Title: Reducing food's environmental impacts through producers and consumers

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Abstract: Food's environmental impacts are created by millions of diverse producers. To identify solutions that are effective under this heterogeneity, we consolidated data covering five environmental indicators; 38,700 farms; and 1600 processors, packaging types, and retailers. Impact can vary 50-fold among producers of the same product, creating substantial mitigation opportunities. However, mitigation is complicated by trade-offs, multiple ways for producers to achieve low impacts, and interactions throughout the supply chain. Producers have limits on how far they can reduce impacts. Most strikingly, impacts of the lowest-impact animal products typically exceed those of vegetable substitutes, providing new evidence for the importance of dietary change. Cumulatively, our findings support an approach where producers monitor their own impacts, flexibly meet environmental targets by choosing from multiple practices, and communicate their impacts to consumers.

Main Text:

With current diets and production practices, feeding 7.6 billion people is degrading terrestrial and aquatic ecosystems, depleting water resources, and driving climate change (*1*, *2*). It is particularly challenging to find solutions that are effective across the large and diverse range of producers that characterize the agricultural sector. More than 570 million farms produce in almost all the world's climates and soils (*3*), each using vastly different agronomic methods; average farm sizes vary from 0.5 hectares in Bangladesh to 3000 hectares in Australia (*3*); average mineral fertilizer use ranges from 1kg of nitrogen per hectare in Uganda to 300kg in China (*4*); and although four crops provide half of the world's food calories (*4*), more than 2 million distinct varieties are recorded in seed vaults (*5*). Further, products range from minimally to heavily processed and packaged, with 17 of every 100kg of food produced transported internationally, increasing to 50kg for nuts and 56kg for oils (*4*).

Previous studies have assessed aspects of this heterogeneity by using geospatial data sets (*6–8*), but global assessments using the inputs, outputs, and practices of actual producers have been limited by data. The recent rapid expansion of the life cycle assessment (LCA) literature is providing this information by surveying producers around the world. LCA then uses models to translate producer data into environmental impacts with sufficient accuracy for most decision-making (*9–11*).

To date, efforts to consolidate these data or build new large-scale data sets have covered greenhouse gas (GHG) emissions only (*8*, *12*, *13*), agriculture only (*13–16*), small numbers of products (8, 14–16), and predominantly Western European producers (*12–16*) and have not corrected for important methodological differences between LCAs (*12–16*). Here, we present a globally reconciled and methodologically harmonized database on the variation in food's multiple impacts. Our results show the need for far-reaching changes in how food's environmental impacts are managed and communicated.

Building the multi-indicator global database

We derived data from a comprehensive meta-analysis, identifying 1530 studies for potential inclusion, which were supplemented with additional data received from 139 authors. Studies were assessed against 11 criteria designed to standardize methodology, resulting in 570 suitable studies with a median reference year of 2010 (*17*). The data set covers ~38,700 commercially viable farms in 119 countries (fig. S2) and 40 products representing ~90% of global protein and calorie consumption. It covers five important environmental impact indicators (*18*): land use; freshwater withdrawals weighted by local water scarcity; and GHG, acidifying, and eutrophying emissions. For crops, yield represents output for a single harvest. Land use includes multiple cropping (up to four harvests per year), fallow (uncultivated periods between crops), and economic allocation to crop coproducts such as straw. This makes it a stronger indicator of both farm productivity and food security than yield.

The system we assess begins with inputs (the initial effect of producer choice) and ends at retail (the point of consumer choice) (fig. S1). For each study, we recorded the inventory of outputs and inputs (including fertilizer quantity and type, irrigation use, soil, and climatic conditions). Where data were not reported, for example, on climate, we used study coordinates and spatial data sets to fill gaps. We recorded environmental impacts at each stage of the supply chain. For GHG emissions, we further disaggregated the farm stage into 20 emission sources. We then used the inventory to recalculate all missing emissions. For nitrate leaching and aquaculture, we developed new models for this study (*17*).

Studies included provided ~1050 estimates of post-farm processes. To fill gaps in processing, packaging, or retail, we used additional meta-analyses of 153 studies providing 550 observations. Transport and losses were included from global data sets. Each observation was weighted by the share of national production it represents, and each country by its share of global production. We then used randomization to capture variance at all stages of the supply chain (*17*).

We validated the global representativeness of our sample by comparing average and 90th-percentile yields to Food and Agriculture Organization (FAO) data (*4*), which reconcile to within ±10% for most crops. Using FAO food balance sheets (*4*), we scaled up our sample data. Total arable land and freshwater withdrawals reconcile to FAO estimates. Emissions from deforestation and agricultural methane fall within ranges of independent models (*17*).

