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# 1 **The environmental footprint of global food production**

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## 37 Abstract

38 **Feeding humanity puts enormous environmental pressure on our planet. These pressures**  
39 **are unequally distributed, yet we have piecemeal knowledge of how they accumulate across**  
40 **marine, freshwater and terrestrial systems. Here we present global geospatial analyses**  
41 **detailing greenhouse gas emissions, freshwater use, habitat disturbance, and nutrient**  
42 **pollution generated by 99% of total reported production of aquatic and terrestrial foods in**  
43 **2017. We further rescale and combine these four pressures to map the estimated**  
44 **cumulative pressure, or “footprint”, of food production. On land, we find five countries**  
45 **contribute nearly half of food’s cumulative footprint. Aquatic systems produce only 1.1%**  
46 **of food but 9.9% of global footprint. Which pressures drive these footprints vary**  
47 **substantially by food and country. Importantly, the cumulative pressure per unit of food**  
48 **production (efficiency) varies spatially for each food type, such that rankings of foods by**  
49 **efficiency differ sharply among countries. These disparities provide the foundation for**  
50 **efforts to steer consumption toward lower-impact foods, and ultimately the system-wide**  
51 **restructuring essential for sustainably feeding humanity.**

## 52 Introduction

53 Human diets have enormous implications for both human and environmental health<sup>1-6</sup>. The  
54 global food system is fueled by extensive appropriation and degradation of Earth’s natural  
55 capital, using roughly 50% of habitable land<sup>7,8</sup> and >70% of available freshwater<sup>9</sup>, emitting 23-  
56 34% of global anthropogenic greenhouse gases (GHG)<sup>8,10</sup>, polluting watersheds and coastal seas  
57 with nutrients<sup>11</sup>, and harvesting aquatic food from nearly every river, lake and ocean<sup>12,13</sup>.  
58 However, food types are strikingly disparate with respect to the environmental pressures that  
59 result from their production<sup>1,2,14-19</sup>.

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

72 Integrative methods from the life-cycle assessment (LCA) literature have yielded important  
73 insights into the environmental pressures of food production<sup>1,14,15,23</sup>, setting the stage for parallel

74 analyses across food types and cumulatively across pressures. Furthermore, previous work for  
75 specific food groups has revealed the global geography of individual environmental pressures,  
76 for example the freshwater use of crops<sup>24</sup> and livestock<sup>25</sup>, GHG emissions from crops<sup>26,27</sup>, and  
77 the distribution of marine fisheries<sup>12,28</sup>. These pressures often coincide in space, hence devising a  
78 coherent and effective set of interventions to minimize environmental pressures requires spatial  
79 analysis of the cumulative pressure (i.e., “footprint”) of all foods.

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

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

101  
102 An assessment focused on pressures is best suited to inform where improvements to production  
103 levels or technologies will be most effective at reducing food’s footprint. GHG emissions, for  
104 example, may drive most of their impact far away, spatially and temporally, from the source of  
105 emissions, but locating the source of those emissions will help inform more sustainable  
106 production. Our findings reveal places and food types that have the smallest and largest  
107 footprints in marine, freshwater and terrestrial systems. We map which individual pressures drive  
108 cumulative pressure, and which foods are most environmentally efficient (cumulative pressures  
109 per unit production) and where these efficiencies occur. These advances create new opportunities  
110 for food producers, consumers, and policy makers to identify leverage points for enhancing the  
111 efficiency of food systems in support of food security and sustainability priorities.

112

## 113 Mapping food's cumulative footprint

114 To estimate the source location and cumulative magnitude of environmental pressures of food  
115 production, we mapped (5 arc-minute resolution, projected to 36km<sup>2</sup> equal-area resolution; see  
116 Methods) the pressures for the majority of food production in 2017, including crops (human and  
117 animal consumption), livestock (meat, eggs, milk), marine aquaculture (finfish, bivalves,  
118 crustaceans), marine fisheries, and freshwater fisheries. We focused on food products that  
119 provide nutrition, for example, in the form of protein, carbohydrates, and fats; we excluded  
120 agricultural items with no, or minimal, nutritional value such as coffee, tea, and tobacco, as well  
121 as nonedible items, such as fiber crops. We mapped four dominant classes of pressure that are  
122 the focus of the vast majority of global research on food sustainability<sup>14,20</sup>: GHG emissions  
123 (CO<sub>2</sub>eq), blue freshwater (FW) use (m<sup>3</sup>), excess nutrients (tonnes N and P estimated to  
124 runoff/leach, and for N, volatilization as NH<sub>3</sub>), and habitat disturbance (D, in km<sup>2</sup>-eq). For each  
125 food type, we multiplied the amount of food production (e.g., standing head of animals, area of  
126 production, tonnes production/capture) in each pixel by regionally specific estimates of pressure  
127 generated per unit of production.

128 We used models and methods similar to life cycle assessments (LCAs) to estimate a suite of  
129 pressures resulting from food production<sup>1,14,15,23</sup>. However, we expand on LCA efforts by  
130 mapping the pressures to the specific locations where they are incurred<sup>29</sup>. We did not attempt to  
131 include the pressures from all components of the full life cycle of food production (and  
132 consumption) because the information required to map these pressures is unavailable. Our focus  
133 was on within farm-gate pressures, and we excluded pressures from indirect activities such as  
134 processing and transportation of product, extraction of fuel, and manufacturing of equipment.  
135 For pressures arising from animal feeds, we always mapped the pressures to the location where  
136 the feed is grown for each animal system, not where it is consumed. To calculate the cumulative  
137 pressure, we adopted similar methods as other cumulative measures<sup>30</sup>, rescaling each individual  
138 pressure (GHG, FW, NP, D; Supplementary Data 1) by dividing the values in each pixel (*i*) by  
139 the total global pressure summed across all food systems and pixels (T; Supplementary Data 2),  
140 such that each pixel describes its proportional contribution to the global total for that pressure.  
141 We then summed these rescaled pressure layers to obtain a total cumulative pressure score (CP)  
142 for each pixel *i*, such that  $CP_i = GHG_i/GHG_T + FW_i/FW_T + NP_i/NP_T + D_i/D_T$ .

