nature sustainability

Article

https://doi.org/10.1038/s41893-022-00965-x

The environmental footprint of global food production

Received: 10 December 2021

Accepted: 2 September 2022

Benjamin S. Halpern[1,2] ✉, Melanie Frazier[1], Juliette Verstaen[1], Paul-Eric Rayner[1], Gage Clawson[1], Julia L. Blanchard[3,4], Richard S. Cottrell[1,5,6], Halley E. Froehlich[7,8], Jessica A. Gephart[9], Nis S. Jacobsen[10], Caitlin D. Kuempel[1,11], Peter B. McIntyre[12], Marc Metian[13], Daniel Moran[14], Kirsty L. Nash[3,4], Johannes Többen[15,16] and David R. Williams[17]

Feeding humanity puts enormous environmental pressure on our planet. These pressures are unequally distributed, yet we have piecemeal knowledge of how they accumulate across marine, freshwater and terrestrial systems. Here we present global geospatial analyses detailing greenhouse gas emissions, freshwater use, habitat disturbance and nutrient pollution generated by 99% of total reported production of aquatic and terrestrial foods in 2017. We further rescale and combine these four pressures to map the estimated cumulative pressure, or 'footprint', of food production. On land, we find five countries contribute nearly half of food's cumulative footprint. Aquatic systems produce only 1.1% of food but 9.9% of the global footprint. Which pressures drive these footprints vary substantially by food and country. Importantly, the cumulative pressure per unit of food production (efficiency) varies spatially for each food type such that rankings of foods by efficiency differ sharply among countries. These disparities provide the foundation for efforts to steer consumption towards lower-impact foods and ultimately the system-wide restructuring essential for sustainably feeding humanity.

Human diets have enormous implications for both human and environmental health[1–6]. The global food system is fuelled by extensive appropriation and degradation of Earth's natural capital, using roughly 50% of habitable land[7,8] and >70% of available freshwater[9], emitting 23–34% of global anthropogenic greenhouse gases (GHG)[8,10], polluting watersheds and coastal seas with nutrients[11] and harvesting aquatic food from nearly every river, lake and ocean[12,13]. However, food types are strikingly

---

[1]National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara, CA, USA. [2]Bren School of Environmental Science and Management, University of California, Santa Barbara, CA, USA. [3]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia. [4]Centre for Marine Socioecology, University of Tasmania, Hobart, Tasmania, Australia. [5]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Australia. [6]Centre for Biodiversity and Conservation Science, The University of Queensland, Brisbane, Australia. [7]Environmental Studies, University of California, Santa Barbara, CA, USA. [8]Ecology, Evolution and Marine Biology, University of California, Santa Barbara, CA, USA. [9]Department of Environmental Science, American University, Washington, DC, USA. [10]Technical University of Denmark, National Institute of Aquatic Resources, Lyngby, Denmark. [11]Australian Rivers Institute, Griffith University, Nathan, Queensland, Australia. [12]Department of Natural Resources and the Environment, Cornell University, Ithaca, NY, USA. [13]International Atomic Energy Agency–Marine Environment Laboratories (IAEA-MEL), Radioecology Laboratory, Principality of Monaco, Monaco. [14]Program for Industrial Ecology, Department of Energy and Process Technology, Norwegian University of Science and Technology, Trondheim, Norway. [15]Institute for Economic Structures Research (GWS), Osnabrück, Germany. [16]Social Metabolism & Impacts, Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Potsdam, Germany. [17]Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, UK. ✉e-mail: halpern@nceas.ucsb.edu

disparate with respect to the environmental pressures that result from their production[1,2,14–19].

There is an urgent need to shift food systems towards food types, locations and production methods that can feed a growing, and increasingly wealthy, human population while reducing environmental degradation and enhancing food security. Making informed decisions to support this transition while accounting for local context requires, as a first step, comprehensive and spatially explicit tracking of all food types and their associated environmental pressures. However, most environmental assessments of food systems have focused on single-food sectors, one or a few classes of environmental pressure and are not spatially explicit[20]. A striking example is that aquatic foods from wild and farmed sources are either overlooked or highly aggregated in prior analyses, despite their importance for global food supply and nutrition[21,22]. Moreover, most assessments of food's environmental pressures have been limited largely to national or global scales[14]. Finer-scale analyses are required to assess where pressures are coming from and how environmental efficiency of production varies among regions.

Integrative methods from the life-cycle assessment (LCA) literature have yielded important insights into the environmental pressures of food production[1,14,15,23], setting the stage for parallel analyses across food types and cumulatively across pressures. Furthermore, previous work for specific food groups has revealed the global geography of individual environmental pressures, for example, the freshwater use of crops[24] and livestock[25], GHG emissions from crops[26,27] and the distribution of marine fisheries[12,28]. These pressures often coincide in space, hence devising a coherent and effective set of interventions to minimize environmental pressures requires spatial analysis of the cumulative pressure (that is, 'footprint') of all foods.

Mapping the location and intensity of environmental pressures for each food type in a standardized, comparable manner is requisite to understanding the footprint of food production across the planet[20,29]. Integrating across food types is also essential; inferences from cumulative analyses often differ from the results of individual pressure assessments[30–33]. Here we advance understanding of environmental consequences of global food production in three ways: (1) expanding standardized assessment of food types to incorporate most marine, freshwater and terrestrial foods, representing 99% of total reported global production (Supplementary Methods); (2) applying a recently developed method for assessing cumulative environmental pressure from food production[29] to calculate and map the aggregate footprint across four dominant classes of environmental pressures (GHG emissions, freshwater use, excess nutrients and area disturbance); and (3) using our spatial cumulative footprint assessment to explore where and how much each type of food contributes to food's total environmental footprint.

We focus our analysis on pressures, defined as the inputs, processes and outputs used to produce different food types[29,33] (Fig. 1). Mapping the environmental pressures from food production is a prerequisite for further translation and tracking of these pressures into spatially explicit environmental impacts that describe the consequences of pressures on biodiversity, human health, nutrition, economics and other systems[34]. Moving beyond pressures to impacts is complex and dependent on the end point of interest. The ultimate impact of pressures on ecosystems, human health, the economy or other systems will depend on what is being displaced, the sensitivity of systems to specific pressures[30] and local biophysical and socio-economic conditions.

An assessment focused on pressures is best suited to inform where improvements to production levels or technologies will be most effective at reducing food's footprint. GHG emissions, for example, may drive most of their impact far away, spatially and temporally, from the source of emissions, but locating the source of those emissions will help inform more sustainable production. Our findings reveal places and food types that have the smallest and largest footprints in marine, freshwater and terrestrial systems. We map which individual pressures drive cumulative pressure and which foods are most environmentally efficient (cumulative pressures per unit of production) and where these efficiencies occur. These advances create new opportunities for food producers, consumers and policymakers to identify leverage points for enhancing the efficiency of food systems in support of food security and sustainability priorities.

Food's cumulative footprint

To estimate the source location and cumulative magnitude of environmental pressures of food production, we mapped (5 arcminute resolution, projected to 36 km^2 equal-area resolution; Methods) the pressures for the majority of food production in 2017, including crops (human and animal consumption), livestock (meat, eggs, milk), marine aquaculture (finfish, bivalves, crustaceans), marine fisheries and freshwater fisheries. We focused on food products that provide nutrition, for example, in the form of protein, carbohydrates and fats; we excluded agricultural items with no, or minimal, nutritional value such as coffee, tea and tobacco and non-edible items, such as fibre crops. We mapped four dominant classes of pressure that are the focus of the vast majority of global research on food sustainability[14,20]: GHG emissions (in CO_2 equivalent, CO_2eq), blue freshwater (FW) use (m^3), excess nutrients (tonnes N and P estimated to run-off/leach and for N, volatilization as NH_3) and habitat disturbance (D, in km^2 equivalent, km^{2}eq). For each food type, we multiplied the amount of food production (for example, standing head of animals, area of production, tonnes production/capture) in each pixel by regionally specific estimates of pressure generated per unit of production.

We used models and methods similar to LCAs to estimate a suite of pressures resulting from food production[1,14,15,23]. However, we expand on LCA efforts by mapping the pressures to the specific locations where they are incurred[29]. We did not attempt to include the pressures from all components of the full life cycle of food production (and consumption) because the information required to map these pressures is unavailable. Our focus was on within-farm-gate pressures, and we excluded pressures from indirect activities such as processing and transportation of product, extraction of fuel and manufacturing of equipment. For pressures arising from animal feeds, we always mapped the pressures to the location where the feed is grown for each animal system, not where it is consumed. To calculate the cumulative pressure, we adopted similar methods as other cumulative measures[30], rescaling each individual pressure (GHG, FW, NP, D; Supplementary Data 1) by dividing the values in each pixel (i) by the total global pressure summed across all food systems and pixels (T; Supplementary Data 2) such that each pixel describes its proportional contribution to the global total for that pressure. We then summed these rescaled pressure layers to obtain a total cumulative pressure score (CP) for each pixel i, such that

$$\mathrm{CP}_i = \mathrm{GHG}_i/\mathrm{GHG}_T + \mathrm{FW}_i/\mathrm{FW}_T + \mathrm{NP}_i/\mathrm{NP}_T + D_i/D_T.$$

High total cumulative pressure can arise from high pressure per unit of production, large amounts of production or both. To disentangle this, we calculated a metric of efficiency (E) by summing the cumulative pressure (CP) for each food type (f) and country (c) and dividing by the unit of production (UP) measured as weight (tonnes), protein content (edible Kg) or energy content (kcal), such that $E_{c,f} = \mathrm{CP}_{c,f} / \mathrm{UP}_{c,f}$ (Supplementary Data 3).

The cumulative footprint of food is remarkably skewed geographically (Fig. 2 and Supplementary Data 4). Contributions from land (89.9% of global cumulative pressure) vastly outweigh those from oceans (9.9%) or freshwater ecosystems (0.2%), yet these ocean pressures are substantial given that relatively little (1.1%, by tonnes) food and feed for fed animals comes from the sea[35,36]. The top 1% of pixels with respect to cumulative pressures (5,114,880 km^2 total) fall nearly entirely on land (only 94,608 km^2, or 1.8% of this top 1%, fall in the ocean and none in the high seas; Fig. 2a) and produce 39.4% of food's global cumulative

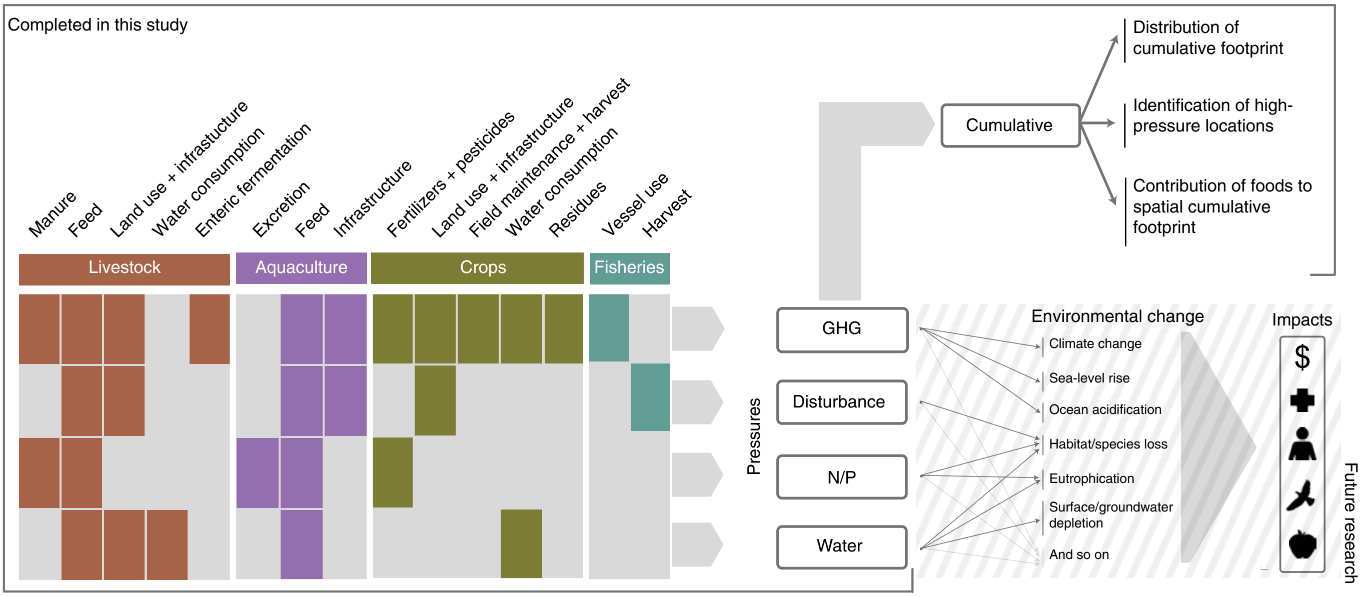


Fig. 1 | Schematic view of methods used to assess and map cumulative pressures from food production. Pathways within the hashed box illustrate possible future research that is outside the scope of the study here. Icons adapted from Canva.com.

pressure and 30.9% of assessed tonnage of food. They occur primarily in India, China, the United States, Brazil and Indonesia (Fig. 2a). Nearly all pressures (92.5%) are exerted in just 10% of pixels.