Environmental impacts of the entire food supply-chain

Today's food supply chain creates ~13.7 billion metric tons of carbon dioxide equivalents (CO_2eq), 26% of anthropogenic GHG emissions. A further 2.8 billion metric tons of CO_2eq (5%) are caused by nonfood agriculture and other drivers of deforestation (*17*). Food production creates ~32% of global terrestrial acidification and ~78% of eutrophication. These emissions can fundamentally alter the species composition of natural ecosystems, reducing biodiversity and ecological resilience (*19*). The farm stage dominates, representing 61% of food's GHG emissions (81% including deforestation), 79% of acidification, and 95% of eutrophication (table S17).

Today's agricultural system is also incredibly resource intensive, covering ~43% of the world's ice- and desert-free land. Of this land, ~87% is for food and 13% is for biofuels and textile crops or is allocated to nonfood uses such as wool and leather. We estimate that two-thirds of freshwater withdrawals are for irrigation. However, irrigation returns less water to rivers and groundwater than industrial and municipal uses and predominates in water-scarce areas and times of the year, driving 90-95% of global scarcity-weighted water use (*17*).

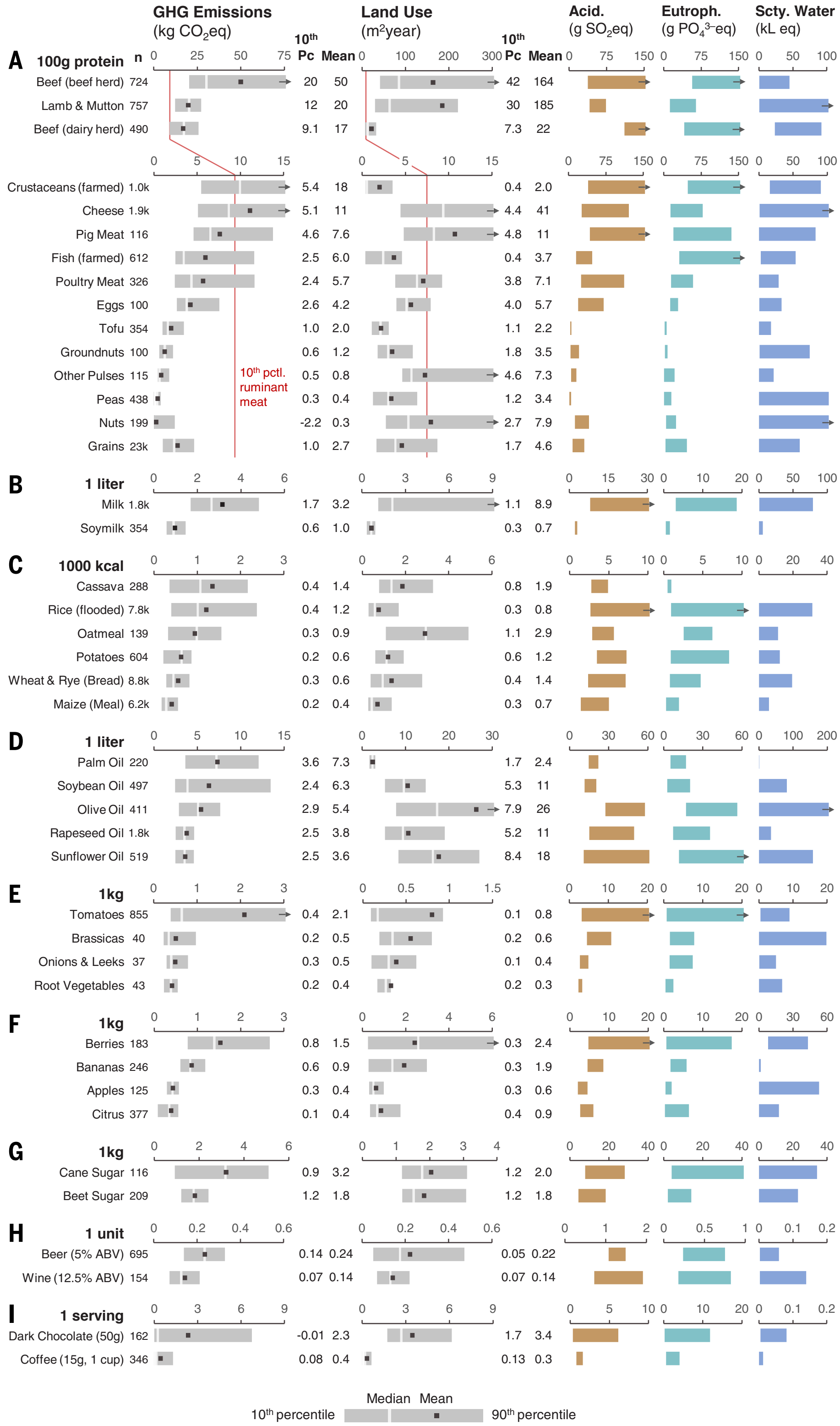
GHG Emissions
(kg CO2eq)
Land Use
(m2year)
Acid.
(g SO2eq)
Eutroph.
(g PO43-eq)
Scty. Water
(kL eq)
10th Pc Mean
A 100g protein n
Beef (beef herd) 724 20 50 42 164
Lamb & Mutton 757 12 20 30 185
Beef (dairy herd) 490 9.1 17 7.3 22
Crustaceans (farmed) 1.0k 5.4 18 0.4 2.0
Cheese 1.9k 5.1 11 4.4 41
Pig Meat 116 4.6 7.6 4.8 11
Fish (farmed) 612 2.5 6.0 0.4 3.7
Poultry Meat 326 2.4 5.7 3.8 7.1
Eggs 100 2.6 4.2 4.0 5.7
Tofu 354 1.0 2.0 1.1 2.2
Groundnuts 100 0.6 1.2 1.8 3.5
Other Pulses 115 0.5 0.8 4.6 7.3
Peas 438 0.3 0.4 1.2 3.4
Nuts 199 -2.2 0.3 2.7 7.9
Grains 23k 1.0 2.7 1.7 4.6
10th pctl. ruminant meat
B 1 liter
Milk 1.8k 1.7 3.2 1.1 8.9
Soymilk 354 0.6 1.0 0.3 0.7
C 1000 kcal
Cassava 288 0.4 1.4 0.8 1.9
Rice (flooded) 7.8k 0.4 1.2 0.3 0.8
Oatmeal 139 0.3 0.9 1.1 2.9
Potatoes 604 0.2 0.6 0.6 1.2
Wheat & Rye (Bread) 8.8k 0.3 0.6 0.4 1.4
Maize (Meal) 6.2k 0.2 0.4 0.3 0.7
D 1 liter
Palm Oil 220 3.6 7.3 1.7 2.4
Soybean Oil 497 2.4 6.3 5.3 11
Olive Oil 411 2.9 5.4 7.9 26
Rapeseed Oil 1.8k 2.5 3.8 5.2 11
Sunflower Oil 519 2.5 3.6 8.4 18
E 1kg
Tomatoes 855 0.4 2.1 0.1 0.8
Brassicas 40 0.2 0.5 0.2 0.6
Onions & Leeks 37 0.3 0.5 0.1 0.4
Root Vegetables 43 0.2 0.4 0.2 0.3
F 1kg
Berries 183 0.8 1.5 0.3 2.4
Bananas 246 0.6 0.9 0.3 1.9
Apples 125 0.3 0.4 0.3 0.6
Citrus 377 0.1 0.4 0.4 0.9
G 1kg
Cane Sugar 116 0.9 3.2 1.2 2.0
Beet Sugar 209 1.2 1.8 1.2 1.8
H 1 unit
Beer (5% ABV) 695 0.14 0.24 0.05 0.22
Wine (12.5% ABV) 154 0.07 0.14 0.07 0.14
I 1 serving
Dark Chocolate (50g) 162 -0.01 2.3 1.7 3.4
Coffee (15g, 1 cup) 346 0.08 0.4 0.13 0.3
Median Mean
10th percentile 90th percentile