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

148 The cumulative footprint of food is remarkably skewed geographically (Fig. 2; Supplementary  
149 Data 4). Contributions from land (89.9% of global cumulative pressure) vastly outweigh those

150 from oceans (9.9%) or freshwater ecosystems (0.2%), yet these ocean pressures are substantial  
151 given that relatively little (1.1%, by tonnes) food and feed for fed animals comes from the  
152 sea<sup>35,36</sup>. The top 1% of pixels with respect to cumulative pressures (5,114,880km<sup>2</sup> total) fall  
153 nearly entirely on land (only 94,608 km<sup>2</sup>, or 1.8% of this top 1%, fall in the ocean, and none in  
154 the high seas; Fig. 2a) and produce 39.4% of food's global cumulative pressure and 30.9% of  
155 assessed tonnage of food. They occur primarily in India, China, the U.S., Brazil, and Indonesia  
156 (Fig. 2a). Nearly all pressures (92.5%) are exerted in just 10% of pixels.

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

164 The cumulative pressure imposed by food production is greatest in India, China, the U.S., Brazil,  
165 and Pakistan (Fig. 4; Extended Data Figs. 1,2; Supplementary Data 5,6). These high population  
166 countries alone contribute nearly half (43.8%; Fig. 4) of global cumulative pressure. Country-  
167 level cumulative pressure derives almost entirely from land-based food production, with the  
168 exception of island nations and some countries with extensive coastlines, such as Norway (88%  
169 from oceans), Japan (40%), Chile (38%), the U.K. (38%), Indonesia (33%), and Vietnam (26%)  
170 (Supplementary Data 7). Marine fisheries and aquaculture contribute >25% of total pressures in  
171 94 countries, primarily in island nations (Supplementary Data 7).

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

183 The cumulative pressure for fed animals spreads far beyond the farm where they are raised. For  
184 example, because marine forage fish comprise an average of ~0.15% of chicken and ~0.02% of  
185 pig feed<sup>35,37</sup>, these livestock have similar cumulative ocean footprints to that of some mariculture

186 species (Fig. 5). Feed for mariculture species increasingly includes crops, and all fed species  
187 have >98% of their footprint on land (Supplementary Data 9).

188 This displacement of cumulative pressures is not limited to feed for fed species. For example, of  
189 the 172 countries with FAO trade data<sup>38</sup>, 152 reported crop imports, which means they displace  
190 at least some portion of their cumulative pressures to obtain their domestic crop supply. Based on  
191 trade data, the largest proportional exporters of crop cumulative pressures will be small, highly  
192 developed countries such as Hong Kong, The Netherlands, Belgium, and Montenegro; countries  
193 in the Middle East with generally poor growing conditions, such as Kuwait, United Arab  
194 Emirates, Jordan, Oman, and Saudi Arabia; and island nations such as the Maldives and Trinidad  
195 and Tobago.

## 196 **Comparing environmental efficiency of food**

197 The environmental efficiency of food production, measured here as the ratio of cumulative  
198 environmental pressures to production per area (e.g., pixel, country, global), such that larger  
199 values represent lower efficiency, varies not only among food types but also geographically  
200 within each food type (Supplementary Data 3). In contrast to earlier treatments of this concept<sup>14</sup>,  
201 we calculate efficiencies based on cumulative rather than single pressures. Our spatially-explicit  
202 approach reveals how cumulative pressure and its components are distributed across the planet,  
203 and importantly *where* efficiencies are greatest or lowest for each food. Efficiencies for the same  
204 crops can vary 4.3 to 17.7 times (90th vs. 10th quantile; average 7.1) among countries (Fig. 6;  
205 Supplementary Data 3) due to differences in water consumption, fertilizer/pesticide use, and  
206 farming practices. For example, the United States (the largest producer of soy<sup>39</sup>) is 2.4 times  
207 more efficient than India (the 5th largest) in producing soy, largely because US farmers have  
208 been able to use technologies to reduce GHG emissions and increase yields<sup>40</sup>. Similarly,  
209 efficiencies for marine fisheries vary up to 22-fold among countries (mean of 6; Supplementary  
210 Data 3) based on the specific species fished and gear types used within a country. For example,  
211 China and Brazil are 1.5 and 1.9 times less efficient than Russia in harvest of demersal fish  
212 (Supplementary Data 3), respectively, primarily because they rely heavily on more destructive  
213 gear types such as bottom trawls<sup>41</sup>, affecting both disturbance and GHG emissions pressures.  
214 Such geographic variation in environmental efficiencies could be leveraged to benefit both food  
215 production and the environment.

216 Important within-country differences exist among foods that deviate from expectations based on  
217 global averages (Fig. 6). For example, measured by tonnes of production, on-farm efficiency for  
218 pig meat is 5.2-fold less efficient than cow meat in Indonesia (Supplementary Data 3). This  
219 pattern is likely due to very low production rates of meat per animal for pigs in Indonesia,  
220 perhaps due to the large proportion (64%) of backyard pigs<sup>42</sup>. In China, while demersal fisheries  
221 are notably inefficient, forage fisheries are even less efficient (1.1-fold; Supplementary Data 3)  
222 because a large percentage of the forage fish catch is caught using destructive gear types<sup>41</sup>. In

223 Morocco, sorghum is 5.8-fold less efficient than millets (Supplementary Data 3), likely because  
224 locally sorghum requires more land use per tonne of product than millets<sup>39</sup>.

225 Efficiencies differed depending on whether food production was measured by protein content  
226 (Fig. 6; Supplementary Data 3), energy content (kcal; Extended Data Fig. 4) or weight (tonnes;  
227 Extended Data Fig. 5). For example, some countries were inefficient when measured by weight  
228 but more efficient measured by protein (e.g., Brazil, China), and vice versa (e.g., U.S., Russia,  
229 Argentina; Fig. 4A; Supplementary Data 3). Changes in efficiency for specific foods primarily  
230 emerged for shellfish (large weight of inedible shell) and many crops (due to variation in protein  
231 content). For example, tree nuts, oils, pulses, rice, soybeans and wheat are more efficient when  
232 measured by protein due to the high protein content of these crops, whereas cassava and  
233 sugarcane are more efficient by energy content. These variations in production efficiencies  
234 across foods and among countries, measured across the cumulative pressures from food, are not  
235 currently captured by dietary guidelines based on generalized sustainability metrics, an important  
236 oversight our work helps address. The ability to view and compare efficiencies in relation to  
237 different denominators (weight, protein, or energy) allows our results to be adapted to different  
238 policy needs.

