, relative performance of our climate-friendly scenarios remains robust to the chosen equivalence method, that is, CO_2we or CO_2eq.

We acknowledge the complexity of adequate nutrition, which depends on a delicate balance of a diverse set of nutrients as well as other socioeconomic determinants and underlying health conditions that are not captured in this study. Similarly, fortification and supplementation, presented as food-based intervention options to fill the nutrient gap in diets, are not considered due to a lack of reliable production/trade data across all countries and products included in our study. More importantly, it is harder to estimate the contribution of fortification in countries where the nutrient gap is highest, such as low-income countries with a high share of rural population, because fortified foods may not be accessible in rural areas and implementation is difficult in small-scale mills[9]. See the Supplementary Information for a thorough discussion of our assumptions and their limitations.

Reporting summary

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

Data availability

All input data are publicly available through online sources as given in the references. All other data supporting the findings of this study are available within the paper. Source data are provided with this paper.

Code availability

Codes related to optimization are publicly available via https://github.com/OzgeGe/opt.git. Further information is available upon request.

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Acknowledgements

The financial support for this research, from the German Research Foundation (DFG) through the Sustainable Food Systems Research Training Group (RTG 2654) and Deakin University, Australia (DUPR-STRATEGIC – 0000018831), both received by O.G., is gratefully acknowledged. We also thank P. Pradhan for kindly sharing preliminary R code used to estimate potential yields via the GAEZ model and G. Ganti for providing data used to determine non-CO_2 emission pathways compatible with the Paris Agreement

Author contributions

O.G., M.H. and B.A.B. designed the study. O.G. collated data and performed the analyses with the help of M.H., who also calculated crop yield gap estimates and climate boundaries. All authors discussed the methods and results, and helped shape the research, analysis and interpretation. O.G. took the lead in writing the manuscript with substantial contributions from all authors.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s43016-022-00648-y.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43016-022-00648-y.

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Peer review information *Nature Food* thanks Laixiang Sun and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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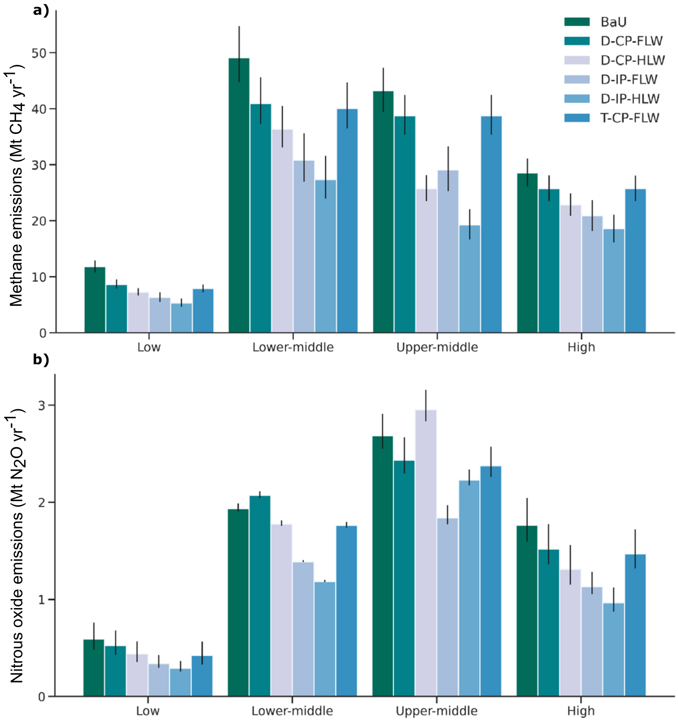

Extended Data Fig. 1 | Breakdown of total GHG emissions by individual climate pollutant. a) CH4 emissions results by scenario and income level. Results are presented in megatons CH4 yr-1. **b**) N2O emissions results by scenario and income level. Results are presented in megatons N2O yr-1. Bars show the total emissions for 128 countries, that is, n = 128, based on default emissions factors (corresponding to mode as the measure of center. Error bars show the 25th and 75th percentiles (see Uncertainty estimates).