Fig. 1. Estimated global variation in GHG emissions, land use, terrestrial acidification, eutrophication, and scarcity-weighted freshwater withdrawals, within and between 40 major foods. n = farm or regional inventories. Land use is area times years occupied (m^2·year). (**A**) Protein-rich products. Grains are also shown here given they contribute 41% of global protein intake, despite lower protein content. (**B**) Milks. (**C**) Starch-rich products. (**D**) Oils. (**E**) Vegetables. (**F**) Fruits. (**G**) Sugars. (**H**) Alcoholic beverages (1 unit = 10ml alcohol). (**I**) Stimulants.

Highly variable and skewed environmental impacts

We now group products by their primary dietary role and express impacts per unit of primary nutritional benefit (Fig. 1 and fig. S3). Immediately apparent in our results is the high variation in impact among both products and producers. Ninetieth-percentile GHG emissions of beef are 105kg of CO_2eq per 100g of protein, and land use (area multiplied by years occupied) is 370 m^2·year. These values are 12 and 50 times greater than 10th-percentile dairy beef impacts (which we report separately given that its production is tied to milk demand). Tenth-percentile GHG emissions and land use of dairy beef are then 36 and 6 times greater than those of peas. High variation within and between protein-rich products is also manifest in acidification, eutrophication, and water use.