239

## 240 **Discussion**

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

248 ***Cumulative pressures matter.*** Cumulative pressures can inform development of more holistic  
249 spatial food production management and policies in a way that individual pressures cannot. The  
250 spatial distribution and concentration of different pressures varies on land and in aquatic  
251 environments (Figs. 2, 3), creating both opportunities and challenges for policy interventions  
252 aimed at reducing food's footprint. The opportunities lie in the multiple pathways that a  
253 cumulative pressure lens helps identify to reduce footprints: by improving efficiencies of  
254 individual foods across multiple pressures, decreasing production of inefficient foods, increasing  
255 production of efficient foods to meet demand, or combinations of these approaches. Spatial  
256 overlap in pressures also identifies where policy can expect co-benefits, where strategies aimed  
257 at one pressure (e.g., nutrient reduction to mitigate eutrophication) has the potential to benefit  
258 another (e.g., GHG emissions reductions), and help avoid potential tradeoffs, where mitigating  
259 one pressure exacerbates another. The challenges arise in finding solutions that are appropriate

260 and effective in different locations and contexts around the world. For example, switching to  
261 high-yielding greenhouse-grown vegetables could reduce cumulative pressures through  
262 improved land-use and fertiliser efficiencies, outweighing the lower GHG efficiency<sup>43</sup>. However,  
263 such a strategy will only be appropriate if the capital and infrastructure required are available,  
264 and the benefit distributed in such a way as to improve economic well-being or food security—  
265 something that is unlikely to be true for many regions of the world. Conversely, if we can meet  
266 global food needs by concentrating pressures in relatively few areas (e.g., land sharing vs.  
267 sparing), we can spare larger areas from these pressures, which has many sustainability benefits  
268 for biodiversity, carbon storage, and other outcomes<sup>44–46</sup>. Concentrating pressures through  
269 intensification may therefore result in lower cumulative environmental pressure but may be at  
270 odds with local-scale socio-economic, ethical or cultural factors that, if ignored, can drive  
271 instability or further inequality, as witnessed in multiple countries during the expansion of  
272 shrimp farming<sup>47,48</sup>.

273 Importantly, food types often rank differently in their global cumulative pressure compared to  
274 ratings derived from per-unit assessments of individual pressures. For example, the cumulative  
275 pressure from catching demersal fishes is triple that of raising sheep for meat (Supplementary  
276 Data 8, which is counter to common generalizations. However, demersal fishing produces 4  
277 times more food<sup>41</sup> than sheep farming<sup>49</sup>. In other cases, per-unit inefficiencies exceed effects  
278 from the scale of production effects. For example, the low efficiency of Brazilian beef  
279 production means that it has a higher total cumulative pressure than United States beef  
280 production (Supplementary Data 3,5), despite producing about 10% less meat<sup>49</sup>. An interesting  
281 case is the sustainable harvest of wild animals and plants, which can be very efficient from a  
282 cumulative pressure standpoint because these organisms do not require human-appropriated  
283 freshwater resources or create excess nutrients, thereby removing two major pressures associated  
284 with farming food. Large-scale, high-disturbance harvesting (e.g., some demersal fishing  
285 practices) can still produce a large cumulative pressure<sup>12,16,28</sup>. This environmental efficiency  
286 underscores the importance of wild foods for food security. However, their generally lower  
287 sustainable production rates per area and the potential impacts of harvesting (for example,  
288 biodiversity loss, ecological/food web impacts, and the potential for zoonotic disease outbreaks)  
289 offer limited capacity for sustainable expansion.

290 ***Cumulative environmental efficiencies are highly variable.*** Perhaps the most striking finding  
291 from our analysis is the dramatic differences in food production efficiencies (Fig. 6;  
292 Supplementary Data 3). Such differences have been found for individual pressures<sup>14</sup>, but the rank  
293 order across food types found here when measured by cumulative pressures often diverge from  
294 individual pressure rankings, and importantly, vary substantially among countries. We estimate  
295 up to >10-fold variation among countries for many livestock, fisheries, and crop products (based  
296 on 90th and 10th quantiles; Fig. 6; Supplementary Data 3). For example, locations of greatest  
297 pressure differ (Fig. 3) despite broadly similar distributions of pressures (Fig. 2). This spatial

298 heterogeneity provides many opportunities for both researchers and policy makers to leverage  
299 that variation to enhance overall food system sustainability.

300

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

313 Comprehensive assessments of patterns of trade and consumption were beyond the scope of our  
314 cumulative pressure analysis, but are clear priorities for future research and highly relevant to  
315 reining in food's footprint, particularly since the geography of consumer demand is at least as  
316 plastic as that of food production. However, our analyses do allow indications of these dynamics.  
317 For example, of the 172 countries with FAO trade data, 152 reported crop imports<sup>38</sup>, which  
318 means they displace at least some portion of their pressures to other countries in order to meet  
319 domestic demand. The countries that import the majority of their crop products include small,  
320 highly developed countries such as Hong Kong, The Netherlands, Belgium, and Montenegro;  
321 countries in the Middle East with generally poor growing conditions, such as Kuwait, United  
322 Arab Emirates, Jordan, Oman, and Saudi Arabia; and island nations such as the Maldives and  
323 Trinidad and Tobago. Coupled with our spatial maps of food footprints, they are also critical  
324 issues for understanding environmental justice implications of these footprints, i.e., who is  
325 benefiting from consuming the food and who is paying the environmental price for its  
326 production.