Because the pressure footprints are concentrated in 10% of the planet, their overall distribution is broadly similar (Fig. 2), but the areas of greatest pressure for each often do not overlap (Fig. 3). Understanding where and how much different pressures overlap is uniquely possible with a multiple pressure assessment and helps identify potential policy and sustainability win–wins, where mitigating a pressure can lead to co-benefits for other pressures and likely trade-offs where improvements in one pressure exacerbate other pressures. Policy aimed at one pressure would not address the key challenges associated with others.

The cumulative pressure imposed by food production is greatest in India, China, the United States, Brazil and Pakistan (Fig. 4, Extended Data Figs. 1 and 2 and Supplementary Data 5 and 6). These high-population countries alone contribute nearly half (43.8%; Fig. 4) of global cumulative pressure. Country-level cumulative pressure derives almost entirely from land-based food production with the exception of island nations and some countries with extensive coastlines, such as Norway (88% from oceans), Japan (40%), Chile (38%), the United Kingdom (38%), Indonesia (33%) and Vietnam (26%) (Supplementary Data 7). Marine fisheries and aquaculture contribute >25% of total pressures in 94 countries, primarily in island nations (Supplementary Data 7).

We find that pigs, beef, rice and wheat crops generate the highest cumulative pressure from food production (Fig. 5 and Supplementary Data 8). However, our analyses reveal that the large global footprint of these products arises from different classes of pressures. For example, the GHG emissions from cattle meat are noteworthy (60% of their cumulative pressures; Supplementary Data 8) due to their ruminant digestive system, along with nutrient emissions from their wastes and feed production (31%). The footprint of rice and wheat crops more strongly reflects water use and disturbed land area (Fig. 5 and Extended Data Fig. 3). Assessing the cumulative pressures of different foods by country also reveals that crop production, consumed by both people and livestock, dominates overall pressure in nearly all countries, but there are some exceptions such as Brazil, which has relatively high cumulative pressures from meat production (Fig. 4b and Supplementary Data 5).

The cumulative pressure for fed animals spreads far beyond the farm where they are raised. For example, because marine forage fish comprise an average of ~0.15% of chicken and ~0.02% of pig feed[35,37], these livestock have similar cumulative ocean footprints to that of some mariculture species (Fig. 5). Feed for mariculture species increasingly includes crops, and all fed species have substantial footprint on land (Supplementary Data 9).

This displacement of cumulative pressures is not limited to feed for fed species. For example, of the 172 countries with Food and Agriculture Organization (FAO) trade data[38], 152 reported crop imports, which means they displace at least some portion of their cumulative pressures to obtain their domestic crop supply. On the basis of trade data, the largest proportional exporters of crop cumulative pressures will be small, highly developed countries such as Hong Kong, the Netherlands, Belgium and Montenegro; countries in the Middle East with generally poor growing conditions, such as Kuwait, United Arab Emirates, Jordan, Oman and Saudi Arabia; and island nations such as the Maldives and Trinidad and Tobago.

Environmental efficiencies of food

The environmental efficiency of food production – measured here as the ratio of cumulative environmental pressures to production per area (for example, pixel, country, global), such that larger values represent lower efficiency – varies not only among food types but also geographically within each food type (Supplementary Data 3). In contrast to earlier treatments of this concept[14], we calculate efficiencies based on cumulative rather than single pressures. Our spatially explicit approach reveals how cumulative pressure and its components are distributed across the planet and importantly *where* efficiencies are greatest or lowest for each food. Efficiencies for the same crops can vary 4.3 to 17.7 times (90th versus 10th quantile; average 7.1) among countries (Fig. 6 and Supplementary Data 3) due to differences in water consumption, fertilizer/pesticide use and farming practices. For example, the United States (the largest producer of soy[39]) is 2.4 times more efficient than India (the 5th largest) in producing soy, largely because US farmers have been able to use technologies to reduce GHG emissions and increase yields[40]. Similarly, efficiencies for marine fisheries vary up to 22-fold among countries (mean of 6; Supplementary Data 3) based on the specific species fished and gear types used within a country. For example, China and Brazil are 1.5 and 1.9 times less efficient than Russia in harvest of demersal fish (Supplementary Data 3), respectively, primarily because they rely heavily on more destructive gear types such as bottom

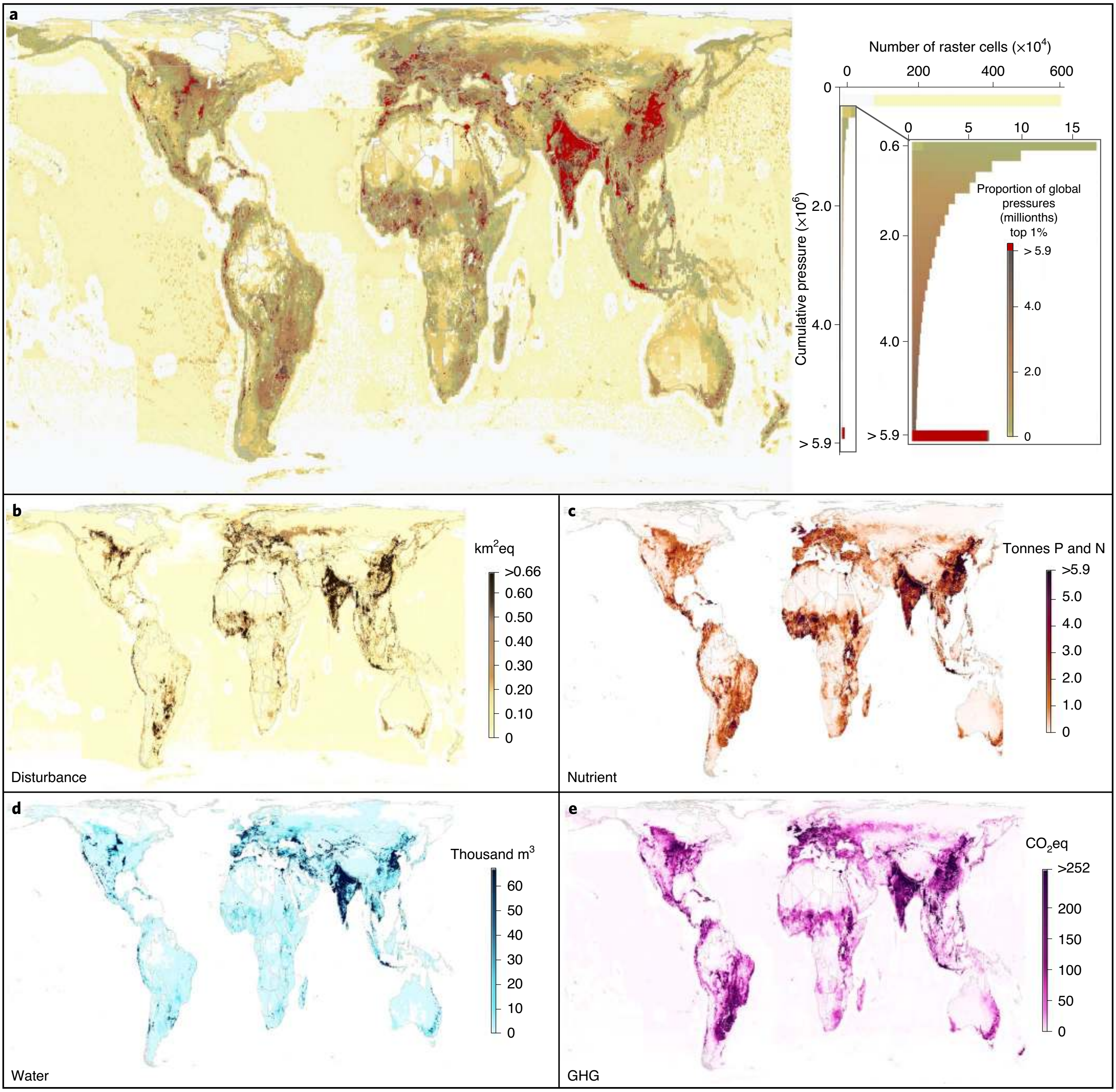


Fig. 2 | Global maps of food's footprint. **a**–**e**, Proportion of global cumulative environmental pressure (in millionths) per pixel from all foods (**a**), representing the combined pressure from disturbance (**b**), excess nutrients from nitrogen and phosphorus (summed) (**c**), blue freshwater use (**d**) and GHG emissions (**e**). The histogram of per-pixel values for cumulative pressure (inset with expanded axis) shows the skewed distribution in values illustrated in the map; the colour ramp for **a** in both the map and histogram is based on per-pixel proportional values, with the top 1% of values >5.9 (99th quantile value) coloured red. The maximum cumulative pressure value is 2.305×10^{-4}, near Ashdod in Israel.

trawls[41], affecting both disturbance and GHG emissions pressures. Such geographic variation in environmental efficiencies could be leveraged to benefit both food production and the environment.

Important within-country differences exist among foods that deviate from expectations based on global averages (Fig. 6). For example, measured by tonnes of production, on-farm efficiency for pig meat is 5.2-fold less efficient than cow meat in Indonesia (Supplementary Data 3). This pattern is likely due to very low production rates of meat per animal for pigs in Indonesia, perhaps due to the large proportion (64%) of backyard pigs[42]. In China, while demersal fisheries are notably inefficient, forage fisheries are even less efficient (1.1-fold; Supplementary Data 3) because a large percentage of the forage fish catch is caught using destructive gear types[41]. In Morocco, sorghum is 5.8-fold less efficient than millets (Supplementary Data 3), likely because locally sorghum requires more land use per tonne of product than millets[39].

Efficiencies differed depending on whether food production was measured by protein content (Fig. 6; Supplementary Data 3), energy content (kcal; Extended Data Fig. 4) or weight (tonnes; Extended Data Fig. 5). For example, some countries were inefficient when measured by weight but more efficient measured by protein (for example, Brazil, China) and vice versa (for example, United States, Russia, Argentina; Fig. 4a and Supplementary Data 3). Changes in efficiency for specific

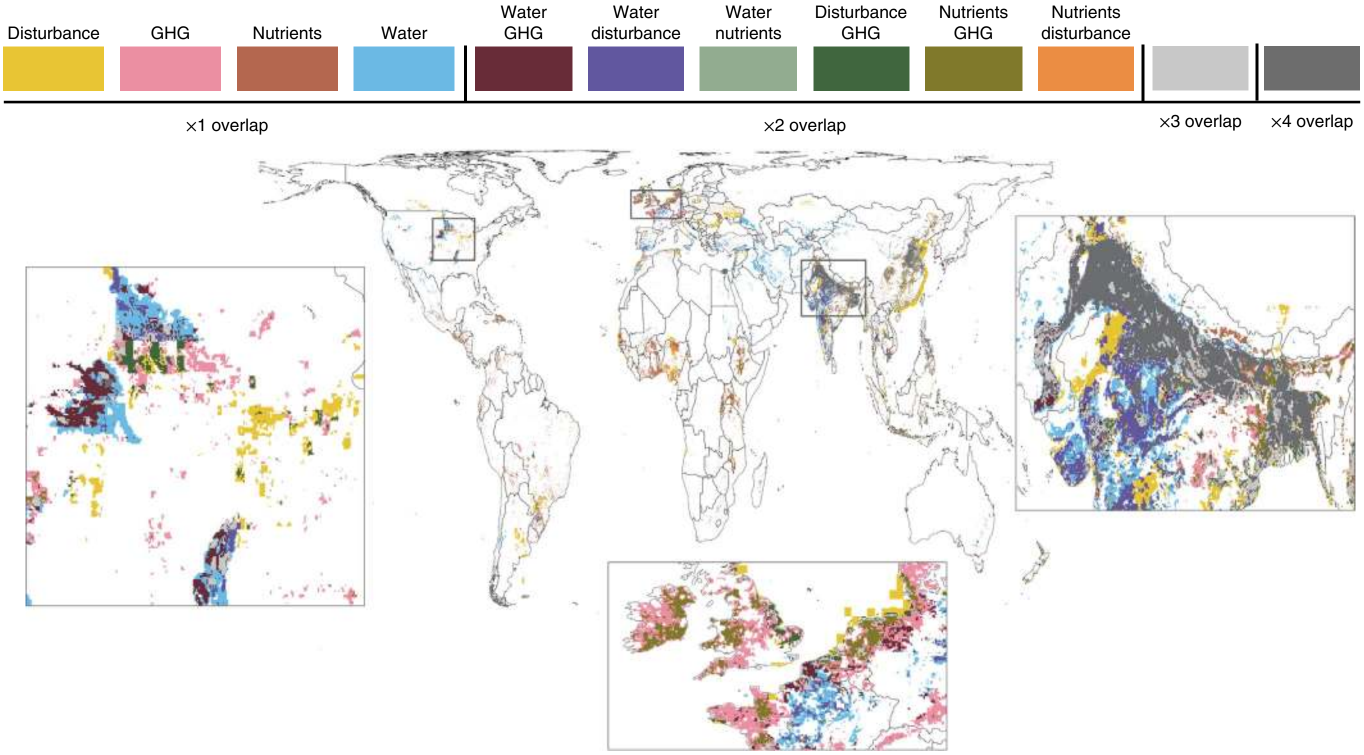


Fig. 3 | Spatial overlap of the top 1% greatest pressure values for each of the four dominant pressures from food production. Colours represent where high pressures are unique (×1 overlap) or where pairs of pressures overlap (×2 overlap). Three-way overlaps (light grey) are not distinguished among the four different possible combinations. Insets show zoomed-in views of three regions with substantial amounts of different groups of overlap.