Within the major crops wheat, maize, and rice, 90th-percentile impacts are more than three times greater than 10th-percentile impacts on all five indicators. Within major growing areas for these crops (the Australian wheat belt, the U.S. corn belt, and the Yangtze river basin), land use becomes less variable, but we observe the same high levels of variation in all other indicators. This variability, even among producers in similar geographic regions, implies substantial potential to reduce environmental impacts and enhance productivity in the food system.

For many products, impacts are skewed by producers with particularly high impacts. This creates opportunities for targeted mitigation, making an immense problem more manageable. For example, for beef originating from beef herds, the highest-impact 25% of producers represent 56% of the beef herd's GHG emissions and 61% of the land use (an estimated 1.3 billion metric tons of CO_2eq and 950 million hectares of land, primarily pasture). Across all products, 25% of producers contribute on average 53% of each product's environmental impact (fig. S3). For scarcity-weighted freshwater withdrawals, the skew is particularly pronounced: Producing just 5% of the world's food calories creates ~40% of the environmental burden. We will now explore how to access these mitigation opportunities through heterogenous producers.

Mitigation through producers

Enable producers to monitor multiple impacts

The first step in mitigation is estimating producer impacts. Prior research (e.g., *7*, *8*, *14*) has suggested that readily measurable proxies predict farm-stage impacts, avoiding the need for detailed assessment. From our larger data set, which includes more practices and geographies than prior studies, we assess the predictive power of common proxies, including crop yield, nitrogen use efficiency, milk yield per cow, liveweight gain, pasture area, and feed conversion ratios. Although most proxies significantly covary with impact, they make poor predictors when used alone, explaining little of the variation among farms (R^2 = 0-27% in 47 of 48 proxy-impact combinations assessed) (fig. S4).

Prior research has also suggested using one impact indicator to predict others (*20*). We find weakly positive and sometimes negative relationships between indicators. For similar products globally, correlations between indicators are low (R^2 = 0-30% in 26 of 32 impact-impact combinations assessed) (fig. S4). Pork, poultry meat, and milk show higher correlations between acidification and eutrophication (R2 ≤ 54%), explained by the dominant role of manure in these impacts, but this does not generalize to other products or indicators. The same conclusion holds for farms in similar geographies or systems (fig. S5).

Monitoring multiple impacts and avoiding proxies supports far better decisions and helps prevent harmful, unintended consequences. However, two recent studies suggest that data on practices and geography, required to quantify impacts, must come directly from producers (*11*, *21*); that quantifying impacts with the use of satellite or census data misses much of the variation among farms.

Set and incentivize mitigation targets

When land use or emissions are low, we find trade-offs between indicators for many crops (fig. S5). This reflects diminishing marginal yield with increasing inputs as crops tend toward their maximum yields (*22*). For example, for already low-emission Northern European barley farms, halving land use can increase GHG emissions per kilogram of grain by 2.5 times and acidification by 3.7 times. To explore trade-offs further, we pair observations from the same study, location, and year that assess a practice change (fig. S6). Of the nine changes assessed, only two (changing from monoculture to diversified cropping and improving degraded pasture) deliver statistically significant reductions in both land use and GHG emissions.

Geography influences these trade-offs. For example, in the Australian wheat belt, where farmers practice low-rainfall, low-input farming, we find that both output per hectare and GHG emissions are in the bottom 15% globally. The environmental and social importance of different impacts also varies locally, given land scarcity, endemic biodiversity, and water quality, among other factors. Setting regional and sector-specific targets will help producers navigate trade-offs and make choices that align with local and global priorities.

Meet targets by choosing from multiple practice changes

To meet these targets, policy might encourage widespread adoption of certain practices. However, the environmental outcomes of many practices, such as conservation agriculture (*23*), organic farming (fig. S6), and even integrated systems of best practice (*24*), are highly variable. Using our data set, we can generalize these findings. To do this, we disaggregate each environmental indicator into its sources or drivers. We consider practice change as a package of measures that targets one or more of these sources. If producers have different impact sources, the effects of practice change will be variable.

We find that sources of impact vary considerably among farms producing the same product (Fig. 2 and figs. S7-S9). Priority areas for reducing impact for one farm may be immaterial for another. For example, measures to reduce direct nitrous oxide emissions from synthetic and organic fertilizer, such as biochar application, are included in many mitigation estimates (*25*). However, for a third of global crop calorie production, these emissions represent less than 5% of farm-stage GHGs. It may be the case that low-impact farms have similar impact drivers. We again find variable sources of impact, even for low-impact farms (Fig. 2, C and D). Reducing impacts means focusing on different areas for different producers and, by implication, adopting different practices.