327 Minimizing the environmental footprint of feeding nearly eight billion people is among the most  
328 important of societal challenges, and will require strategies operating at both local and global  
329 scales. Just as foods and their environmental pressures are exported worldwide, so must policy  
330 makers, communities, corporations, and researchers seek sustainability through coordination and  
331 shared learning around the globe. Knowing where and how food production exerts  
332 environmental pressures provides foundational information that, when combined with local-scale  
333 knowledge about species and ecosystem vulnerability to these pressures, can uncover where (and  
334 why) some producers are more environmentally efficient than others, where to concentrate

335 production in less sensitive regions, and how to design mitigation efforts where needed. Our  
336 findings represent a vital step toward a spatially-explicit, comprehensive, system-wide  
337 perspective that is essential for identifying environmentally efficient options to achieve both food  
338 security and environmental sustainability.

## 339 **Methods**

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

## 342 **Foods included**

343 We include data for most types of food and every country and its Exclusive Economic Zone  
344 (EEZ), as well as the high seas (Supplementary Methods, Section 2, Description of food  
345 systems). We define food as substances “consisting essentially of protein, carbohydrate, and (or)  
346 fat used in the body of an organism to sustain growth, repair, and vital processes and to furnish  
347 energy” (Merriam-Webster). We estimated pressures for nearly 99% of food production reported  
348 by the United Nations Food and Agricultural Organisation (FAO, based on tonnes of production;  
349 Supplementary Methods). Specifically, we assessed pressures for 26 crop categories (plus  
350 fodder, which is only consumed as feed); 19 livestock categories, accounting for animal (cattle,  
351 buffalo, goats, sheep, pigs, chickens), product (meat, milk, eggs), and rearing system (industrial,  
352 mixed, backyard, grassland); 7 categories of marine fisheries, including forage fish species used  
353 for fishmeal and oil, other small pelagics, medium pelagics, large pelagics, benthic, demersal,  
354 and reef-associated; freshwater fisheries, with one group for all sizes and taxa; and 6 categories  
355 of marine aquaculture, including salmonids, unfed or algae fed shellfish, shrimp and prawns,  
356 tuna, other marine finfish, other crustaceans.

357 Omissions of land-based animals include game, livestock with relatively low production levels  
358 (e.g., turkey, ducks, rodents), and food not reported by FAO (e.g., insects). We excluded wild-  
359 harvest and mariculture of seaweed and freshwater aquaculture because no comprehensive data  
360 exist for farm locations; however, the vast majority of freshwater aquaculture occurs in Asia  
361 (77.6% of global production in tonnes, with China producing 59.8%)<sup>52</sup>, and so inclusion of these  
362 data would primarily increase pressures in Asia. For inland capture fisheries, we do not account  
363 for fish from the world’s great lakes and fish reported exclusively in household surveys<sup>13</sup>,  
364 although their omission has a small effect on results because pressures from inland capture are  
365 relatively low.

## 366 **Pressure overview**

367 We map four dominant global pressures of food production: disturbance (km<sup>2</sup>eq); blue  
368 freshwater consumption (m<sup>3</sup> water); excess nutrients (tonnes NP); and greenhouse gas emissions  
369 (tonnes CO<sub>2</sub>eq) (Supplementary Methods, Table S3; Section S3, Pressure overview).

370 Disturbance is similar to the water pressure in that both measure the amount of something  
371 (nature, water) removed from the system, whereas GHG emissions and excess nutrients measure  
372 additions to the system. We primarily assess pressures from sources occurring within the farm-  
373 gate (i.e., at the production site; Supplementary Methods, Table S4; Section S5, Pressure  
374 assessment: farm and capture). In most cases, we exclude activities occurring beyond the farm-  
375 gate, such as processing and transportation of product, manufacture of equipment, and extraction  
376 of fuel because we were generally unable to map the location of these activities (Supplementary  
377 Methods, Table S5).  
378

### 379 **Spatial Resolution**

380 Most mapped food studies report results at 5 arc-minute latitude/longitude (WGS84;  
381 Supplementary Data 10), representing an area of about 85 km<sup>2</sup> at the equator. We mapped  
382 pressures to this resolution, but to assess cumulative pressure, and for accurate visualisation, we  
383 projected data to an equal area coordinate reference system (Gall-Peters; Supplementary  
384 Methods, Section S9, Spatial units) with a resolution of 36km<sup>2</sup> which is similar to the average  
385 area of grid cells located near the poles in the original data.

### 386 **Mapping location and quantity of food production**

387 Mapping pressures from food production required determining the location and intensity of food  
388 production for each food type (Supplementary Methods, Section S4, Mapping location of food  
389 systems). For crops, tonnes and area of production were taken from the Spatial Production  
390 Allocation Model, SPAM v2.0<sup>53</sup>, which provides 2010 crop production and physical crop area  
391 data for 42 crops (we aggregate some of these categories and exclude agricultural items with no,  
392 or minimal, nutritional content such as: fibers, tea, tobacco, and coffee; Supplementary Methods  
393 Table S6) at 5 arc minute resolution. For each crop, SPAM identifies four production systems:  
394 irrigated high inputs, rainfed high inputs, rainfed low inputs, rainfed subsistence. We adjusted  
395 SPAM production values in each pixel based on the proportional change in FAOSTAT crop  
396 production from 2010 to 2017 for each country<sup>39</sup>. For livestock, we determined the relative  
397 distribution of animals within a country using FAO Gridded Livestock of the World data<sup>42</sup>,  
398 which describes headcounts in 2010 at 5 arc minute resolution. However, the actual number of  
399 animals in a country was from FAO livestock headcount data<sup>49</sup>. We used additional information  
400 (Supplementary Methods, Section S4, Mapping location of food systems) to map the location of  
401 specific rearing systems (e.g., grazed vs. feedlot) and products (e.g., milk vs. meat). We were  
402 unable to remove animals used for non-food purposes (e.g., wool), which overestimates  
403 pressures attributed to meat/milk production. For maps describing marine fish capture, we used  
404 spatialized global catch data<sup>41</sup> describing tonnes of global catch in 2017 at 0.5 degree resolution  
405 estimated by allocating FAO country catch data to gridded areas based on the spatial distribution  
406 of fished taxa and the location of country fleets given fishing access agreements. For global

407 inland freshwater fisheries, we used gridded map data<sup>13</sup> describing catch tonnage at 5 arc  
408 minutes averaged across 1997-2014. Maps of mariculture farms were synthesized from many  
409 data sources and modeled locations<sup>54</sup>, with production based on 2017 FAO data<sup>52</sup>.