foods primarily emerged for shellfish (large weight of inedible shell) and many crops (due to variation in protein content). For example, tree nuts, oils, pulses, rice, soybeans and wheat are more efficient when measured by protein due to the high protein content of these crops, whereas cassava and sugarcane are more efficient by energy content. These variations in production efficiencies across foods and among countries, measured across the cumulative pressures from food, are not currently captured by dietary guidelines based on generalized sustainability metrics, an important oversight our work helps address. The ability to view and compare efficiencies in relation to different denominators (weight, protein or energy) allows our results to be adapted to different policy needs.

Discussion

Our inclusive assessment of all foods and cumulative pressures builds on previous understanding from single-food or single-pressure assessments and provides support for some previous results. For example, we confirm that beef dominates food's global footprint and that environmental pressures from food are widespread. However, simultaneously mapping of four major classes of environmental pressure across land and sea also reveals many hidden realities of the current food system. Two aspects of our results have particularly important policy implications for both food security and environmental conservation.

Cumulative pressures matter

Cumulative pressures can inform development of more holistic spatial food-production management and policies in a way that individual pressures cannot. The spatial distribution and concentration of different pressures varies on land and in aquatic environments (Figs. 2 and 3), creating both opportunities and challenges for policy interventions aimed at reducing food's footprint. The opportunities lie in the multiple pathways that a cumulative pressure lens helps identify to reduce footprints: by improving efficiencies of individual foods across multiple pressures, decreasing production of inefficient foods, increasing production of efficient foods to meet demand or combinations of these approaches. Spatial overlap in pressures also identifies where policy can expect co-benefits, where strategies aimed at one pressure (for example, nutrient reduction to mitigate eutrophication) has the potential to benefit another (for example, GHG emissions reductions) and help avoid potential trade-offs, where mitigating one pressure exacerbates another. The challenges arise in finding solutions that are appropriate and effective in different locations and contexts around the world. For example, switching to high-yielding greenhouse-grown vegetables could reduce cumulative pressures through improved land-use and fertilizer efficiencies, outweighing the lower GHG efficiency[43]. However, such a strategy will only be appropriate if the capital and infrastructure required are available and the benefit distributed in such a way as to improve economic well being or food security—something that is unlikely to be true for many regions of the world. Conversely, if we can meet global food needs by concentrating pressures in relatively few areas (for example, land sharing versus sparing), we can spare larger areas from these pressures, which has many sustainability benefits for biodiversity, carbon storage and other outcomes[44–46]. Concentrating pressures through intensification may therefore result in lower cumulative environmental pressure but may be at odds with local-scale socio-economic, ethical or cultural factors that, if ignored, can drive instability or further inequality, as witnessed in multiple countries during the expansion of shrimp farming[47,48].

Importantly, food types often rank differently in their global cumulative pressure compared with ratings derived from per-unit assessments of individual pressures. For example, the cumulative pressure from catching demersal fish is triple that of raising sheep for meat (Supplementary Data 8), which is counter to common generalizations. However, demersal fishing produces four times more food[41] than sheep farming[49]. In other cases, per-unit inefficiencies exceed effects from the scale of production effects. For example, the

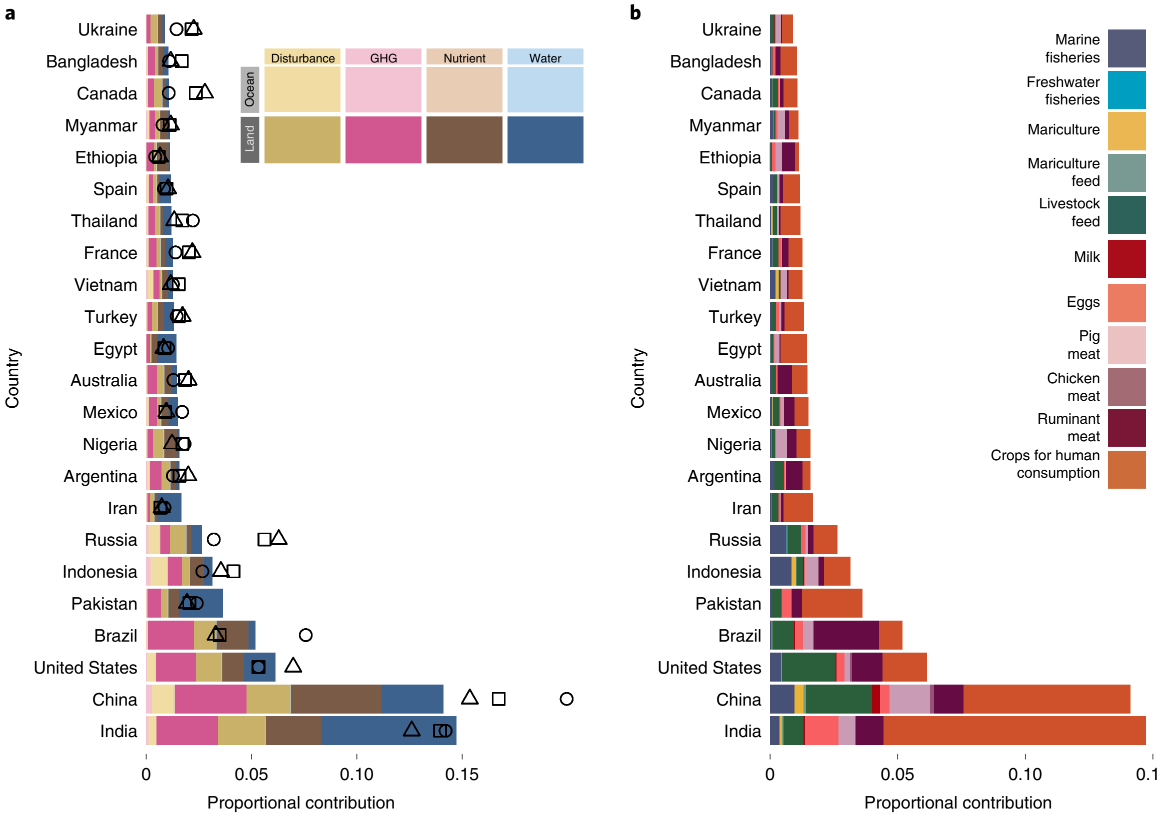


Fig. 4 | Proportional contribution to the cumulative food footprint in the highest-ranking countries. a,**b**, Proportional contribution to the cumulative food footprint in the highest-ranking countries for each pressure summed across all food types (**a**) or each food type summed across four pressure classes (**b**). These areas have the highest proportion of cumulative environmental pressure and collectively account for 70.2% of the global footprint of food production. In **a**, stacked bars show the proportional contribution of marine (lighter colours, calculated as the Exclusive Economic Zone) and terrestrial (darker colours) pressures from all foods combined. Symbols indicate the proportion of global food production (excluding feed) for each country as measured by tonnes (circles), protein (triangles) and kcal (squares). Where symbols overlap the bar, the production of food is low relative to the cumulative environmental pressure. In **b**, bars for animal production include environmental pressures arising from animal feeds. Additional countries are shown in Extended Data Figs. 1 and 2.

low efficiency of Brazilian beef production means that it has a higher total cumulative pressure than US beef production (Supplementary Data 3 and 5), despite producing about 10% less meat[49]. An interesting case is the sustainable harvest of wild animals and plants, which can be very efficient from a cumulative pressure standpoint because these organisms do not require human-appropriated freshwater resources or create excess nutrients, thereby removing two major pressures associated with farming food. Large-scale, high-disturbance harvesting (for example, some demersal fishing practices) can still produce a large cumulative pressure[12,16,28]. This environmental efficiency underscores the importance of wild foods for food security. However, their generally lower sustainable production rates per area and the potential impacts of harvesting (for example, biodiversity loss, ecological/food web impacts and the potential for zoonotic disease outbreaks) offer limited capacity for sustainable expansion.

Cumulative environmental efficiencies are highly variable

Perhaps the most striking finding from our analysis is the dramatic differences in food-production efficiencies (Fig. 6 and Supplementary Data 3). Such differences have been found for individual pressures[14], but the rank order across food types found here when measured by cumulative pressures often diverge from individual pressure rankings, and importantly, vary substantially among countries. We estimate up to >tenfold variation among countries for many livestock, fisheries and crop products (based on 90th and 10th quantiles; Fig. 6 and Supplementary Data 3). For example, locations of greatest pressure differ (Fig. 3) despite broadly similar distributions of pressures (Fig. 2). This spatial heterogeneity provides many opportunities for both researchers and policymakers to leverage that variation to enhance overall food system sustainability.

Looking forward

Comprehensive and standardized data on where production exerts pressures reveal where interventions will be most effective and are the critical foundation to determine ultimate impacts in a given area. Critically, these pressure data are needed to help identify where trade-offs between objectives may exist—what is best for biodiversity may not be optimal for economic growth, for example. Substantial farm-scale variation in environmental efficiency of production offers additional opportunities for identifying system-specific best practices[14,15,50]. While we included subnational variation in production and pressures when possible, downscaling our approach in regions where farm-scale data are available would be a compelling addition, allowing decisionmakers to pinpoint where more environmentally efficient production would be most effective. For animal foods, our mapping of cumulative pressures focused on where food is produced rather than consumed, yet intra- and inter-national trade has globalized consumption so that the location of production can be wholly decoupled from where food is consumed[38,51].