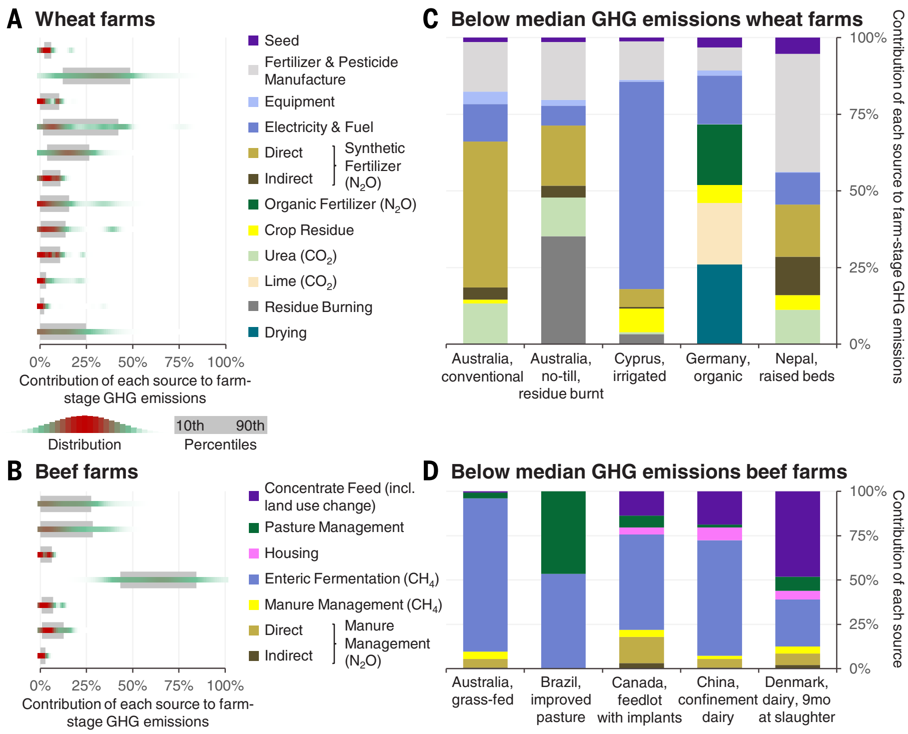

Fig. 2. Contributions of emission sources to total farm-stage GHG emissions. (**A**, and **B**). Gray bars show 10th- and 90th-percentile contributions. Shaded bars represent the distribution. For example, the 90th-percentile contribution of organic fertilizer N_2O to farm-stage emissions is 16%, but for most wheat producers the contribution is near 0%. Density is estimated using a Gaussian kernel with bandwidth selection performed with biased cross-validation. (**C**, and **D**) Contributions of emission sources for example producers with below median GHG emissions.

To explore this further, we use sensitivity analysis (*26*) to decompose the variance in each product's impact into its sources. Numerous sources contribute to variance (fig. S10). Most notably, for all crop calorie production globally, differences in fallow duration and multiple cropping drive 40% of the variance in land use. This is important as most strategies to increase productivity are focused on increasing single crop yields (*27*). But for many producers, increasing cropping intensity through the use of early-maturing varieties, intercropping, catch crops, and enhanced irrigation can provide more economically viable and trade-off–free ways to boost productivity and reduce impacts (*27*).

Geography plays a major role in this variation and affects the economic and environmental desirability of different practices (*28*). However, at the heart of agriculture is changing site conditions to enhance productivity (such as liming, terracing, or installing drainage), meaning that statements on the importance of geography have limitations. Nevertheless, some impact sources stand out. We find that freshwater aquaculture ponds create 0-450g of methane per kg of liveweight (for context, enteric fermentation in dairy cows creates ~30-400g per kg of liveweight). Of this variation, a third is explained by temperature (*17*), which accelerates methanogenesis and net primary production. Improving aeration and limiting addition of surplus feed to ponds can abate these emissions, particularly important in warm countries. Further, for every kilogram of nitrogen applied to crops, between 60-400g is lost in reactive forms. Of this wide range, ~40% is explained by site conditions, including soil pH, temperature, and drainage (*17*). Prior research has also found that the potential of soil to store carbon varies significantly with soil properties, slope, and prior practice (29).

Providing producers with multiple ways to reduce their environmental impacts recognizes the variability in sources and drivers of impact but requires a step change in thinking: that practices such as conservation agriculture or organic farming are not environmental solutions in themselves but options that producers choose from to achieve environmental targets.