410

## 411 **Mapping food pressures**

412 We used the maps describing the intensity of production for each food type to estimate pressures  
413 using a variety of approaches (Supplementary Methods, Section S5, Pressure assessment: farm  
414 and capture). Instead of omitting regions or foods with missing data or assuming NA or zero  
415 values, which causes bias, we estimated these values.

416 ***Disturbance:*** We define disturbance as the proportion of native plants and animals displaced by  
417 agricultural activities within a region, and this pressure is reported in units of km<sup>2</sup>eq which  
418 incorporates both the occupancy area and a measure of disruption. For crops and  
419 industrial/mixed livestock rearing, we assume these activities completely displace native  
420 ecosystems (i.e., disruption is equal to 1) which means disturbance equals the area occupied by  
421 fields and farm structures. We modified this general approach for more complex systems, such as  
422 grazing animals and marine fisheries, where some animals and plants coexist alongside these  
423 activities (i.e., disruption <1). In these cases, we estimate disturbance as the amount of native  
424 biomass removed relative to total biomass (i.e., the proportion of biomass removed).

425 To estimate disturbance from grazing animals we assume that the magnitude of the pressure  
426 corresponds to the amount of consumption (a function of feeding rate and number of animals)  
427 relative to the amount of primary production (i.e., NPP)<sup>55</sup>. We treat most marine aquaculture  
428 similarly to mixed and industrial livestock, but only consider the two-dimensional surface area of  
429 rearing infrastructure (e.g., ponds, cages). For inland fisheries, the area of disturbance was equal  
430 to river area because we assume all streams and rivers are fully fished, but we assume a  
431 relatively low disruption of 0.3 because river systems persist where fished. Marine fisheries can  
432 cause disturbance by destroying seafloor habitat when certain gear types are used (e.g., bottom  
433 trawls) as well as through biomass removal throughout the water column and from the seafloor.  
434 We estimate the degree of seafloor destruction based on fishing effort<sup>12,56</sup> (hours) using demersal  
435 destructive gear types. For biomass removal, we would ideally measure the total proportion of  
436 fish biomass removed, but because these data do not exist, we standardize total catch by dividing  
437 the tonnes of catch<sup>41</sup> by NPP to produce an impact metric relative to natural production. The  
438 raster maps describing both forms of marine fisheries disturbance (i.e., seafloor destruction and  
439 biomass removal) are rescaled to values between 0 to 1 by determining, for each map, the value  
440 across all the raster cells corresponding to the 99.9th quantile and dividing all the raster cells by  
441 this value. The two rescaled rasters are then averaged to get total marine fisheries disturbance.  
442 To make this measure comparable to land disturbance (measured in km<sup>2</sup>), we multiply this  
443 rescaled score by the 2-dimensional area of the ocean cell. Our decision to rescale fisheries

444 disturbance by the 99.9th quantile assumes 0.1% of ocean area is highly disturbed by fishing  
445 (e.g., has a fully disturbed value of 1). However, this value is highly uncertain, and we explore  
446 the sensitivity of our results to alternative assumptions (Supplementary Methods Table S12).

447 **Freshwater use:** For water pressure, we report total blue water consumption which results in  
448 aquifer and surface water depletion. In general, blue water use has a higher impact than green  
449 water (rainfall), but green water use reduces availability of water to species, ecosystems, and  
450 standing water<sup>24</sup>. Given the importance of green water consumption we also provide these data.

451 For crops, we use subnational water footprint data describing tonnes blue water per tonne  
452 production<sup>24</sup>. For livestock, we estimated on-farm consumptive freshwater use<sup>25</sup> (m<sup>3</sup>) based on  
453 average air temperature and additional service water, which we assume to be blue water. We did  
454 not include water use for aquatic systems (inland and marine fisheries and on-farm marine  
455 aquaculture) because freshwater use in these systems is primarily passive, with limited  
456 freshwater consumption<sup>57</sup>.

457 **Excess nutrients:** We estimated excess nitrogen and phosphorus inputs to systems from crops,  
458 livestock, and aquaculture; capture fisheries were excluded because this pressure is assumed to  
459 be minimal at the capture stage. For each system, we mapped excess N and P separately and, at  
460 the last step, added them to obtain a general indicator of excess nutrients, however, we provide  
461 these data separately so others can explore the *impact* of these nutrients independently. We  
462 define excess N and P inputs as those that are likely to runoff/leach into surrounding  
463 environments<sup>58–60</sup>, and in the case of N volatilize as NH<sub>3</sub> which subsequently deposits on the  
464 Earth's surface<sup>60</sup>.

465 We estimated excess nutrient inputs from N and P<sub>2</sub>O<sub>5</sub> synthetic fertilizers applied to crops. Many  
466 studies include organic (i.e., manure) fertilizers as well, however, we account for this at the site  
467 of the livestock farm. We distributed the N and P quantities described at the country scale<sup>61</sup>  
468 among raster cells according to: the national fertilizer use by crop rates<sup>62,63</sup>; the total hectares of  
469 harvested area for each crop, and the intensity of the agriculture system as defined by SPAM<sup>53</sup>.  
470 We estimated excess nitrogen and phosphorus as the tonnes likely to runoff/leach, and for  
471 nitrogen we also included the tonnes that volatilizes as NH<sub>3</sub> based on supranational volatilization  
472 estimates<sup>60</sup>. Our analysis for livestock was similar but used different parameters to estimate  
473 excess N and P given the various pathways manure can take: managed and then spread on  
474 fields/crops, directly spread on fields crops, left on fields. For livestock, we also included  
475 synthetic fertilizers applied to grasslands for the benefit of grazing animals. For mariculture,  
476 excess nutrients largely come from two sources: uneaten feed and faecal matter. We quantified  
477 dissolved N and P added to the marine system using models and parameters from others<sup>64–66</sup>.