Extended Data Table 1 | List of countries

Income level	ISO3	Country name	Income level	ISO3	Country name
High	AUS	Australia	Lower-middle	CIV	Cote d'Ivoire
High	AUT	Austria	Lower-middle	CMR	Cameroon
High	BHS	Bahamas	Lower-middle	COG	Congo
High	BRB	Barbados	Lower-middle	CPV	Cabo Verde
High	BRN	Brunei Darussalam	Lower-middle	EGY	Egypt
High	CAN	Canada	Lower-middle	GEO	Georgia
High	CHE	Switzerland	Lower-middle	GHA	Ghana
High	CHL	Chile	Lower-middle	GTM	Guatemala
High	CYP	Cyprus	Lower-middle	GUY	Guyana
High	CZE	Czechia	Lower-middle	HND	Honduras
High	DEU	Germany	Lower-middle	IDN	Indonesia
High	DNK	Denmark	Lower-middle	IND	India
High	ESP	Spain	Lower-middle	KEN	Kenya
High	EST	Estonia	Lower-middle	KGZ	Kyrgyzstan
High	FIN	Finland	Lower-middle	LKA	Sri Lanka
High	FRA	France	Lower-middle	MAR	Morocco
High	GBR	United Kingdom of Great Britain and Northern Ireland	Lower-middle	MDA	Republic of Moldova
High	GRC	Greece	Lower-middle	MNG	Mongolia
High	HRV	Croatia	Lower-middle	NGA	Nigeria
High	HUN	Hungary	Lower-middle	NIC	Nicaragua
High	IRL	Ireland	Lower-middle	PAK	Pakistan
High	ISL	Iceland	Lower-middle	PHL	Philippines
High	ISR	Israel	Lower-middle	SEN	Senegal
High	ITA	Italy	Lower-middle	SLV	El Salvador
High	JPN	Japan	Lower-middle	SWZ	Eswatini
High	KOR	Republic of Korea	Lower-middle	SYR	Syrian Arab Republic
High	KWT	Kuwait	Lower-middle	UKR	Ukraine
High	LTU	Lithuania	Lower-middle	YEM	Yemen
High	LVA	Latvia	Lower-middle	ZMB	Zambia
High	MLT	Malta	Upper-middle	ALB	Albania
High	NLD	Netherlands	Upper-middle	ARG	Argentina
High	NOR	Norway	Upper-middle	AZE	Azerbaijan
High	NZL	New Zealand	Upper-middle	BGR	Bulgaria
High	OMN	Oman	Upper-middle	BLR	Belarus
High	POL	Poland	Upper-middle	BLZ	Belize
High	PRT	Portugal	Upper-middle	BRA	Brazil
High	RUS	Russian Federation	Upper-middle	BWA	Botswana
High	SAU	Saudi Arabia	Upper-middle	COL	Colombia
High	SGP	Singapore	Upper-middle	CPR	China
High	SVK	Slovakia	Upper-middle	CRI	Costa Rica
High	SVN	Slovenia	Upper-middle	DZA	Algeria
High	SWE	Sweden	Upper-middle	ECU	Ecuador
High	TTO	Trinidad and Tobago	Upper-middle	GRD	Grenada
High	URY	Uruguay	Upper-middle	IRN	Iran (Islamic Republic of)
High	USA	United States of America	Upper-middle	JAM	Jamaica
Low	BDI	Burundi	Upper-middle	JOR	Jordan
Low	BEN	Benin	Upper-middle	KAZ	Kazakhstan
Low	BFA	Burkina Faso	Upper-middle	LBN	Lebanon
Low	CAF	Central African Republic	Upper-middle	LCA	Saint Lucia
Low	ETH	Ethiopia	Upper-middle	MDV	Maldives
Low	GIN	Guinea	Upper-middle	MEX	Mexico
Low	GMB	Gambia	Upper-middle	MKD	North Macedonia
Low	MDG	Madagascar	Upper-middle	MUS	Mauritius
Low	MLI	Mali	Upper-middle	MYS	Malaysia
Low	MWI	Malawi	Upper-middle	NAM	Namibia
Low	NER	Niger	Upper-middle	PAN	Panama
Low	RWA	Rwanda	Upper-middle	PER	Peru
Low	TGO	Togo	Upper-middle	PRY	Paraguay
Low	TZA	United Republic of Tanzania	Upper-middle	ROU	Romania
Low	UGA	Uganda	Upper-middle	SUR	Suriname
Low	ZWE	Zimbabwe	Upper-middle	THA	Thailand
Lower-middle	BGD	Bangladesh	Upper-middle	TUN	Tunisia
Lower-middle	BOL	Bolivia (Plurinational State of)	Upper-middle	TUR	Turkey