However, some practice changes can be pursued across all producers. Methane from flooded rice, enteric methane from ruminants, and concentrate feed for pigs and poultry are sizeable globally, representing 30% of food's GHG emissions; are material for all producers, contributing at least 17% of farm-stage emissions (Fig. 2B and fig. S7); and can be mitigated with relatively trade-off–free approaches such as shorter and shallower rice flooding (*30*), improving degraded pasture (fig. S6), and improving lifetime animal productivity (*8*). Further, emissions from deforestation and cultivated organic soils drive on average 42% of the variance in each product's agricultural GHG emissions (fig. S10) and dominate the highest-impact producers' emissions (fig. S11), further justifying ongoing efforts to curb forest loss and limit cultivation on peatlands.

Communicate impacts up the supply-chain

Processors, distributors, and retailers can substantially reduce their own impacts. For any product, 90th-percentile post-farm emissions are 2-140 times larger than 10th-percentile emissions, indicating large mitigation potential (fig. S12). For example, returnable stainless-steel kegs create just 20g of CO_2eq per liter of beer, but recycled glass bottles create 300-750g of CO_2eq, and bottles sent to landfills create 450-2500g of CO_2eq.

Processing, more durable packaging, and greater usage of coproducts can also reduce food waste. For example, wastage of processed fruit and vegetables is ~14% lower than that of fresh fruit and vegetables, and wastage of processed fish and seafood is ~8% lower (*24*). Providing processors and retailers with information about the impacts of their providers could encourage them to reduce waste where it matters most. For products such as beef, distribution and retail losses contribute 12-15% of emissions (fig. S13), whereas the sum of emissions from packaging, transport, and retail contributes just 1-9%. Here, reducing losses is a clear priority.

As a third strategy, procurement could source from low-impact farms. Although this strategy is important, and possible only with information about the impacts of providers, it has clear limitations. To be effective, it relies on high-impact production not simply being purchased elsewhere in the market. The case of the Roundtable on Sustainable Palm Oil (RSPO) shows that this is hard to achieve: despite one-fifth of 2017 palm oil production being certified, there remains virtually no demand in China, India, and Indonesia (*31*). Alternatively, this strategy would be effective if higher prices for sustainable production incentivized low-impact producers to increase output or high-impact producers to change practices. The case of organic food shows how passing premiums to consumers limits total market size and widespread practice change.

However, processors and retailers routinely demand that products meet taste, quality, and food safety standards. These markets are concentrated, with just 10 retailers representing 52% of U.S. grocery sales and 15% of global sales (*32*). This sometimes means that standards achieve market transformation (*33*), where virtually all producers adhere to gain market access. A fourth strategy for producers is setting environmental standards. These are particularly important: Although many environmental issues can be monitored and mitigated in a flexible way, issues such as harmful pesticide usage and deforestation require strict controls, and issues such as on-farm biodiversity are hard to quantify (*28*). Procurement, farming organizations, and international policy-makers must come together to implement a safety net for global agriculture—comprehensive standards to manage the worst and hardest-to-quantify environmental issues, extending the successes of existing schemes and enabling a flexible mitigation approach to operate effectively.

Producer mitigation limits and the role of consumers

Though producers are a vital part of the solution, their ability to reduce environmental impacts is limited. These limits can mean that a product has higher impacts than another nutritionally equivalent product, however it is produced.

In particular, the impacts of animal products can markedly exceed those of vegetable substitutes (Fig. 1). To such a degree that meat, aquaculture, eggs, and dairy use ~83% of the world's farmland and contribute 56-58% of food's different emissions, despite providing only 37% of our protein and 18% of our calories. Can animal products be produced with sufficiently low impacts to redress this vast imbalance? Or will reducing animal product consumption deliver greater environmental benefits?

We find that the impacts of the lowest-impact animal products exceed average impacts of substitute vegetable proteins across GHG emissions, eutrophication, acidification (excluding nuts), and frequently land use (Fig. 1 and data S2). These stark differences are not apparent in any product groups except protein-rich products and milk.

Although tree crops can temporarily sequester carbon and reduce nutrient leaching, the impact of nuts is dominated by low-yielding cashews and water-, fertilizer-, and pesticide-intensive almonds. Production of nuts doubled between 2000 and 2015 (*4*), and more work is required to improve their resource use efficiency. Although aquaculture can have low land requirements, in part by converting by-products into edible protein, the lowest-impact aquaculture systems still exceed emissions of vegetable proteins. This challenges recommendations to expand aquaculture (*1*) without major innovation in production practices first. Further, though ruminants convert ~2.7

billion metric tons of grass dry matter, of which 65% grows on land unsuitable for crops (*34*), into human-edible protein each year, the environmental impacts of this conversion are immense under any production method practiced today.