Comprehensive assessments of patterns of trade and consumption were beyond the scope of our cumulative pressure analysis but are clear priorities for future research and highly relevant to reining in food's footprint, particularly since the geography of consumer demand is at least as plastic as that of food production. However, our analyses do

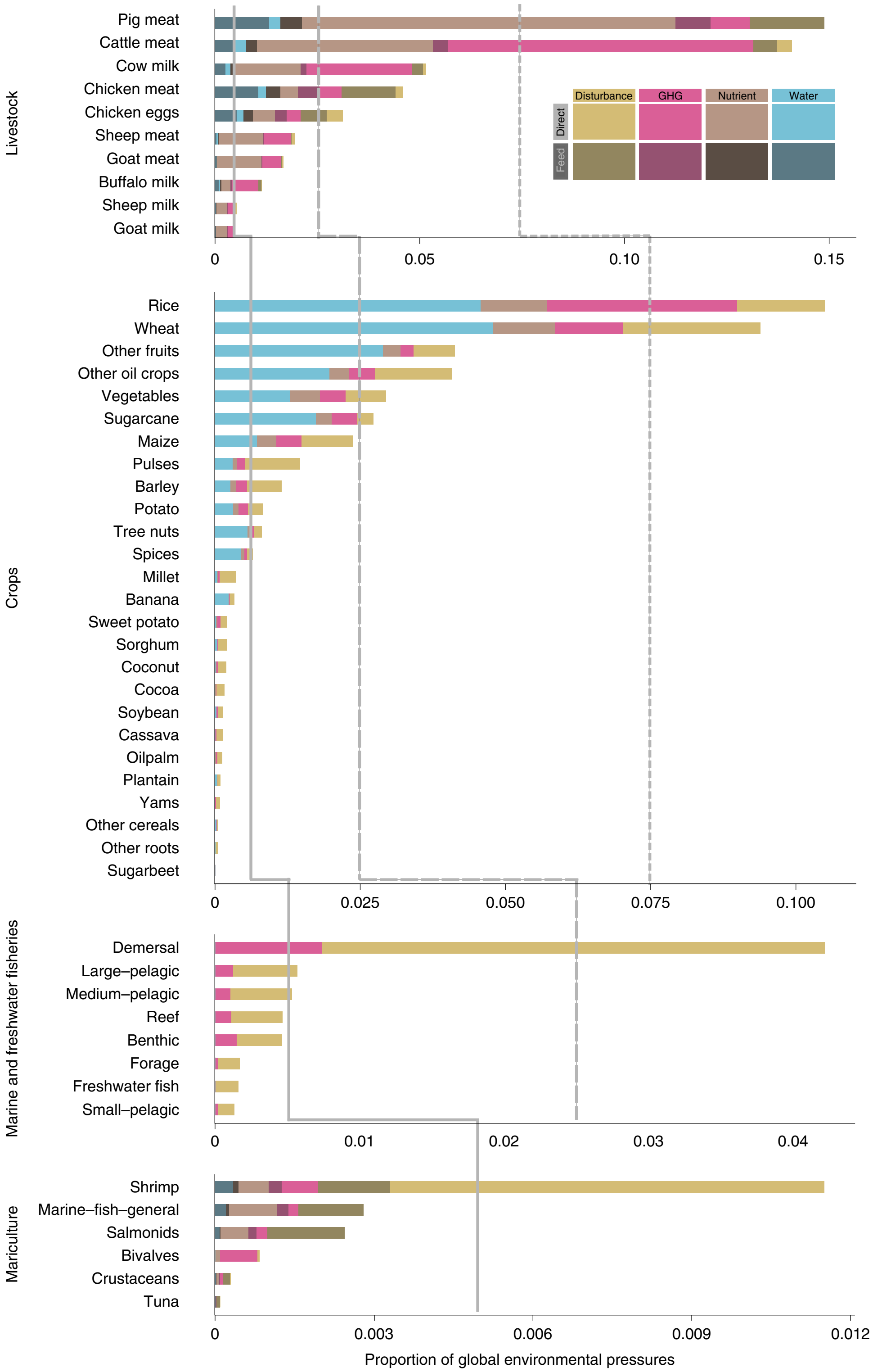


Fig. 5 | Proportion of total global cumulative environmental pressure for each food type (bar length), broken down by classes of pressure (components of each bar). Proportional amounts are the per-unit pressures times the total global production of each food type. Feed inputs are included in the pressure estimates of fed livestock and mariculture animals. To avoid double counting, pressures from crops and forage fish (reduced into fishmeal and fish oil) include the portion of production used primarily for human food (Extended Data Fig. 3 includes feed component). Note that the scale is expanded for each successive set of food types. Dashed and dotted lines show equivalent levels to facilitate comparisons across plots.

allow indications of these dynamics. For example, of the 172 countries with FAO trade data, 152 reported crop imports[38], which means they displace at least some portion of their pressures to other countries to meet domestic demand. The countries that import the majority of their crop products include small, highly developed countries such as Hong Kong, the Netherlands, Belgium and Montenegro; countries in the Middle East with generally poor growing conditions, such as Kuwait, United Arab Emirates, Jordan, Oman and Saudi Arabia; and

https://doi.org/10.1038/s41893-022-00965-x

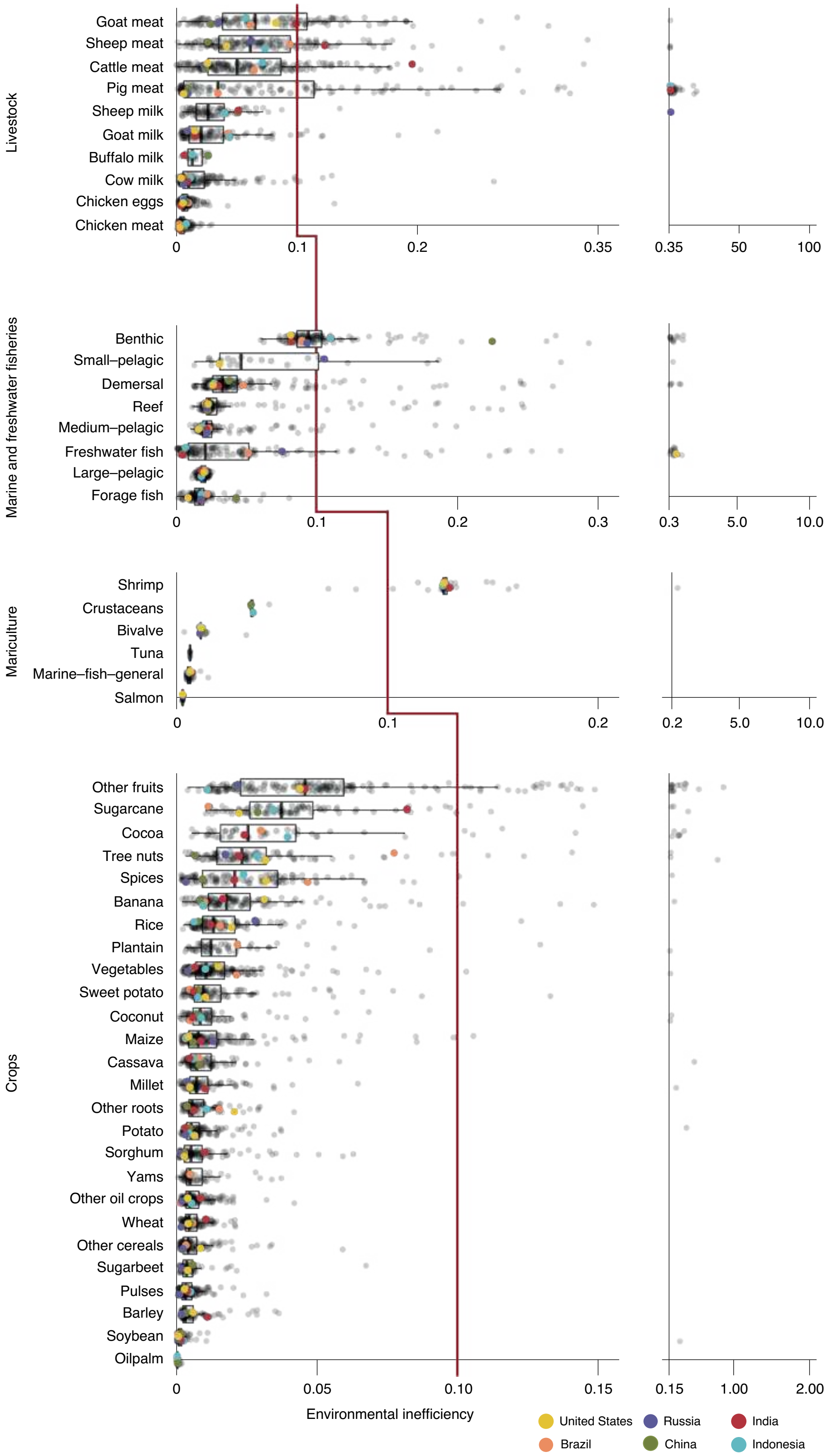


Fig. 6 | Environmental efficiency (cumulative environmental pressure per tonne of protein produced) for major food types. Larger values represent less efficient foods. Fed animals include only on-farm pressures and do not include feed; the full cumulative environmental pressure of fed animals (livestock and mariculture, excluding bivalves) would be obtained by summing on-farm pressures and feed pressures. Each point is a country (jittered for visibility), with median and interquartile range indicated by the boxes. Plots to the right show outliers, which likely reflect measurement and reporting error. Note that food groups are reported on separate scales. Coloured points indicate six examples of countries with high food footprints but divergent environmental efficiencies of production (yellow: United States; green: China; orange: Brazil; red: India; teal: Indonesia; purple: Russia). The red line indicates an equivalent value across the four plots with different x-axis scales to facilitate comparison across plots. Countries with production in any category less than 100 tonnes livestock, 50 tonnes crop, or 50 tonnes fisheries were removed due to high uncertainty. A few extreme outliers for pigs ($n = 6$) and freshwater fisheries ($n = 1$) are not shown. Versions of this figure measured by tonnes and energy content are presented in Extended Data Figs. 4 and 5.

island nations such as the Maldives and Trinidad and Tobago. Coupled with our spatial maps of food footprints, consumption and trade are also critical issues for understanding environmental justice implications of these footprints, that is, who is benefitting from consuming the food and who is paying the environmental price for its production.

Minimizing the environmental footprint of feeding nearly eight billion people is among the most important of societal challenges and will require strategies operating at both local and global scales. Just as foods and their environmental pressures are exported worldwide, so must policymakers, communities, corporations and researchers seek sustainability through coordination and shared learning around the globe. Knowing where and how food production exerts environmental pressures provides foundational information that, when combined with local-scale knowledge about species and ecosystem vulnerability to these pressures, can uncover where (and why) some producers are more environmentally efficient than others, where to concentrate production in less sensitive regions and how to design mitigation efforts where needed. Our findings represent a vital step towards a spatially explicit, comprehensive, system-wide perspective that is essential for identifying environmentally efficient options to achieve both food security and environmental sustainability.

Methods

The following provides an overview of our methodological approaches with extensive details on all methods and data sources provided in the Supplementary Methods.

Foods included

We included data for most types of food and every country and its Exclusive Economic Zone and the high seas (Supplementary Methods). We defined food as substances 'consisting essentially of protein, carbohydrate and (or) fat used in the body of an organism to sustain growth, repair and vital processes and to furnish energy' (Merriam–Webster). We estimated pressures for nearly 99% of food production reported by the United Nations Food and Agricultural Organisation (FAO, based on tonnes of production; Supplementary Methods). Specifically, we assessed pressures for 26 crop categories (plus fodder, which is consumed only as feed); 19 livestock categories, accounting for animal (cattle, buffalo, goats, sheep, pigs, chickens), product (meat, milk, eggs) and rearing system (industrial, mixed, backyard, grassland); seven categories of marine fisheries, including forage fish species used for fishmeal and oil, other small pelagics, medium pelagics, large pelagics, benthic, demersal and reef-associated; freshwater fisheries, with one group for all sizes and taxa; and six categories of marine aquaculture, including salmonids, unfed or algae fed shellfish, shrimp and prawns, tuna, other marine finfish and other crustaceans.

Omissions of land-based animals include game, livestock with relatively low production levels (for example, turkey, ducks, rodents) and food not reported by FAO (for example, insects). We excluded wild-harvest and mariculture of seaweed and freshwater aquaculture because no comprehensive data exist for farm locations; however, the vast majority of freshwater aquaculture occurs in Asia (77.6% of global production in tonnes, with China producing 59.8%) (ref. [52]), and so inclusion of these data would primarily increase pressures in Asia. For inland capture fisheries, we did not account for fish from the world's great lakes and fish reported exclusively in household surveys[13], although their omission has a small effect on results because pressures from inland capture are relatively low.

Pressure overview

We mapped four dominant global pressures of food production: disturbance (km^{2}eq); blue freshwater consumption (m^3 water); excess nutrients (tonnes NP); and greenhouse gas emissions (tonnes CO$_2$eq) (Supplementary Methods). Disturbance is similar to the water pressure in that both measure the amount of something (nature, water) removed from the system, whereas GHG emissions and excess nutrients measure additions to the system. We primarily assessed pressures from sources occurring within the farm gate (that is, at the production site; Supplementary Methods and Supplementary Table 4). In most cases, we excluded activities occurring beyond the farm gate, such as processing and transportation of product, manufacture of equipment and extraction of fuel because we were generally unable to map the location of these activities (Supplementary Methods and Supplementary Table 5).

Spatial resolution

Most mapped food studies report results at 5 arcminute latitude/longitude (WGS84; Supplementary Data 10), representing an area of about 85 km^2 at the equator. We mapped pressures to this resolution, but to assess cumulative pressure and for accurate visualisation, we projected data to an equal-area coordinate reference system (Gall–Peters; Supplementary Methods) with a resolution of 36 km^2, which is similar to the average area of grid cells located near the poles in the original data.