Countries included in this study are listed with respective ISO3 codes and income levels according to the World Bank classification[80].

Extended Data Table 2 | Relative proportion of N fertiliser use by crop group

Country	Wheat	Rice	Maize	Other cereals	Soybean	Oil Palm	Other oilseeds	Sugar Crops	Roots & Tubers	Fruits	Vegetables
Argentina	0.265	0.004	0.255	0.100	0.081	0.000	0.021	0.030	0.012	0.042	0.012
Australia	0.393	0.006	0.011	0.142	0.000	0.000	0.088	0.057	0.043	0.014	0.023
Austria	0.292	0.004	0.134	0.114	0.000	0.000	0.107	0.015	0.017	0.042	0.023
Bangladesh	0.015	0.776	0.024	0.000	0.008	0.000	0.008	0.020	0.009	0.038	0.030
Belarus	0.158	0.000	0.223	0.286	0.000	0.000	0.108	0.002	0.033	0.009	0.001
Brazil	0.046	0.047	0.274	0.013	0.069	0.003	0.002	0.207	0.010	0.031	0.016
Bulgaria	0.135	0.155	0.185	0.008	0.008	0.000	0.030	0.019	0.038	0.135	0.185
Canada	0.300	0.000	0.078	0.128	0.006	0.000	0.381	0.000	0.010	0.008	0.005
Chile	0.190	0.008	0.130	0.066	0.000	0.000	0.008	0.013	0.030	0.170	0.034
China	0.135	0.155	0.185	0.008	0.008	0.000	0.030	0.019	0.038	0.135	0.185
Croatia	0.233	0.291	0.049	0.054	0.016	0.000	0.075	0.050	0.008	0.015	0.025
Cyprus	0.132	0.017	0.472	0.038	0.015	0.000	0.012	0.008	0.010	0.008	0.011
Czechia	0.292	0.004	0.134	0.114	0.000	0.000	0.107	0.015	0.017	0.042	0.023
Denmark	0.135	0.155	0.185	0.008	0.008	0.000	0.030	0.019	0.038	0.135	0.185
Egypt	0.212	0.136	0.237	0.015	0.001	0.000	0.022	0.070	0.030	0.080	0.130
Estonia	0.233	0.291	0.049	0.054	0.016	0.000	0.075	0.050	0.008	0.015	0.025
Finland	0.132	0.017	0.472	0.038	0.015	0.000	0.012	0.008	0.010	0.008	0.011
France	0.292	0.004	0.134	0.114	0.000	0.000	0.107	0.015	0.017	0.042	0.023
Germany	0.135	0.155	0.185	0.008	0.008	0.000	0.030	0.019	0.038	0.135	0.185
Greece	0.233	0.291	0.049	0.054	0.016	0.000	0.075	0.050	0.008	0.015	0.025
Hungary	0.132	0.017	0.472	0.038	0.015	0.000	0.012	0.008	0.010	0.008	0.011
India	0.233	0.291	0.049	0.054	0.016	0.000	0.075	0.050	0.008	0.015	0.025
Indonesia	0.000	0.400	0.150	0.000	0.005	0.250	0.005	0.020	0.030	0.035	0.050
Iran	0.332	0.062	0.047	0.067	0.001	0.000	0.026	0.012	0.031	0.040	0.160
Ireland	0.292	0.004	0.134	0.114	0.000	0.000	0.107	0.015	0.017	0.042	0.023
Italy	0.233	0.291	0.049	0.054	0.016	0.000	0.075	0.050	0.008	0.015	0.025