478 **GHG emissions:** We calculated GHG emissions (tonnes CO<sub>2</sub>eq) for the majority of activities or  
479 processes occurring at the location of food production, such as tillage and crop residue burning  
480 and enteric fermentation. We mostly excluded indirect emissions such as construction of farming

481 infrastructure and extraction of fuel. We were unable to account for pressures resulting from land  
482 use change (e.g., deforestation and peatland degradation) which results in substantial GHG  
483 emissions due to the difficulty of mapping land use change to specific food systems and  
484 modeling more complex systems, such as marine environments. Based on other studies, from  
485 2007-2016<sup>67</sup>, land use change (e.g., converting forest to cropland) accounted for 36% of food  
486 production emissions.

487 For crop production, we included emissions for crop residue burning and volatilization, pumping  
488 of irrigation water, field maintenance, machinery operations, volatilization of synthetic  
489 fertilizers, and production of fertilizers and pesticides. For rice, we also included emissions from  
490 anaerobic decomposition of organic matter in paddy fields. For livestock, we included emissions  
491 from enteric fermentation, direct energy use on the farm, all manure related emissions, and  
492 synthetic fertilizers applied to grazed grasslands. Capture fisheries included emissions from  
493 vessel fuel use<sup>68</sup>, although for freshwater fisheries this is assumed to be relatively low for  
494 developing countries, and zero for remaining countries. Mariculture emissions include on-farm  
495 energy use<sup>68</sup>, and N<sub>2</sub>O from microbial nitrification and denitrification of waste<sup>69</sup>.

496 We standardized GHG (e.g., CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>) emissions to CO<sub>2</sub>eq using the Global Warming  
497 Potential for 100-year time scale (GWP<sub>100</sub>) as per the Kyoto Protocol<sup>70</sup>, with CH<sub>4</sub> multiplied by  
498 25 and N<sub>2</sub>O by 298. An important caveat is that the GWP<sub>100</sub> does not differentiate between long-  
499 and short-lived climate pollutants<sup>71</sup>. Depending on how emission rates change over time, this  
500 could dramatically reduce the warming potential of GHG emissions from livestock that are  
501 enteric ruminants, such as cows, and flooded rice production which have large CH<sub>4</sub> emissions.

502  
503 **Feed pressures:** Many crops and forage fish from marine fisheries can be directly consumed by  
504 humans or used as animal feed (Supplementary Methods, Section S6, Pressure assessment: feed).  
505 For feed components, we map the pressures to the location where the crops are grown or fish are  
506 captured (vs. where they are fed to animals). Identifying the likely location where feed is grown  
507 or captured is complicated by the fact that the country where the product is consumed is often  
508 not the country of production. To get at this, we first estimate the amount of each crop or fish  
509 product consumed by each country and animal system based on feed consumption rates and feed  
510 composition. We then determine the country (or location in ocean) where the feed likely  
511 originates using global trade data<sup>38,51</sup>. After determining the tonnes of each crop feed product  
512 produced for each animal system in each country, we divided this value by the total production  
513 in the country to estimate the proportion going to each food system. Once we account for all the  
514 animal feed use, we assume the remainder of the crop or fish oil/fishmeal catch is consumed by  
515 humans or used for other purposes.

516  
517 To determine the pressures from feed, for each country we multiplied the total pressures from  
518 each crop by the proportion going to each animal food system regardless of country of  
519 consumption.

520 For livestock, feed consumption rates (tonnes head<sup>-1</sup> year<sup>-1</sup>) and diet composition data were  
521 primarily from GLEAM<sup>72</sup>, and fishmeal/fish oil consumption for pigs and chickens from  
522 Froehlich and colleagues<sup>35</sup>. For aquaculture, we used feed conversion ratios (FCR) and diet  
523 composition data from recent studies<sup>37,73</sup>.

524 To convert the percent composition of each dietary component to tonnes of crop or forage fish  
525 consumption, we used the fish-in fish-out (FIFO) approach<sup>74</sup>. This accounts for loss (e.g., waste)  
526 during processing, which includes water loss, loss in machinery, and by-products not used for  
527 food/feed.

## 528 **Cumulative pressure calculation**

529 In addition to spatially describing the magnitude of individual pressures, we combine rescaled  
530 pressures to create a cumulative pressure index that describes the general magnitude of human  
531 influence resulting from food production<sup>29</sup> (Supplementary Methods, Section S7, Cumulative  
532 pressure calculations). The cumulative pressure index allows direct comparisons among foods,  
533 regions, and pressures to identify where: individual pressures are high relative to other pressures,  
534 multiple pressures overlap, and hotspots of cumulative pressure are located. This information  
535 provides a more complete picture of the environmental pressures occurring at any global area  
536 and from each food type (Supplementary Methods, Fig. S2).

537  
538 To calculate cumulative pressure, we first rescale each per-food pressure map by dividing each  
539 pixel's pressure value by the total global pressure generated by all foods and across all raster  
540 cells. The result is that each rescaled pixel is a unitless value describing its proportional  
541 contribution to the total global pressure. The four rescaled pressure raster maps are then summed  
542 to derive a general measure of the cell's total contribution to the global pressure. Summing  
543 individual pressure scores implicitly weights pressures equally, a reasonable assumption for  
544 providing a general measure of human influence<sup>20,30,75</sup> and an overall index of pressure from  
545 food production. The ultimate impact, or weight, of each pressure will vary according to the  
546 particular system being impacted (e.g., loss of habitat, increased species vulnerability, reduced  
547 food security, etc.; Fig. 1) as well as complex interactions between the pressure and local  
548 environment. Assessments of impact are not common for global scale analyses because the  
549 systems of concern will vary by region (and, researcher) and will often require environmental  
550 data not available at the global scale.

551  
552 The resulting total cumulative pressure across all the global pixels equal 4 (by definition), and  
553 the maximum observed pixel value was  $2.305 \times 10^{-4}$ , near Ashdod, in Israel (Fig. 2).