Mapping location and quantity of food production

Mapping pressures from food production required determining the location and intensity of food production for each food type (Supplementary Methods). For crops, tonnes and area of production were taken from the Spatial Production Allocation Model, SPAM v2.0 (ref. [53]), which provides 2010 crop production and physical crop area data for 42 crops (we aggregated some of these categories and excluded agricultural items with no, or minimal, nutritional content such as: fibres, tea, tobacco and coffee; Supplementary Methods and Supplementary Table 6) at 5 arcminute resolution. For each crop, SPAM identifies four production systems: irrigated high inputs, rainfed high inputs, rainfed low inputs and rainfed subsistence. We adjusted SPAM production values in each pixel based on the proportional change in FAO statistics (FAOSTAT) data for crop production from 2010 to 2017 for each country[39]. For livestock, we determined the relative distribution of animals within a country using FAO Gridded Livestock of the World data[42], which describes headcounts in 2010 at 5 arcminute resolution. However, the actual number of animals in a country was from FAO livestock headcount data[49]. We used additional information (Supplementary Methods) to map the location of specific rearing systems (for example, grazed versus feedlot) and products (for example, milk versus meat). We were unable to remove animals used for non-food purposes (for example, wool), which overestimates pressures attributed to meat/milk production. For maps describing marine fish capture, we used spatialized global catch data[41] describing tonnes of global catch in 2017 at 0.5-degree resolution estimated by allocating FAO country catch data to gridded areas based on the spatial distribution of fished taxa and the location of country fleets given fishing access agreements. For global inland freshwater fisheries, we used gridded map data[13] describing catch tonnage at 5 arcminutes averaged across 1997–2014. Maps of mariculture farms were synthesized from many data sources and modelled locations[54], with production based on 2017 FAO data[52].

Mapping food pressures

We used the maps describing the intensity of production for each food type to estimate pressures using a variety of approaches (Supplementary Methods). Instead of omitting regions or foods with missing data or assuming not applicable (NA) or zero values, which causes bias, we estimated these values.

Disturbance. We defined disturbance as the proportion of native plants and animals displaced by agricultural activities within a region, and this pressure is reported in units of km^{2}eq, which incorporates both the occupancy area and a measure of disruption. For crops and industrial/mixed livestock rearing, we assumed these activities completely displace native ecosystems (that is, disruption is equal to 1) which means disturbance equals the area occupied by fields and farm structures.

We modified this general approach for more complex systems, such as grazing animals and marine fisheries, where some animals and plants coexist alongside these activities (that is, disruption <1). In these cases, we estimated disturbance as the amount of native biomass removed relative to total biomass (that is, the proportion of biomass removed).

To estimate disturbance from grazing animals, we assumed that the magnitude of the pressure corresponds to the amount of consumption (a function of feeding rate and number of animals) relative to the amount of primary production (that is, NPP)[55]. We treated most marine aquaculture similarly to mixed and industrial livestock but consider only the two-dimensional surface area of rearing infrastructure (for example, ponds, cages). For inland fisheries, the area of disturbance was equal to river area because we assumed all streams and rivers are fully fished, but we assume a relatively low disruption of 0.3 because river systems persist where fished. Marine fisheries can cause disturbance by destroying seafloor habitat when certain gear types are used (for example, bottom trawls) and through biomass removal throughout the water column and from the seafloor. We estimated the degree of seafloor destruction based on fishing effort[12,56] (hours) using demersal destructive gear types. For biomass removal, we would ideally measure the total proportion of fish biomass removed, but because these data do not exist, we standardized total catch by dividing the tonnes of catch[41] by NPP to produce an impact metric relative to natural production. The raster maps describing both forms of marine fisheries disturbance (that is, seafloor destruction and biomass removal) are rescaled to values between 0 to 1 by determining, for each map, the value across all the raster cells corresponding to the 99.9th quantile and dividing all the raster cells by this value. The two rescaled rasters were then averaged to get total marine fisheries disturbance. To make this measure comparable to land disturbance (measured in km^2), we multiplied this rescaled score by the two-dimensional area of the ocean cell. Our decision to rescale fisheries disturbance by the 99.9th quantile assumes 0.1% of ocean area is highly disturbed by fishing (for example, has a fully disturbed value of 1). However, this value is highly uncertain, and we explored the sensitivity of our results to alternative assumptions (Supplementary Methods and Supplementary Table 12).

Freshwater use. For water pressure, we report total blue water consumption, which results in aquifer and surface water depletion. In general, blue water use has a higher impact than green water (rainfall), but green water use reduces availability of water to species, ecosystems and standing water[24]. Given the importance of green water consumption, we also provide these data.

For crops, we used subnational water footprint data describing tonnes blue water per tonne production[24]. For livestock, we estimated on-farm consumptive freshwater use[25] (m^3) based on average air temperature and additional service water, which we assumed to be blue water. We did not include water use for aquatic systems (inland and marine fisheries and on-farm marine aquaculture) because freshwater use in these systems is primarily passive, with limited freshwater consumption[57].

Excess nutrients. We estimated excess nitrogen and phosphorus inputs to systems from crops, livestock and aquaculture; capture fisheries were excluded because this pressure is assumed to be minimal at the capture stage. For each system, we mapped excess N and P separately and, at the last step, added them to obtain a general indicator of excess nutrients; however, we provide these data separately so others can explore the *impact* of these nutrients independently. We defined excess N and P inputs as those that are likely to run-off/leach into surrounding environments[58–60], and in the case of N, volatilize as NH_3 which subsequently deposits on Earth's surface[60].

We estimated excess nutrient inputs from N and P_2O_5 synthetic fertilizers applied to crops. Many studies include organic (that is, manure) fertilizers as well, however, we account for this at the site of the livestock farm. We distributed the N and P quantities described at the country scale[61] among raster cells according to: the national fertilizer use by crop rates[62,63]; the total hectares of harvested area for each crop and the intensity of the agriculture system as defined by SPAM[53]. We estimated excess nitrogen and phosphorus as the tonnes likely to run-off/leach, and for nitrogen, we also included the tonnes that volatilize as NH_3 based on supernational volatilization estimates[60]. Our analysis for livestock was similar but used different parameters to estimate excess N and P given the various pathways manure can take: managed and then spread on fields/crops, directly spread on fields crops or left on fields. For livestock, we also included synthetic fertilizers applied to grasslands for the benefit of grazing animals. For mariculture, excess nutrients largely come from two sources: uneaten feed and faecal matter. We quantified dissolved N and P added to the marine system using models and parameters from others[64–66].

GHG emissions. We calculated GHG emissions (tonnes CO_2eq) for the majority of activities or processes occurring at the location of food production, such as tillage and crop residue burning and enteric fermentation. We mostly excluded indirect emissions such as construction of farming infrastructure and extraction of fuel. We were unable to account for pressures resulting from land-use change (for example, deforestation and peatland degradation), which results in substantial GHG emissions, due to the difficulty of mapping land-use change to specific food systems and modelling more complex systems, such as marine environments. On the basis of other studies, from 2007–2016[67], land-use change (for example, converting forest to cropland) accounted for 36% of food-production emissions.

For crop production, we included emissions for crop residue burning and volatilization, pumping of irrigation water, field maintenance, machinery operations, volatilization of synthetic fertilizers and production of fertilizers and pesticides. For rice, we also included emissions from anaerobic decomposition of organic matter in paddy fields. For livestock, we included emissions from enteric fermentation, direct energy use on the farm, all manure-related emissions and synthetic fertilizers applied to grazed grasslands. Capture fisheries included emissions from vessel fuel use[68], although for freshwater fisheries, this is assumed to be relatively low for developing countries and zero for remaining countries. Mariculture emissions include on-farm energy use[68] and N_2O from microbial nitrification and denitrification of waste[69].

We standardized GHG (for example, CO_2, N_2O, CH_4) emissions to CO_2eq using the Global Warming Potential for 100-year time scale (GWP_{100}) as per the Kyoto Protocol[70], with CH_4 multiplied by 25 and N_2O by 298. An important caveat is that the GWP_{100} does not differentiate between long- and short-lived climate pollutants[71]. Depending on how emission rates change over time, this could dramatically reduce the warming potential of GHG emissions from livestock that are enteric ruminants, such as cows and flooded rice production, which have large CH_4 emissions.

Feed pressures. Many crops and forage fish from marine fisheries can be directly consumed by humans or used as animal feed (Supplementary Methods). For feed components, we mapped the pressures to the location where the crops are grown or fish are captured (versus where they are fed to animals). Identifying the likely location where feed is grown or captured is complicated by the fact that the country where the product is consumed is often not the country of production. To get at this, we first estimated the amount of each crop or fish product consumed by each country and animal system based on feed consumption rates and feed composition. We then determined the country (or location in ocean) where the feed likely originated using global trade data[38,51]. After determining the tonnes of each crop feed product produced for each animal system in each country, we divided this value by the total production in the country to estimate the proportion going to each food system. Once we accounted for all the animal feed use, we assumed the remainder of the crop or fish oil/fishmeal catch is consumed by humans or used for other purposes.

To determine the pressures from feed, for each country, we multiplied the total pressures from each crop by the proportion going to each animal food system regardless of country of consumption.

For livestock, feed consumption rates (tonnes per head per year) and diet composition data were primarily from the Global Livestock Environmental Assessment Model (GLEAM)[72], and fishmeal/fish oil consumption for pigs and chickens from Froehlich and colleagues[35]. For aquaculture, we used feed conversion ratios and diet composition data from recent studies[37,73].

To convert the percent composition of each dietary component to tonnes of crop or forage fish consumption, we used the fish-in fish-out (FIFO) approach[74]. This accounts for loss (for example, waste) during processing, which includes water loss, loss in machinery and by-products not used for food/feed.

Cumulative pressure calculation

In addition to spatially describing the magnitude of individual pressures, we combined rescaled pressures to create a cumulative pressure index that describes the general magnitude of human influence resulting from food production[29] (Supplementary Methods). The cumulative pressure index allows direct comparisons among foods, regions and pressures to identify where: individual pressures are high relative to other pressures, multiple pressures overlap and hotspots of cumulative pressure are located. This information provides a more complete picture of the environmental pressures occurring at any global area and from each food type (Supplementary Methods and Supplementary Fig. 2).

To calculate cumulative pressure, we first rescaled each per-food pressure map by dividing each pixel's pressure value by the total global pressure generated by all foods and across all raster cells. The result is that each rescaled pixel is a unitless value describing its proportional contribution to the total global pressure. The four rescaled pressure raster maps are then summed to derive a general measure of the cell's total contribution to the global pressure. Summing individual pressure scores implicitly weights pressures equally, a reasonable assumption for providing a general measure of human influence[20,30,75] and an overall index of pressure from food production. The ultimate impact, or weight, of each pressure will vary according to the particular system being impacted (for example, loss of habitat, increased species vulnerability, reduced food security and so on; Fig. 1) and complex interactions between the pressure and local environment. Assessments of impact are not common for global-scale analyses because the systems of concern will vary by region (and researcher) and will often require environmental data not available at the global scale.

The resulting total cumulative pressure across all the global pixels equals 4 (by definition), and the maximum observed pixel value was 2.305×10^{-4}, near Ashdod in Israel (Fig. 2).

Environmental efficiency of food production

For each country, we calculated the environmental efficiency of each food system by dividing its total cumulative pressure by the total tonnes of production according to FAO data and the food's nutritional value (kcal or protein) after adjusting for the edible portion (Supplementary Methods). Within a food group, the variation observed among countries can be due to differences in cumulative pressure production (as measured here) or several sources of error (for example, for livestock, number of heads are used to model pressures, but efficiency is based on tonnes production which introduces uncertainty).

Data quality and uncertainty

The estimate of pressure in each mapped pixel represents a point estimate of the mean based on the standardized and aligned input data. We were unable to perform a quantitative estimate of the error around each of these estimates because most of the data sources we relied on do not report uncertainty and/or error.

We did, however, conduct a qualitative analysis of the data used in our analyses (Supplementary Methods), which varied in quality and resolution (relative to our objectives). Given our objective of globally mapping food pressures for each food system at 0.5-degree resolution in year 2017, we assessed how well each dataset matched our desired spatial (extent and resolution), temporal and system-specificity criteria (Supplementary Data 10 and Extended Data Figs. 6 and 7). Although there were additional sources of data quality we were unable to incorporate into our assessments, this information will nonetheless inform users of these data of the limitations and strengths of our data.

Data availability

The source data used for these analyses is provided in Supplementary Table 25. All data are available[76].

Code availability

The code used for these analyses is available from GitHub[76] (https://github.com/OHI-Science/global_food_pressures).