Japan	0.093	0.290	0.000	0.005	0.012	0.000	0.000	0.038	0.054	0.114	0.192
Latvia	0.132	0.017	0.472	0.038	0.015	0.000	0.012	0.008	0.010	0.008	0.011
Lithuania	0.135	0.155	0.185	0.008	0.008	0.000	0.030	0.019	0.038	0.135	0.185
Malaysia	0.000	0.131	0.002	0.000	0.000	0.748	0.000	0.000	0.002	0.001	0.030
Malta	0.233	0.291	0.049	0.054	0.016	0.000	0.075	0.050	0.008	0.015	0.025
Mexico	0.054	0.005	0.591	0.033	0.000	0.005	0.006	0.008	0.065	0.006	0.099
Morocco	0.390	0.002	0.043	0.155	0.000	0.000	0.030	0.040	0.025	0.155	0.105
Netherlands	0.132	0.017	0.472	0.038	0.015	0.000	0.012	0.008	0.010	0.008	0.011
Pakistan	0.410	0.150	0.045	0.005	0.000	0.000	0.010	0.060	0.010	0.040	0.020
Philippines	0.000	0.530	0.210	0.000	0.000	0.005	0.020	0.070	0.007	0.090	0.010
Poland	0.292	0.004	0.134	0.114	0.000	0.000	0.107	0.015	0.017	0.042	0.023
Portugal	0.135	0.155	0.185	0.008	0.008	0.000	0.030	0.019	0.038	0.135	0.185
Romania	0.233	0.291	0.049	0.054	0.016	0.000	0.075	0.050	0.008	0.015	0.025
Russia	0.410	0.010	0.110	0.145	0.020	0.000	0.070	0.055	0.010	0.001	0.004
Slovakia	0.132	0.017	0.472	0.038	0.015	0.000	0.012	0.008	0.010	0.008	0.011
Slovenia	0.292	0.004	0.134	0.114	0.000	0.000	0.107	0.015	0.017	0.042	0.023
South Africa	0.051	0.000	0.580	0.010	0.004	0.000	0.020	0.084	0.023	0.076	0.051
Spain	0.135	0.155	0.185	0.008	0.008	0.000	0.030	0.019	0.038	0.135	0.185
Thailand	0.000	0.700	0.060	0.003	0.000	0.025	0.003	0.002	0.060	0.020	0.027
Turkey	0.420	0.010	0.080	0.110	0.002	0.000	0.055	0.033	0.021	0.015	0.100
Ukraine	0.361	0.004	0.179	0.142	0.034	0.000	0.157	0.077	0.003	0.003	0.005
USA	0.132	0.017	0.472	0.038	0.015	0.000	0.012	0.008	0.010	0.008	0.011
Uzbekistan	0.330	0.012	0.011	0.018	0.000	0.000	0.011	0.000	0.012	0.060	0.060
Vietnam	0.000	0.600	0.120	0.000	0.004	0.000	0.015	0.001	0.040	0.020	0.042
ROW	0.117	0.151	0.150	0.058	0.006	0.022	0.049	0.054	0.032	0.095	0.139

Individual proportions (% of total use) may not add up to 100% because of the contribution by fibre crops and other non-food sources which is not included in this study. We used this information to link fertiliser emissions with respective crops and dietary nutrients. Data adopted from Heffer et al. (2017). ROW: Rest of the World.