## 554 **Environmental efficiency of food production**

555 For each country, we calculated the environmental efficiency of each food system by dividing its  
556 total cumulative pressure by the total tonnes of production according to FAO data as well as the

557 food's nutritional value (kcal or protein) after adjusting for the edible portion (Supplementary  
558 Methods, Section S8, Efficiency of production). Within a food group, the variation observed  
559 among countries can be due to differences in cumulative pressure production (as measured here),  
560 or several sources of error (e.g., for livestock, number of heads are used to model pressures but  
561 efficiency is based on tonnes production which introduces uncertainty).

## 562 **Data quality and uncertainty**

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

567  
568 We did, however, conduct a qualitative analysis of the data used in our analyses (Supplementary  
569 Methods, Section S10. Data quality and uncertainty), which varied in quality and resolution  
570 (relative to our objectives). Given our objective of globally mapping food pressures for each  
571 food system at 0.5 degree resolution in year 2017 we assessed how well each dataset matched  
572 our desired spatial (extent and resolution), temporal, and system specificity criteria  
573 (Supplementary Data 10; Extended Data Figs. 6, 7). Although there were additional sources of  
574 data quality we were unable to incorporate into our assessments, this information will  
575 nonetheless inform users of these data of the limitations and strengths of our data.

576

## 577 **Data availability**

578 The source data used for these analyses is provided in Supplementary Methods Table S25. All  
579 results data are available<sup>76</sup>.

## 580 **Code availability**

581 The code used for these analyses is available from GitHub<sup>76</sup> ([https://github.com/OHI-  
582 Science/global\\_food\\_pressures](https://github.com/OHI-Science/global_food_pressures)).

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591

592 **Author Contributions Statement**

593 *Conceptualization*: all authors contributed to the conceptualization of the project.

594 *Methodology*: MF, JV, PER, GC, BSH

595 *Software*: MF, JV, PER, GC

596 *Validation*: MF, JV, PER, GC

597 *Formal analysis*: MF, JV, PER, GC

598 *Data Curation*: MF, JV, PER, GC

599 *Writing – Original Draft*: BSH

600 *Writing – Review and Editing*: all authors

601 *Visualization*: JV, MF, BSH

602 *Supervision*: BSH

603 *Project administration*: MF and BSH

604 *Funding acquisition*: BSH

605

606 **Competing Interests Statement**

607 The authors declare no competing interests.

608

609 **Figure Legends/Captions**

610 **Fig. 1.** Schematic view of methods used to assess and map cumulative pressures from food  
611 production. Pathways within the hashed box illustrate possible future research that is outside the  
612 scope of the study here.

613 **Fig. 2.** Global maps of food's footprint. A) Proportion of global cumulative environmental  
614 pressure (in millionths) per pixel from all foods, representing the combined pressure from B)  
615 disturbance, C) excess nutrients from nitrogen and phosphorus (summed), D) blue freshwater  
616 use, and E) greenhouse gas (GHG) emissions. The histogram of per-pixel values for cumulative  
617 pressure (inset with expanded axis) shows the skewed distribution in values illustrated in the  
618 map; the colour ramp for A) in both the map and histogram is based on per-pixel proportional  
619 values, with the top 1% of values  $>5.9$  (99th quantile value) coloured red. The maximum  
620 cumulative pressure value is  $2.305 \times 10^{-4}$ , near Ashdod, in Israel.

621 **Fig. 3.** Spatial overlap of the top 1% greatest pressure values for each of the four dominant  
622 pressures from food production. Colours represent where high pressures are unique (x1 overlap)  
623 or where pairs of pressures overlap (x2 overlap). Three-way overlaps (light gray) are not  
624 distinguished among the four different possible combinations. Insets show zoomed-in views of  
625 three regions with substantial amounts of different groups of overlap.

626 **Fig. 4.** Proportional contribution to the cumulative food footprint in the highest ranking countries  
627 for A) each pressure summed across all food types, or B) each food type summed across four

628 pressure classes. These areas have the highest proportion of cumulative environmental pressure,  
629 and collectively account for 70.23% of the global footprint of food production. In A, stacked bars  
630 show the proportional contribution of marine (lighter colours, calculated as the Exclusive  
631 Economic Zone) and terrestrial (darker colours) pressures from all foods combined. Symbols  
632 indicate the proportion of global food production (excluding feed) for each country as measured  
633 by tonnes (circles), protein (triangles) and kcal (squares). Where symbols overlap the bar, the  
634 production of food is low relative to the cumulative environmental pressure. In B, bars for  
635 animal production include environmental pressures arising from animal feeds. Additional  
636 countries are shown in Extended Data Figs. 1,2.

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

645 **Fig. 6.** Environmental efficiency (cumulative environmental pressure per tonne of protein  
646 produced) for major food types. Larger values represent less efficient foods. Fed animals include  
647 only on-farm pressures, and do not include feed; the full cumulative environmental pressure of  
648 fed animals (livestock and mariculture, excluding bivalves) would be obtained by summing on-  
649 farm pressures and feed pressures. Each point is a country (jittered for visibility), with median  
650 and inter-quartile range indicated by the boxes. Plots to the right show outliers, which likely  
651 reflect measurement and reporting error. Note that food groups are reported on separate scales.  
652 Coloured points indicate six examples of countries with high food footprints but divergent  
653 environmental efficiencies of production (yellow: USA; green: China; orange: Brazil; red: India;  
654 teal: Indonesia; purple: Russia). Countries with production, in any category, less than 100 tonnes  
655 livestock, 50 tonnes crop, 50 tonnes fisheries were removed due to high uncertainty. We also do  
656 not show a few extreme outliers for pigs (n=6) and freshwater fisheries (n=1). Versions of this  
657 figure measured by tonnes and energy content are presented in Extended Data Figs. 4,5.