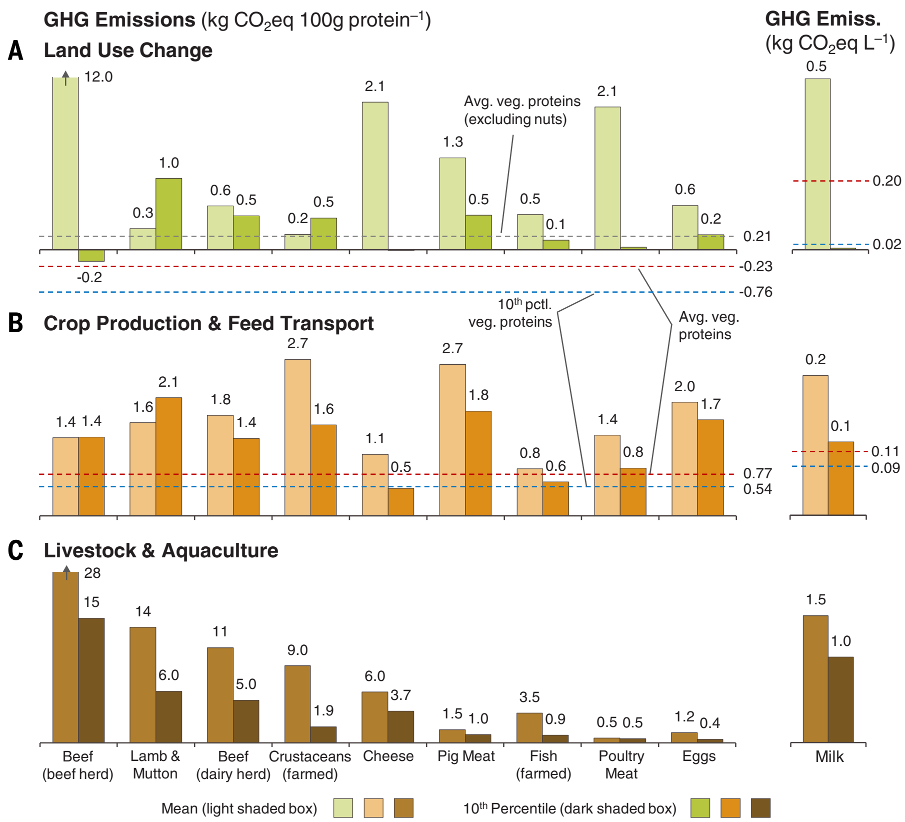

Fig. 3. Mean and 10th percentile GHG emissions of protein-rich products across three major production stages. Red lines represent average vegetable protein emissions, and blue lines represent 10th-percentile emissions. The gray line represents average emissions excluding nuts, which can temporarily sequester carbon if grown on cropland or pasture. To calculate 10th-percentile emissions by stage, we averaged across farms that have total emissions between the 5th and 15th percentiles, controlling for burden shifting between stages.

Using GHG emissions (Fig. 3), we identified five primarily biophysical reasons for these results. These reasons suggest that the differences between animal and vegetable proteins will hold into the future unless major technological changes disproportionately target animal products. First, emissions from feed production typically exceed emissions of vegetable protein farming. This is because feed-to-edible protein conversion ratios are greater than 2 for most animals (*13*, *34*); because high usage of low-impact by-products is typically offset by low digestibility and growth; and because additional transport is required to take feed to livestock. Second, we find that deforestation for agriculture is dominated (67%) by feed, particularly soy, maize, and pasture, resulting in losses of above- and below-ground carbon. Improved pasture management can temporarily sequester carbon (*25*), but it reduces life-cycle ruminant emissions by a maximum of 22%, with greater sequestration requiring more land. Third, animals create additional emissions from enteric fermentation, manure, and aquaculture ponds. For these emissions alone, 10th-percentile values are 0.4-15kg of CO_2eq per 100g of protein. Fourth, emissions from processing, particularly emissions from slaughterhouse effluent, add a further 0.3-1.1kg of CO_2eq, which is greater than processing emissions for most other products. Last, wastage is high for fresh animal products, which are prone to spoilage.

Mitigation through consumers

Today, and probably into the future, dietary change can deliver environmental benefits on a scale not achievable by producers. Moving from current diets to a diet that excludes animal products (table S13) (*35*) has transformative potential, reducing food's land use by 3.1 (2.8-3.3) billion hectares (a 76% reduction), including a 19% reduction in arable land; food's GHG emissions by 6.6 (5.5-7.4) billion metric tons of CO_2eq (a 49% reduction); acidification by 50% (45-54%);

eutrophication by 49% (37-56%); and scarcity-weighted freshwater withdrawals by 19% (−5 to 32%) for a 2010 reference year. The ranges are based on producing new vegetable proteins with impacts between the 10th- and 90th-percentile impacts of existing production. In addition to the reduction in food's annual GHG emissions, the land no longer required for food production could remove ~8.1 billion metric tons of CO_2eq from the atmosphere each year over 100 years as natural vegetation reestablishes and soil carbon re-accumulates, based on simulations conducted in the IMAGE integrated assessment model. For the United States, where per capita meat consumption is three times the global average, dietary change has the potential for a far greater effect on food's different emissions, reducing them by 61-73%. See supplementary text (*17*) for diet compositions and sensitivity analyses and fig. S14 for alternative scenarios.