References

1. Tilman, D. & Clark, M. Global diets link environmental sustainability and human health. *Nature* **515**, 518–522 (2014).
2. Godfray, H. C. J. et al. Meat consumption, health, and the environment. *Science* **361**, eaam5324 (2018).
3. Hicks, C. C. et al. Harnessing global fisheries to tackle micronutrient deficiencies. *Nature* **574**, 95–98 (2019).
4. Willett, W. et al. Food in the Anthropocene: the EAT–*Lancet* Commission on healthy diets from sustainable food systems. *Lancet* **393**, 447–492 (2019).
5. Maxwell, S. L., Fuller, R. A., Brooks, T. M. & Watson, J. E. M. Biodiversity: the ravages of guns, nets and bulldozers. *Nature* **536**, 143–145 (2016).
6. Tilman, D. et al. Future threats to biodiversity and pathways to their prevention. *Nature* **546**, 73–81 (2017).
7. Ellis, E. C., Goldewikj, K. K., Siebert, S., Lightman, D. & Ramankutty, N. Anthropogenic transformation of the biomes, 1700 to 2000. *Glob. Ecol. Biogeogr.* **19**, 589–606 (2010).
8. Crippa, M. et al. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food* **2**, 198–209 (2021).
9. Rosegrant, M. W., Ringler, C. & Zhu, T. Water for agriculture: maintaining food security under growing scarcity. *Annu. Rev. Environ. Resour.* **34**, 205–222 (2009).
10. Tubiello, F. N. et al. The contribution of agriculture, forestry and other land use activities to global warming, 1990–2012. *Glob. Change Biol.* **21**, 2655–2660 (2015).
11. Lee, R. Y., Seitzinger, S. & Mayorga, E. Land-based nutrient loading to LMEs: a global watershed perspective on magnitudes and sources. *Environ. Dev.* **17**, 220–229 (2016).
12. Kroodsma, D. A. et al. Tracking the global footprint of fisheries. *Science* **359**, 904–908 (2018).
13. McIntyre, P. B., Liermann, C. A. R. & Revenga, C. Linking freshwater fishery management to global food security and biodiversity conservation. *Proc. Natl Acad. Sci. USA* **113**, 12880–12885 (2016).
14. Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992 (2018).
15. Hilborn, R., Banobi, J., Hall, S. J., Pucylowski, T. & Walsworth, T. E. The environmental cost of animal source foods. *Front. Ecol. Environ.* **16**, 329–335 (2018).
16. Parker, R. W. R. et al. Fuel use and greenhouse gas emissions of world fisheries. *Nat. Clim. Change* **8**, 333–337 (2018).
17. Davis, K. F. et al. Meeting future food demand with current agricultural resources. *Glob. Environ. Change* **39**, 125–132 (2016).

18. Gephart, J. A. et al. The environmental cost of subsistence: optimizing diets to minimize footprints. *Sci. Total Environ.* **553**, 120–127 (2016).
19. Gephart, J. A. et al. Environmental performance of blue foods. *Nature* **597**, 360–365 (2021).
20. Halpern, B. S. et al. Putting all foods on the same table: achieving sustainable food systems requires full accounting. *Proc. Natl Acad. Sci. USA* **116**, 18152–18156 (2019).
21. Béné, C. et al. Feeding 9 billion by 2050—putting fish back on the menu. *Food Secur.* **7**, 261–274 (2015).
22. Tacon, A. G. J. & Metian, M. Fish matters: importance of aquatic foods in human nutrition and global food supply. *Rev. Fish. Sci.* **21**, 22–38 (2013).
23. Verones, F., Moran, D., Stadler, K., Kanemoto, K. & Wood, R. Resource footprints and their ecosystem consequences. *Sci. Rep.* **7**, 40743 (2017).
24. Mekonnen, M. M. & Hoekstra, A. Y. The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci.* **15**, 1577–1600 (2011).
25. Mekonnen, M. M. & Hoekstra, A. Y. *The Green, Blue and Grey Water Footprint of Farm Animals and Animal Products* (UNESCO-IHE, 2010).
26. Carlson, K. M. et al. Greenhouse gas emissions intensity of global croplands. *Nat. Clim. Change* **7**, 63–68 (2017).
27. Hong, C. et al. Global and regional drivers of land-use emissions in 1961–2017. *Nature* **589**, 554–561 (2021).
28. Amoroso, R. O. et al. Bottom trawl fishing footprints on the world's continental shelves. *Proc. Natl Acad. Sci. USA* **115**, E10275–E10282 (2018).
29. Kuempel, C. D. et al. Integrating life cycle and impact assessments to map food's cumulative environmental footprint. *One Earth* **3**, 65–78 (2020).
30. Halpern, B. S. et al. A global map of human impact on marine ecosystems. *Science* **319**, 948–952 (2008).
31. Crain, C. M., Kroeker, K. & Halpern, B. S. Interactive and cumulative effects of multiple human stressors in marine systems. *Ecol. Lett.* **11**, 1304–1315 (2008).
32. Birk, S. et al. Impacts of multiple stressors on freshwater biota across spatial scales and ecosystems. *Nat. Ecol. Evol.* **4**, 1060–1068 (2020).
33. Judd, A. D., Backhaus, T. & Goodsir, F. An effective set of principles for practical implementation of marine cumulative effects assessment. *Environ. Sci. Policy* **54**, 254–262 (2015).
34. IPBES *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES, 2019).
35. Froehlich, H. E., Jacobsen, N. S., Essington, T. E., Clavelle, T. & Halpern, B. S. Avoiding the ecological limits of forage fish for fed aquaculture. *Nat. Sustain.* **1**, 298–303 (2018).
36. FAO *The State of World Fisheries and Aquaculture 2020* (FAO, 2020).
37. Froehlich, H. E., Runge, C. A., Gentry, R. R., Gaines, S. D. & Halpern, B. S. Comparative terrestrial feed and land use of an aquaculture-dominant world. *Proc. Natl Acad. Sci. USA* **115**, 5295–5300 (2018).
38. *FAOSTAT Database: New Food Balances* (FAO, 2020); http://www.fao.org/faostat/en/#data/FBS
39. *FAOSTAT Database: Production, Crops* (FAO, 2020); http://www.fao.org/faostat/en/#data/QC
40. Dong, F. et al. Assessing sustainability and improvements in US Midwestern soybean production systems using a PCA–DEA approach. *Renew. Agric. Food Syst.* **31**, 524–539 (2016).
41. Watson, R. A. & Tidd, A. Mapping nearly a century and a half of global marine fishing: 1869–2015. *Mar. Policy* **93**, 171–177 (2018).
42. Robinson, T. P. et al. Mapping the global distribution of livestock. *PLoS ONE* **9**, e96084 (2014).
43. Clark, M. & Tilman, D. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environ. Res. Lett.* **12**, 064016 (2017).
44. Balmford, B., Green, R. E., Onial, M., Phalan, B. & Balmford, A. How imperfect can land sparing be before land sharing is more favourable for wild species? *J. Appl. Ecol.* **56**, 73–84 (2019).
45. Luskin, M. S., Lee, J. S. H., Edwards, D. P., Gibson, L. & Potts, M. D. Study context shapes recommendations of land-sparing and sharing; a quantitative review. *Glob. Food Secur.* **16**, 29–35 (2018).
46. Williams, D. R., Phalan, B., Feniuk, C., Green, R. E. & Balmford, A. Carbon storage and land-use strategies in agricultural landscapes across three continents. *Curr. Biol.* **28**, 2500–2505.e4 (2018).
47. Paul, B. G. & Vogl, C. R. Impacts of shrimp farming in Bangladesh: challenges and alternatives. *Ocean Coastal Manage.* **54**, 201–211 (2011).
48. Ahmed, N., Cheung, W. W. L., Thompson, S. & Glaser, M. Solutions to blue carbon emissions: shrimp cultivation, mangrove deforestation and climate change in coastal Bangladesh. *Mar. Policy* **82**, 68–75 (2017).
49. *FAOSTAT Database: Livestock Primary* (FAO, 2020); http://www.fao.org/faostat/en/#data/QL
50. Ramankutty, N., Ricciardi, V., Mehrabi, Z. & Seufert, V. Trade-offs in the performance of alternative farming systems. *Agric. Econ.* **50**, 97–105 (2019).
51. *FAOSTAT Database: Detailed Trade Matrix* (FAO, 2020); http://www.fao.org/faostat/en/#data/TM
52. *Fisheries & Aquaculture—Fishery Statistical Collections—Fishery Commodities and Trade* (FAO, 2019); http://www.fao.org/fishery/statistics/global-commodities-production/en
53. International Food Policy Research Institute. Global spatially-disaggregated crop production statistics data for 2010, version 2.0. *Harvard Dataverse* https://doi.org/10.7910/DVN/PRFF8V (2019).
54. Clawson, G. et al. Mapping the spatial distribution of global mariculture production. *Aquaculture* **553**, 738066 (2022).
55. Petz, K. et al. Mapping and modelling trade-offs and synergies between grazing intensity and ecosystem services in rangelands using global-scale datasets and models. *Glob. Environ. Change* **29**, 223–234 (2014).
56. Global Fishing Watch. Fishing effort. Fleet daily, v2 100th degree. (2021). https://globalfishingwatch.org/dataset-and-code-fishing-effort/
57. Verdegem, M. C. J., Bosma, R. H. & Verreth, J. A. J. Reducing water use for animal production through aquaculture. *Int. J. Water Resour. Dev.* **22**, 101–113 (2006).
58. Bouwman, A. F., Beusen, A. H. W. & Billen, G. Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050. *Glob. Biogeochem. Cycles* **23**, GB0A04 (2009).
59. Bouwman, A. F., Van Drecht, G. & Van der Hoek, K. W. Nitrogen surface balances in intensive agricultural production systems in different world regions for the period 1970–2030. *Pedosphere* **15**, 137–155 (2005).
60. Bouwman, A., Boumans, L. J. M. & Batjes, N. Estimation of global NH_3 volatilization loss from synthetic fertilizers and animal manure applied to arable lands and grasslands. *Glob. Biogeochem. Cycles* **16**, 8-1–8-14 (2002).
61. *FAOSTAT Database: Inputs, Fertilizers by Nutrient* (FAO, 2020); http://www.fao.org/faostat/en/#data/RFN
62. Heffer, P., Gruere, A. & Roberts, T. Assessment of fertilizer use by crop at the global level 2014–2014/15, International Fertilizer Association (2017).
63. *Fertilizer Use by Crop* 5th edn (FAO, IFA & IFDC, 2002).

64. Islam, Md. S. Nitrogen and phosphorus budget in coastal and marine cage aquaculture and impacts of effluent loading on ecosystem: review and analysis towards model development. *Mar. Pollut. Bull.* **50**, 48–61 (2005).
65. Wang, J., Beusen, A. H. W., Liu, X. & Bouwman, A. F. Aquaculture production is a large, spatially concentrated source of nutrients in Chinese freshwater and coastal seas. *Environ. Sci. Technol.* **54**, 1464–1474 (2020).
66. Bouwman, A. F. et al. Hindcasts and future projections of global inland and coastal nitrogen and phosphorus loads due to finfish aquaculture. *Rev. Fish. Sci.* **21**, 112–156 (2013).
67. Gavrilova, O. et al. in *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* Ch. 10, Intergovernmental Panel on Climate Change (IPCC); Review Editors on Overview: Dario Gómez (Argentina) and William Irving (USA) (2019).
68. *Seafood Carbon Emissions Tool*, Lisa Max, Robert Parker, Peter Tyedmers, editors; (2020); http://seafoodco2.dal.ca/
69. Hu, Z., Lee, J. W., Chandran, K., Kim, S. & Khanal, S. K. Nitrous oxide (N_2O) emission from aquaculture: a review. *Environ. Sci. Technol.* **46**, 6470–6480 (2012).
70. IPCC *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. et al.) (Cambridge Univ. Press, 2007).
71. Lynch, J., Cain, M., Pierrehumbert, R. & Allen, M. Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environ. Res. Lett.* **15**, 044023 (2020).
72. Global Livestock Environmental Assessment Model, GLEAM, v.2.0.121 (FAO, 2018).
73. Aas, T. S., Ytrestøyl, T. & Åsgård, T. Utilization of feed resources in the production of Atlantic salmon (*Salmo salar*) in Norway: an update for 2016. *Aquacult. Rep.* **15**, 100216 (2019).
74. Jackson, A. Fish in-fish out (FIFO) explained. *Aquacult. Eur.* **34**, 5–10 (2009).
75. Halpern, B. S. et al. Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nat. Commun.* **6**, 7615 (2015).
76. Frazier, M. et al. Global food system pressure data. https://knb.ecoinformatics.org/view/doi:10.5063/F1V69H1B

Acknowledgements

This research was a collaborative endeavour conducted by the Global Food Systems Working Group at the National Center for Ecological Analysis and Synthesis at the University of California Santa Barbara. The Global Food Systems Working Group was funded by the Zegar Family Foundation. The National Center for Ecological Analysis and Synthesis at UC Santa Barbara provided invaluable infrastructural support for this work. J.T. was additionally supported by the German Federal Ministry of Education and Research (funding code 031B0792A). K.L.N. was supported by the Australian Research Council (DE210100606).