Extended Data Table 3 | List of food products

Cereals	Crops, other	Crops, other	Eggs	Non-ruminant meat	Roots and tubers	Ruminant meat and dairy	Vegetables
Barley	Almonds, with shell	Kiwi fruit	Eggs, dried	Meat, nes	Cassava	Meat, buffalo	Artichokes
Buckwheat	Apples	Lemons and limes	Eggs, hen, in shell	Meat, bird nes	Potatoes	Meat, camel	Asparagus
Cereals, nes	Apricots	Lentils		Meat, chicken	Roots and tubers, nes	Meat, cattle	Beans, green
Maize	Avocados	Linseed	Eggs, other bird, in shell	Meat, duck	Sweet potatoes	Meat, goat	Cabbages and other brassicas
Millet	Bambara beans	Mangoes, mangosteens, guavas		Meat, game	Taro (cocoyam)	Meat, horse	Carrots and turnips
Oats	Bananas	Mustard seed		Meat, goose and guinea fowl	Yams	Meat, mule	Cassava leaves
Quinoa	Beans, dry	Nuts, nes		Meat, pig	Yautia (cocoyam)	Meat, other camelids	Cauliflowers and broccoli
Rice, paddy	Berries nes	Oil palm fruit		Meat, rabbit		Meat, sheep	Chillies and peppers, green
Rye	Blueberries	Oilseeds nes		Meat, turkey		Milk, whole fresh buffalo	Cucumbers and gherkins
Sorghum	Brazil nuts, with shell	Olives				Milk, whole fresh camel	Eggplants (aubergines)
Triticale	Broad beans, horse beans, dry	Oranges				Milk, whole fresh cow	Garlic
Wheat	Cashew nuts, with shell	Papayas				Milk, whole fresh goat	Leeks, other alliaceous vegetables
Wheat	Cashewapple	Peaches and nectarines				Milk, whole fresh sheep	Lettuce and chicory
	Cherries	Peas, dry					Maize, green
	Cherries, sour	Persimmons					Melons, other (inc.cantaloupes)
	Chestnut	Pigeon peas					Mushrooms and truffles
	Chick peas	Pineapples					Okra
	Cocoa, beans	Pistachios					Onions, dry
	Coconuts	Plantains and others					Onions, shallots, green
	Cow peas, dry	Plums and sloes					Peas, green
	Cranberries	Poppy seed					Pumpkins, squash and gourds
	Currants	Pulses, nes					Spinach
	Dates	Quinces					String beans
	Figs	Rapeseed					Tomatoes
	Fruit, citrus nes	Raspberries					Vegetables, fresh nes
	Fruit, fresh nes	Safflower seed					Vegetables, leguminous nes
	Fruit, tropical fresh nes	Sesame seed					Watermelons
	Gooseberries	Soybeans					
	Grapefruit (inc. pomelos)	Strawberries					
	Grapes	Sunflower seed					
	Groundnuts, with shell	Tangerines, mandarins, clementines, satsumas					
	Hazelnuts, with shell	Walnuts, with shell					

Primary food groups and their product composition that are used in optimization models and for visualization purposes. *nes: not elsewhere stated

Extended Data Table 4 | Technical conversion factors for oilseed processing

Product	Top producing countries	Conversion factor
Coconut oil	Philippines, Indonesia	0.59
Groundnut oil	China, India	0.43
Linseed oil	China, Belgium, United States	0.34
Olive oil	Turkey, Italy, France	0.17
Safflower oil	United States, India, Mexico	0.32
Sesame oil	China, Myanmar, India, Nigeria	0.41
Soybean oil	China, United States, Brazil	0.17
Sunflower oil	Ukraine, Russian Federation, Argentina, Turkey	0.43

Technical conversion factors were used to convert oilseed crops into vegetable oils[67]. We used the weighted average conversion factor of the top producers. Rapeseed and oil palm were originally converted to oil equivalents in nutrient production data we used[57].