Consumers can play another important role by avoiding high-impact producers. We consider a second scenario where consumption of each animal product is halved by replacing production with above-median GHG emissions with vegetable equivalents. This achieves 71% of the previous scenario's GHG reduction (a reduction of ~10.4 billion metric tons of CO_2eq per year, including atmospheric CO_2 removal by regrowing vegetation) and 67, 64, and 55% of the land use, acidification, and eutrophication reductions. Further, lowering consumption of more discretionary products (oils, sugar, alcohol, and stimulants) by 20% by avoiding production with the highest land use reduces the land use of these products by 39% on average. For emissions, the reductions are 31 to 46%, and for scarcity-weighted freshwater withdrawals, 87%.

Communicating average product impacts to consumers enables dietary change and should be pursued. Though dietary change is realistic for any individual, widespread behavioral change will be hard to achieve in the narrow timeframe remaining to limit global warming and prevent further, irreversible biodiversity loss. Communicating producer impacts allows access to the second scenario, which multiplies the effects of smaller consumer changes.

An integrated mitigation framework

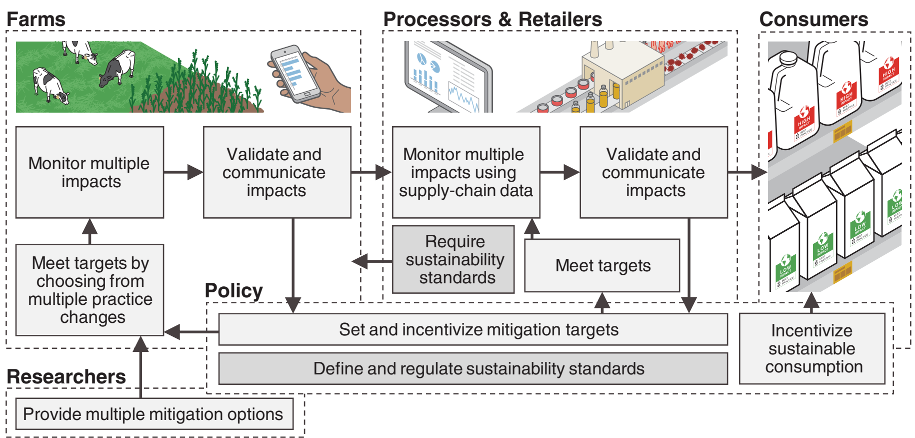

Fig. 4. Graphical representation of the mitigation framework.

In Fig. 4 we illustrate a potential framework implied by our findings, prior research, and emerging policy (*9*). First, producers would monitor their impacts using digital tools (*36*). Data would be validated against known ranges for each value (e.g., maximum yields given inputs) and validated or certified independently. In the United States these tools have already been integrated with existing farm software (*31*); in Africa and South Asia they are being trialed with 2G mobile phones (*37*); and in China they have been operated by extension services with extremely successful results (*24*).

Second, policy-makers would set targets on environmental indicators and incentivize them by providing producers with credit or tax breaks or by reallocating agricultural subsidies that now exceed half a trillion dollars a year worldwide (*38*). Third, the assessment tools would provide multiple mitigation and productivity enhancement options to producers. Ideally these tools would become platforms that consolidate the vast amounts of research conducted by scientists around the world, while also sharing producer best practices. In particular, practice sharing offers a very effective way to engage producers (*24*). Maximum flexibility also ensures least-cost mitigation (*39*) and supports producer-led innovation (*24*).

Finally, impacts would be communicated up the supply chain and through to consumers. For commodity crops that are hard to trace (*31*), this may not be feasible and mitigation efforts may have to focus on producers. For animal products, stringent traceability is already required in many countries (*40*), suggesting that communicating impacts is most feasible where it matters the most. Communication could occur through a combination of environmental labels, taxes or subsidies designed to reflect environmental costs in product prices (*35*), and broader education on the true cost of food.

We have consolidated information on the practices and impacts of a wide range of producers. From this research, we have provided a unified exposition of the environmental science for making major changes to the food system. We hope this stimulates progress in this crucially important area.

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Supplementary Materials:

Materials and Methods

Supplementary Text

Figs. S1 to S14

Tables S1 to S17

Captions for Data S1 to S2

References (*41–151*)