Author contributions

All authors contributed to the conceptualization of the project. M.F., J.V., P.-E.R., G.C. and B.S.H. contributed to methodology. M.F., J.V., P.-E.R. and G.C. contributed to software, validation, formal analysis and data curation. B.S.H. wrote the original draft. All authors contributed to writing the final draft and editing. J.V., M.F. and B.S.H. contributed to visualization. B.S.H. supervised the research. M.F. and B.S.H. provided project administration. B.S.H. acquired funding.

Competing interests

The authors declare no competing interests.

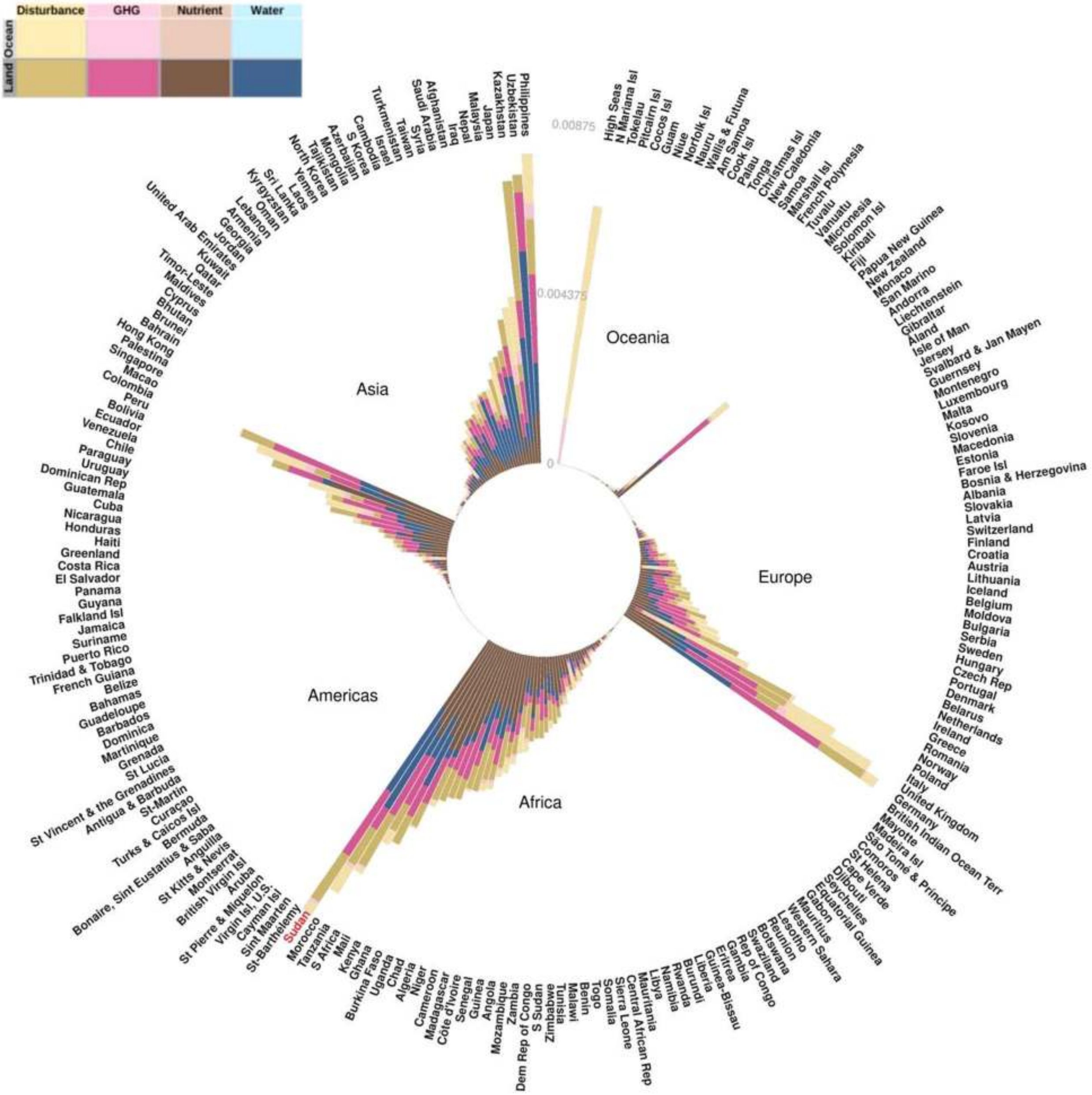
Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41893-022-00965-x.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41893-022-00965-x.

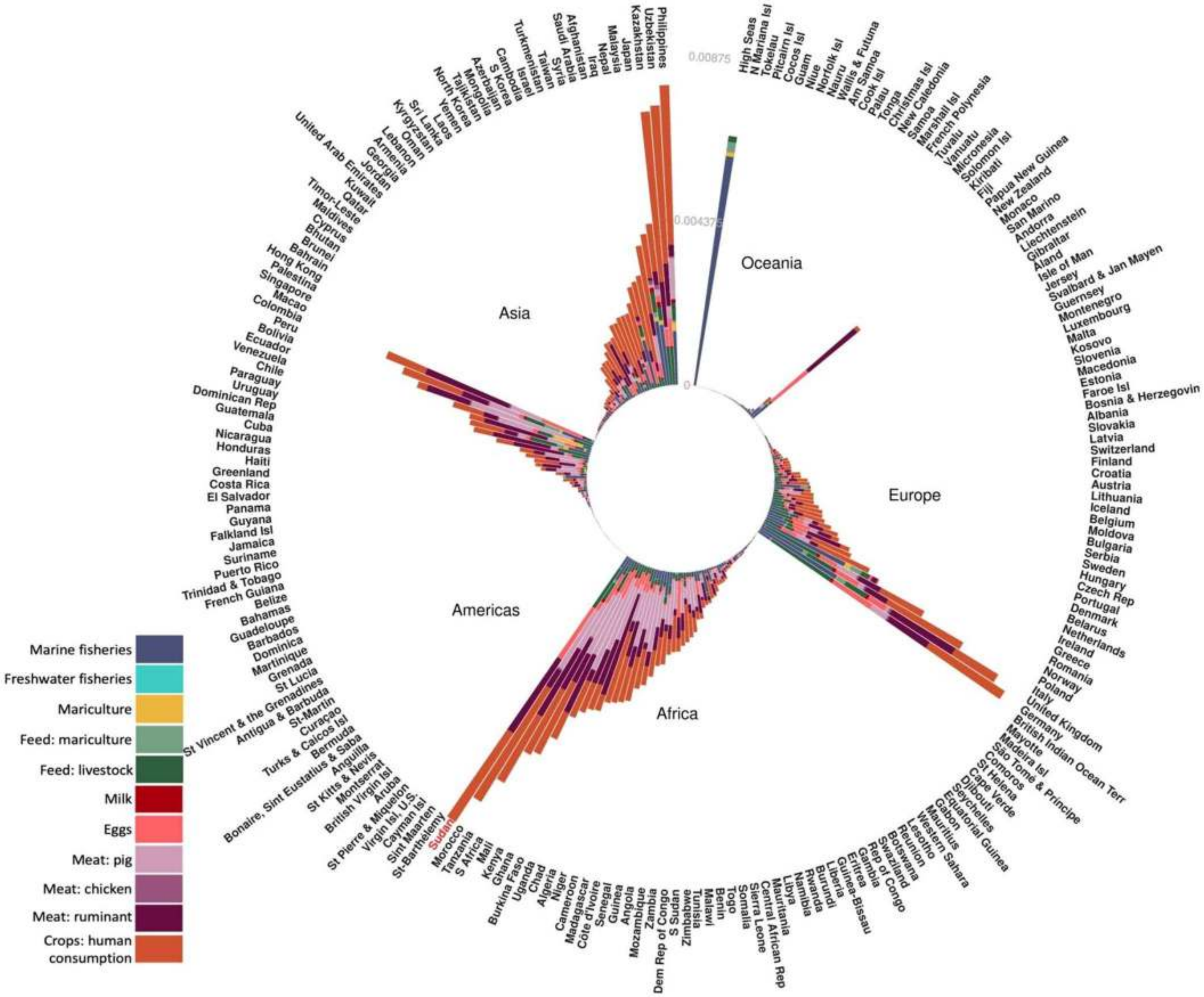
Correspondence and requests for materials should be addressed to Benjamin S. Halpern.

Peer review information *Nature Materials* thanks Luc Doyen, Pablo Elverdin and Günther Fischer for their contribution to the peer review of this work.

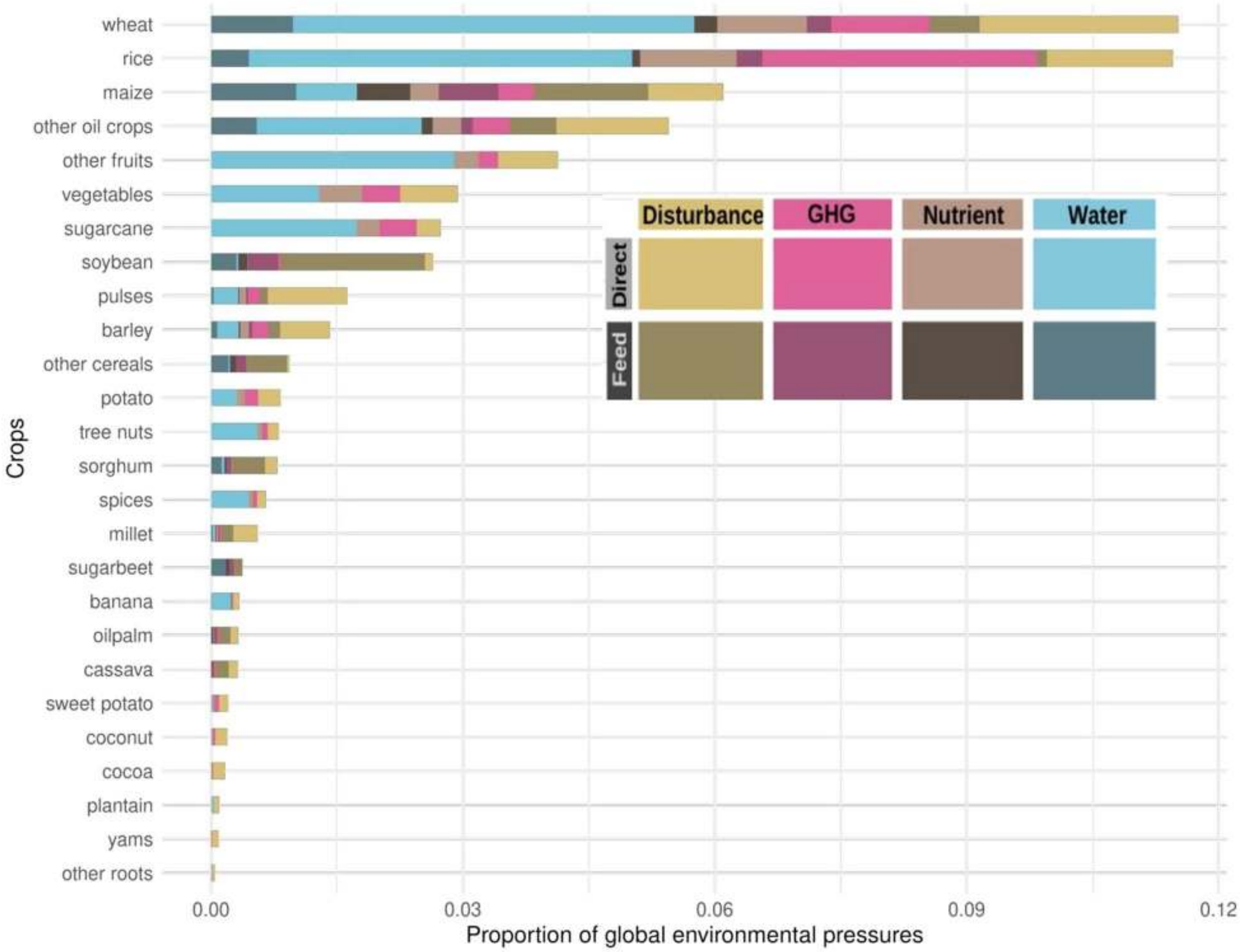


Extended Data Fig. 1 | Proportional contribution of pressures within each country. Proportional contribution of each pressure to the cumulative food footprint in each country, summed across all foods. These countries collectively account for about 30% of pressure from food production (top countries are presented in Fig. 4a in the text). Stacked bars show the proportional contribution of marine (lighter colours, calculated as the Exclusive Economic Zone) and terrestrial (darker colours) pressures from all foods combined, including the high seas.