Extended Data Table 5 | Livestock GHG mitigation potential

			OECD				
Product	**South/ South-East Asia**	**South America**	**North America**	**Western Europe**	**Oceania**	**West Africa**	**East Africa**
Mixed dairy	38	32	17	6	9	24	24
Beef	27	29	27	27	27	27	27
Buffalo meat	41	41	41	41	41	41	41
Buffalo milk	22	22	22	22	22	22	22
Eggs	38	38	38	38	38	38	38
Poultry	40	40	40	40	40	40	40
Small ruminant milk	36	36	036	36	36	41	41
Small ruminant meat	31	31	31	31	31	41	41
Pig	10	19	19	19	19	28	19

Mitigation potential (% reduction) in GHG emissions intensity via improved feed quality and grazing management, and reduced mortality[44]. The mitigation potential was estimated based on constant output (for example, milk and meat) in the GLEAM model. For example, GHG emissions intensity per unit milk production from mixed dairy in Western Europe can be reduced by 6%.

Extended Data Table 6 | Proportional consumption of crop feed by livestock group

	1995		2030		2015 (interpolated)	
Regions	**Ruminants**	**Pigs and poultry**	**Ruminants**	**Pigs and poultry**	**Ruminants**	**Pigs and poultry**
USA	0.566	0.434	0.543	0.457	0.553	0.447
South America	0.404	0.596	0.453	0.547	0.432	0.568
Eastern Africa	0.500	0.500	0.286	0.714	0.378	0.622
Western Europe	92.000	0.664	0.269	0.731	39.582	0.702
Former USSR	0.608	0.392	0.576	0.424	0.590	0.410
Middle East	0.519	0.481	0.481	0.519	0.497	0.503
South Asia	0.611	0.389	0.448	0.552	0.518	0.482
East Asia	0.200	0.800	0.246	0.754	0.226	0.774
Rest of the World	0.566	0.434	0.543	0.457	0.553	0.447

We used these shares (% of total consumption) to attribute crop feed emissions to respective food sources. Original estimations are for 1995 and 2030[69]. We linearly interpolated these to derive 2015 values.

Extended Data Table 7 | Average aquafeed use per unit production

Species	Economic Group	Maize	Wheat	Oil crops	Soybean	Pulses
Shrimps, prawns	A	0.072	0.539	0.036	0.252	0.312
Salmons, trouts, smelts	A	0.060	0.452	0.030	0.211	0.261
Marine Fish NEI	A	0.099	0.743	0.050	0.347	0.429
Carps, barbels and other cyprinids	A	0.057	0.427	0.028	0.199	0.247
Tilapias and other cichlids	A	0.091	0.683	0.046	0.319	0.394
River eels	A	0.052	0.393	0.026	0.184	0.227
Freshwater crustaceans	A	0.053	0.396	0.026	0.185	0.229
Miscellaneous freshwater fishes	A	0.038	0.283	0.019	0.132	0.164
Shrimps, prawns	B	0.084	0.551	0.036	0.240	0.300
Salmons, trouts, smelts	B	0.070	0.462	0.030	0.201	0.251
Marine Fish NEI	B	0.116	0.759	0.050	0.330	0.413
Carps, barbels and other cyprinids	B	0.066	0.437	0.028	0.190	0.237
Tilapias and other cichlids	B	0.106	0.698	0.046	0.303	0.379
River eels	B	0.061	0.402	0.026	0.175	0.218
Freshwater crustaceans	B	0.062	0.405	0.026	0.176	0.220
Miscellaneous freshwater fishes	B	0.044	0.290	0.019	0.126	0.157
Shrimps, prawns	C	0.355	0.587	0.000	0.220	0.049
Salmons, trouts, smelts	C	0.297	0.492	0.000	0.184	0.041
Marine Fish NEI	C	0.488	0.808	0.000	0.303	0.067
Carps, barbels and other cyprinids	C	0.281	0.465	0.000	0.174	0.039
Tilapias and other cichlids	C	0.449	0.743	0.000	0.279	0.062
River eels	C	0.259	0.428	0.000	0.160	0.036
Freshwater crustaceans	C	0.260	0.431	0.000	0.162	0.036
Miscellaneous freshwater fishes	C	0.186	0.308	0.000	0.116	0.026
Shrimps, prawns	China	0.436	0.169	0.000	0.605	0.000
Salmons, trouts, smelts	China	0.365	0.142	0.000	0.507	0.000
Marine Fish NEI	China	0.600	0.233	0.000	0.834	0.000
Carps, barbels and other cyprinids	China	0.345	0.134	0.000	0.480	0.000
Tilapias and other cichlids	China	0.552	0.215	0.000	0.766	0.000
River eels	China	0.318	0.124	0.000	0.441	0.000
Freshwater crustaceans	China	0.320	0.124	0.000	0.445	0.000
Miscellaneous freshwater fishes	China	0.229	0.089	0.000	0.318	0.000
Shrimps, prawns	D	0.281	0.440	0.012	0.318	0.159
Salmons, trouts, smelts	D	0.236	0.369	0.010	0.266	0.133
Marine Fish NEI	D	0.387	0.606	0.017	0.438	0.219
Carps, barbels and other cyprinids	D	0.223	0.349	0.010	0.252	0.126
Tilapias and other cichlids	D	0.356	0.557	0.015	0.402	0.201
River eels	D	0.205	0.321	0.009	0.232	0.116
Freshwater crustaceans	D	0.207	0.323	0.009	0.234	0.117
Miscellaneous freshwater fishes	D	0.148	0.231	0.006	0.167	0.084
Shrimps, prawns	E	0.448	0.169	0.000	0.593	0.000
Salmons, trouts, smelts	E	0.375	0.142	0.000	0.497	0.000
Marine Fish NEI	E	0.617	0.233	0.000	0.817	0.000
Carps, barbels and other cyprinids	E	0.355	0.134	0.000	0.470	0.000
Tilapias and other cichlids	E	0.567	0.215	0.000	0.751	0.000
River eels	E	0.327	0.124	0.000	0.432	0.000
Freshwater crustaceans	E	0.329	0.124	0.000	0.436	0.000
Miscellaneous freshwater fishes	E	0.235	0.089	0.000	0.312	0.000
Shrimps, prawns	F	0.563	0.240	0.000	0.408	0.000
Salmons, trouts, smelts	F	0.472	0.201	0.000	0.341	0.000
Marine Fish NEI	F	0.776	0.330	0.000	0.561	0.000
Carps, barbels and other cyprinids	F	0.446	0.190	0.000	0.323	0.000
Tilapias and other cichlids	F	0.713	0.303	0.000	0.516	0.000
River eels	F	0.411	0.175	0.000	0.297	0.000
Freshwater crustaceans	F	0.414	0.176	0.000	0.299	0.000
Miscellaneous freshwater fishes	F	0.296	0.126	0.000	0.214	0.000
Shrimps, prawns	India	0.436	0.133	0.000	0.642	0.000
Salmons, trouts, smelts	India	0.365	0.112	0.000	0.537	0.000
Marine Fish NEI	India	0.600	0.183	0.000	0.884	0.000
Carps, barbels and other cyprinids	India	0.345	0.106	0.000	0.508	0.000
Tilapias and other cichlids	India	0.552	0.169	0.000	0.812	0.000
River eels	India	0.318	0.097	0.000	0.468	0.000
Freshwater crustaceans	India	0.320	0.098	0.000	0.471	0.000
Miscellaneous freshwater fishes	India	0.229	0.070	0.000	0.337	0.000

Values are calculated based on proportional crop contribution as provided by Tilman and Clark[65] and species-specific total aquafeed use provided by Naylor et al.[64]. The values show the ratio of kg crop use per kg aquaculture production. Economic groups refer to regionalization by Tilman and Clark[65]. Only fed aquaculture is considered.

Extended Data Table 8 | Technical conversion factors

Commodity	Primary commodity	Top producers	Technical conversion factor
Oil cake	Soybean	China, United States of America, Brazil, Argentina, India	0.8
Oil cake	Sunflower seed	Ukraine, Russian Federation, Argentina, Turkey, China, France, Hungary, Spain, Romania, Bulgaria	0.6
	Rapeseed	China, Germany, Canada, India, France, Poland, Japan, United Kingdom, United States of America, Belgium	

Technical conversion factors are used to convert aquafeed back to primary crop equivalents[95]. We used the weighted average conversion factor of the top producers.