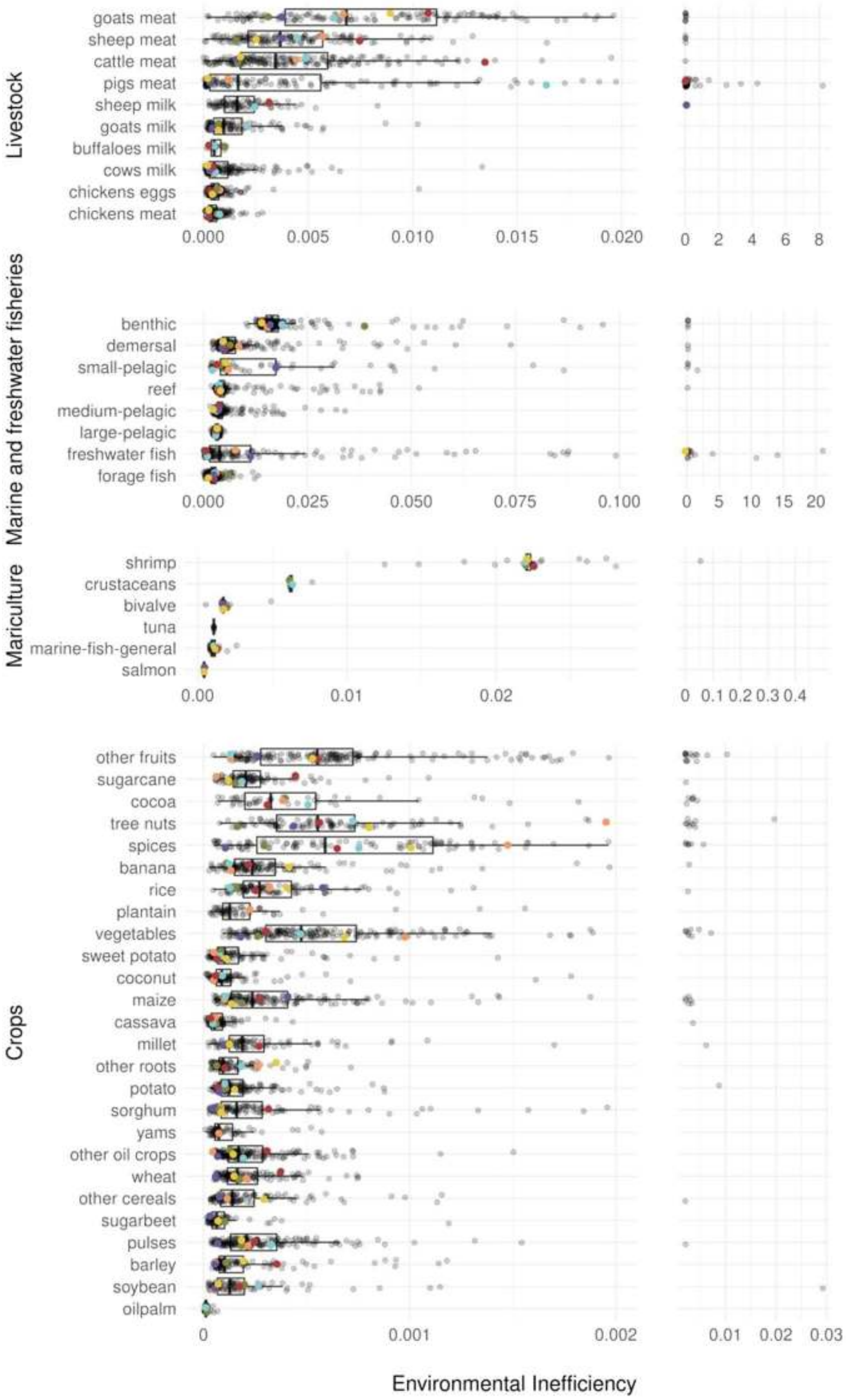
https://doi.org/10.1038/s41893-022-00965-x



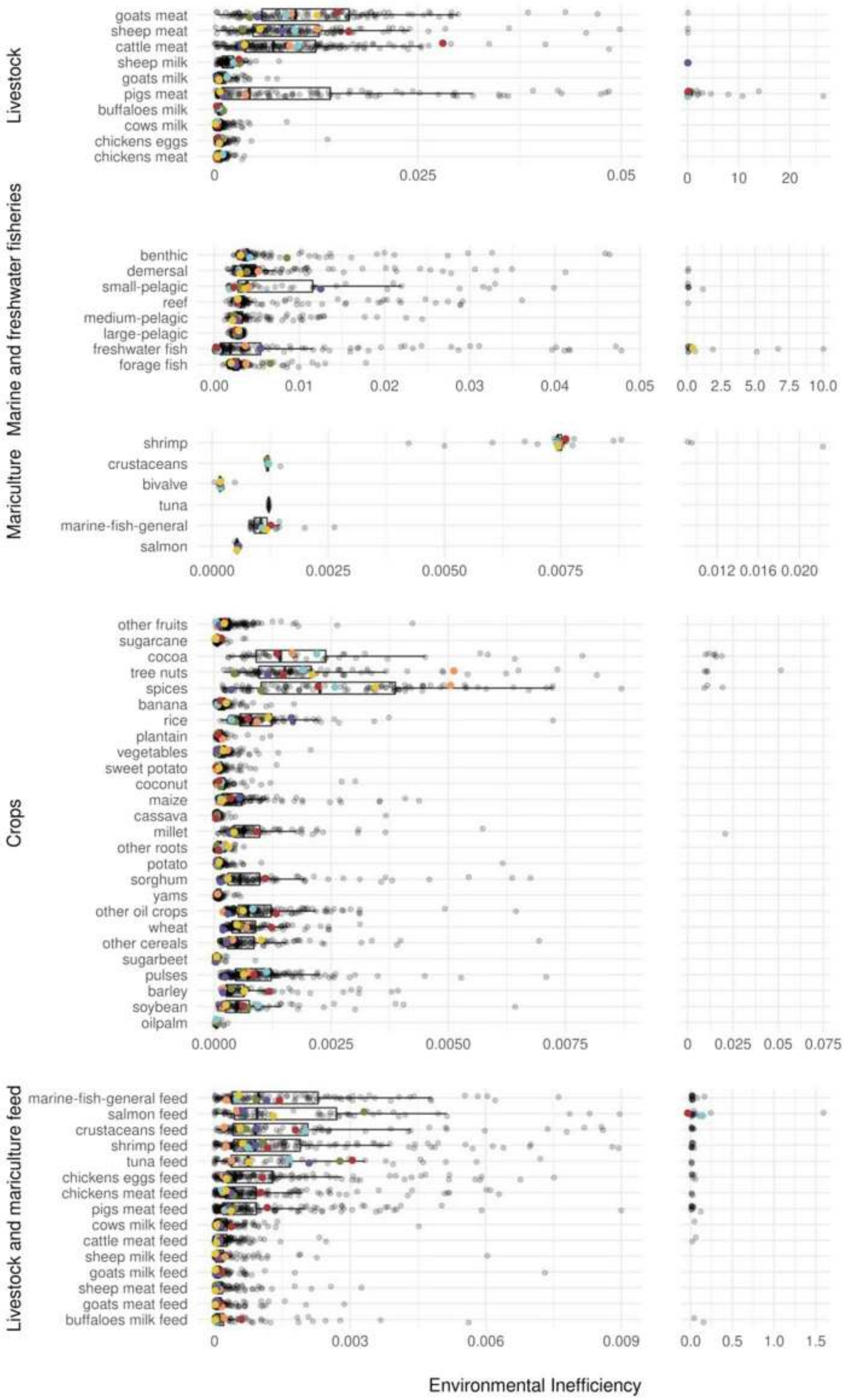
Extended Data Fig. 2 | Proportional contribution of food categories to pressures within each country. Proportional contribution of each food group to the cumulative food footprint in each country. These countries collectively account for about 30% of pressure from food production (top countries are presented in Fig. 4b in the text). Stacked bars are the proportional contribution of each major food group, including feed for livestock and aquaculture, summed for all four pressures in each country and the high seas.



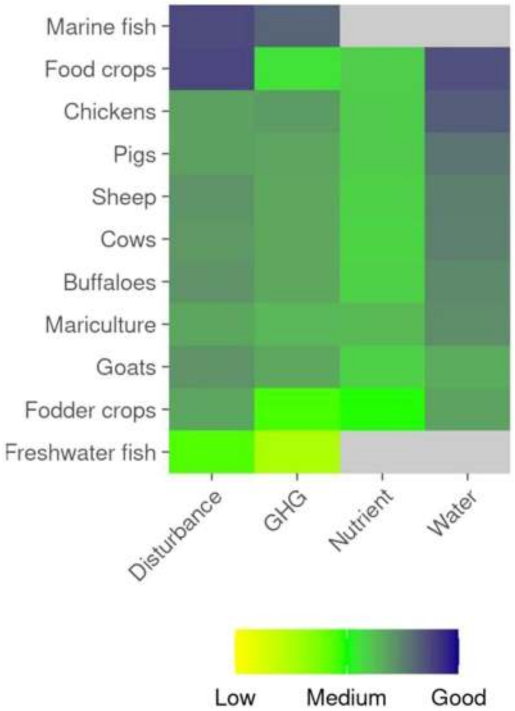
Extended Data Fig. 3 | Proportion of total global cumulative pressure for crops, broken down by pressure (components of each bar). Proportional amounts are the per-unit pressures times the total global production. This includes crops for consumed primarily by humans and animal feed.



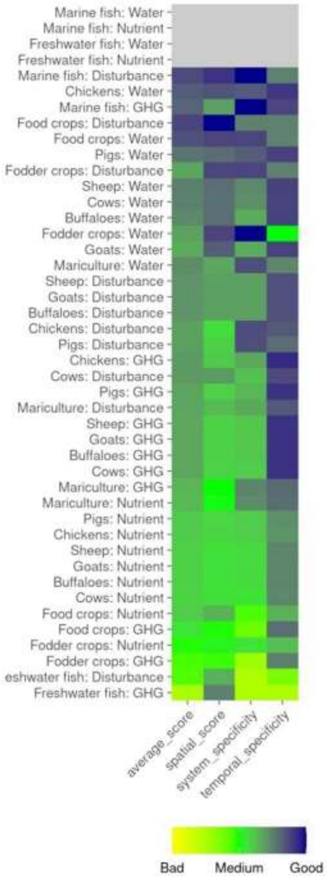
Extended Data Fig. 4 | Environmental Efficiency by kcal for Major Food Types. Environmental efficiency (cumulative environmental pressure per million kcal produced) for major food types. Larger values represent less efficient foods. Each point is a country (jittered for visibility), with median and interquartile range indicated by the boxes. Plots to the right show extreme positive values and are on separate scales. Feed is not included in livestock primary and secondary products or mariculture.



Extended Data Fig. 5 | Environmental Efficiency by Tonnes Production for Major Food Types. Environmental efficiency (cumulative environmental pressure per tonne reported production) for major food types. Larger values represent less efficient foods. Each point is a country (jittered for visibility), with median and interquartile range indicated by the boxes. Plots to the right show extreme positive values and are on separate scales. Feed is not included in livestock primary and secondary products or mariculture.



Extended Data Fig. 6 | Data quality assessment by food type. Data quality assessment of each food system and pressure scored on a scale ranging from 1–5. Data quality was assessed using a bottom-up approach, where each data source was scored on spatial resolution, spatial extent, system specificity, and temporal accuracy.



Extended Data Fig. 7 | Data quality assessment by food type and stressor. Data quality assessment breakdown for each food system, pressure, and score scored on a scale from 1–5. Data quality was assessed using a bottom-up approach, where each data source was scored on spatial resolution, spatial extent, system specificity, and temporal accuracy.