Extended Data Table 9 | Uncertainty range of emission factors

Emission source	Greenhouse gas	Uncertainty range as percent deviation from the default value
Enteric fermentation	CH_4	±30%
Manure management	CH_4	±30%
	N_2O	±50%
Manure applied to soils/pasture	***Indirect N_2O*** Emisison factor$_{\text{Leaching}}$	0.0005 - 0.025 kg N_2O-N (-93%, +233%)
	Fraction$_{\text{Leaching}}$	0.1 - 0.8 (-67%, +167%)
	Emission factor$_{\text{Volatilisation}}$	0.002 - 0.05 kg N_2O-N (-80%, +400%)
	Fraction$_{\text{Volatilisation, manure}}$	0.05 - 0.05 kg N_2O-N (-75%, +150%)
	Direct N_2O Emission factor$_{\text{Direct}}$	None
Crop residues	***Indirect N_2O*** Emission factor$_{\text{Leaching}}$	0.0005 - 0.025 kg N_2O-N (-93%, +233%)
	Fraction$_{\text{Leaching}}$	0.1 - 0.8 (-67%, +167%)
	Direct N_2O Emission factor$_{\text{Direct}}$	0.002, 0.05 kg N_2O-N (-80%, +400%)
Synthetic fertilizers	***Indirect N_2O*** Emisison factor$_{\text{Leaching}}$	0.0005 - 0.025 kg N_2O-N (-93%, +233%)
	Fraction$_{\text{Leaching}}$	0.2 - 0.8 (-67%, +167%)
	Emission factor$_{\text{Volatilisation}}$	0.002 - 0.05 kg N_2O-N (-80%, +400%)
	Fraction$_{\text{Volatilisation, fertiliser}}$	0.03 - 0.3 kg N_2O-N (-70%, +167%)
	Direct N_2O Emission factor$_{\text{Direct}}$	0.002 – 0.05 N_2O-N (-80%, +400%)
Rice cultivation	CH_4	0.8 – 2.20 (kg CH_4/ha) (-38%, +69%)

Uncertainty ranges are provided for each emission source covered in this study. Data extracted from IPCC (2006). Absolute values are converted into percentage change as shown in the parentheses.

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NATFOOD-22040272

Last updated by author(s): Oct 19, 2022

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used for data collection purposes.
Data analysis	We used linprog function from SciPy library in Python (version 3.8.11) for linear programming. We also use qpert function from mc2d package to draw lower and upper percentiles and tmap package in R (version 3.6.2). Codes related to optimization are publicly available via https://github.com/OzgeGe/opt.git as stated in the code availability section of our manuscript.

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Study description	This study is a nutritionally- and environmentally-extended linear modeling exercise. We quantified the minimum emissions arising from meeting the population-level dietary requirements. Our findings are presented for alternative scenarios that aim to reduce emissions intensity of food production at the farm level.
Research sample	We used publicly available national, and product-level where applicable, data on greenhouse gas emissions data from the Food and Agricultural Organization of the United Nations. We derived data on dietary nutrient production, trade, and population-level dietary nutrient requirements from the literature and associated data repositories such as Mendeley Data. We also used the United Nations population prospects for 2030 to extrapolate population-level dietary nutrient requirements into the future.
Sampling strategy	We did not perform any sampling for this analysis.
Data collection	All data was publicly available in a tabular format; hence, it was done manually.
Timing and spatial scale	We used 2020 version of FAOSTAT data on greenhouse gas emissions, production, and detailed trade. We used country- and commodity-level data where applicable.
Data exclusions	We did not include countries which did not have reported data for all domains (i.e., production, bilateral trade, and greenhouse gas emissions). This resulted in inclusion of 128 countries in total.
Reproducibility	Experimental reproducibility was not applicable. We kept version control of the data and open-source software for reproducibility of the methodology.
Randomization	Not applicable.
Blinding	No blinding was necessary for this study based on secondary data sources.

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