658

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832 **Supplementary information is available for this paper**

833 Supplementary Methods

834 Extended Data Figures 1-7

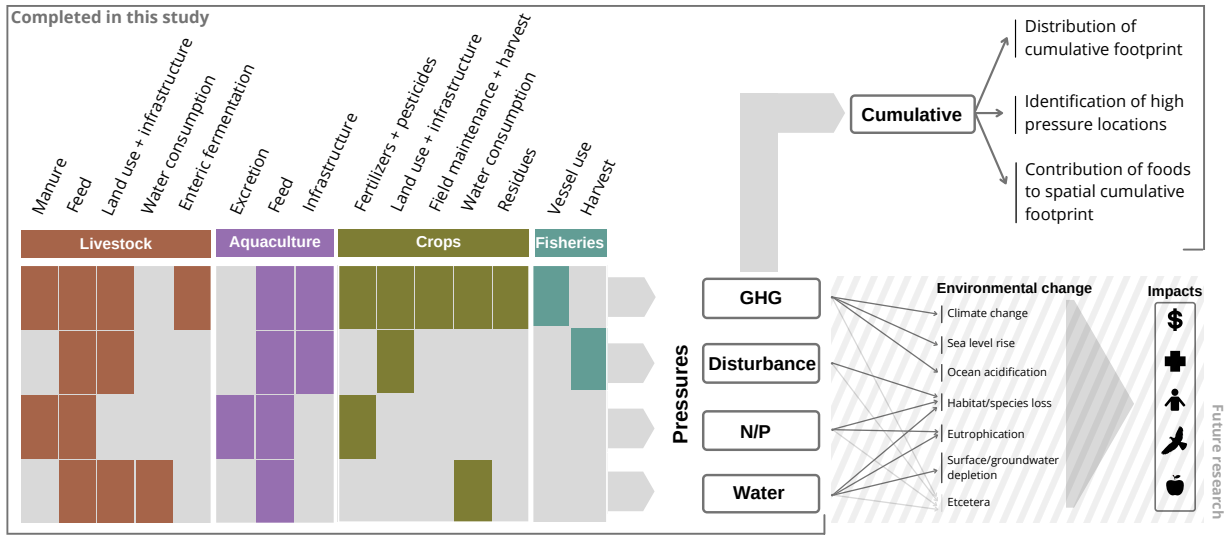
835 Supplementary Data

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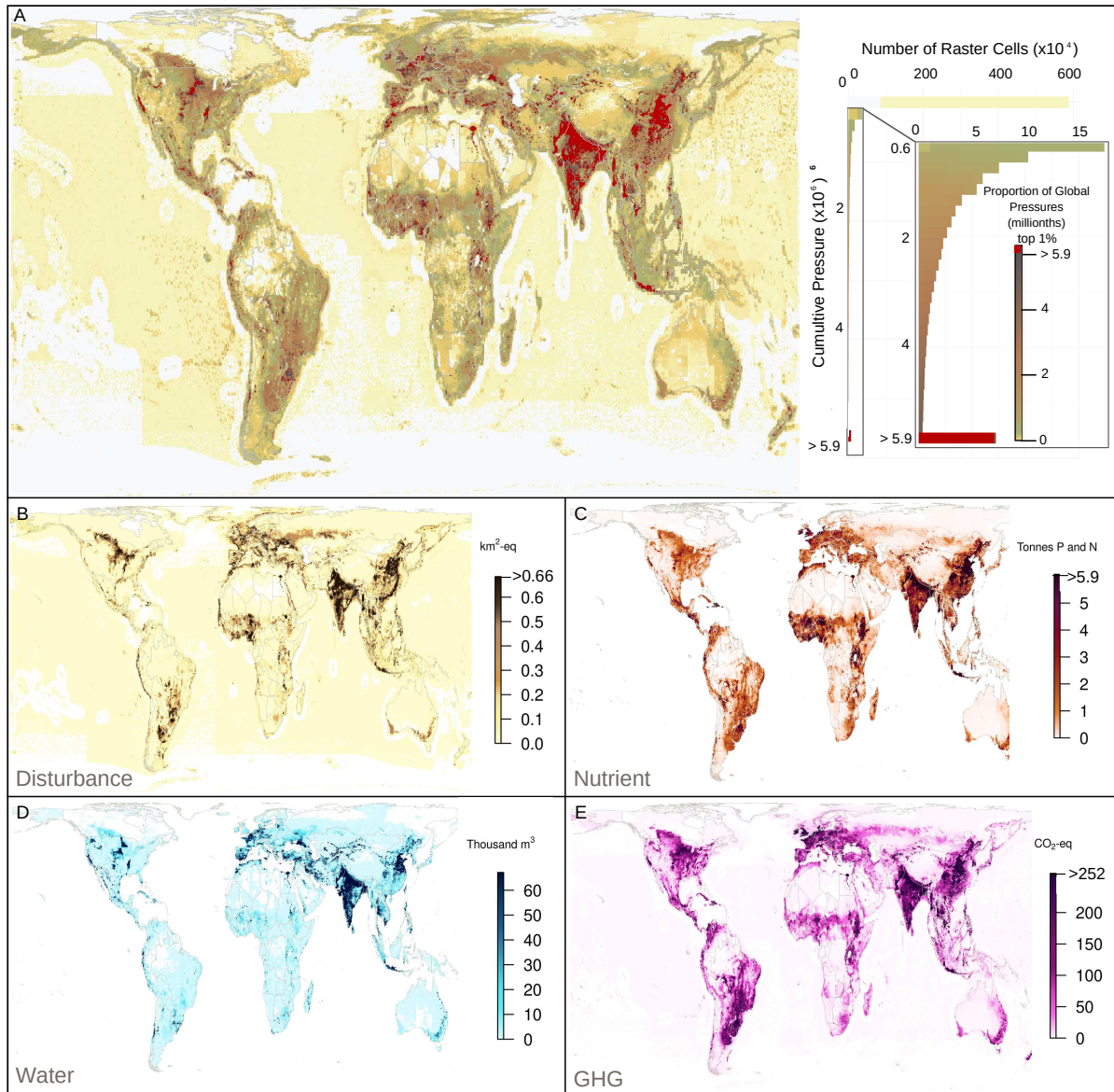
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839 Figure 1



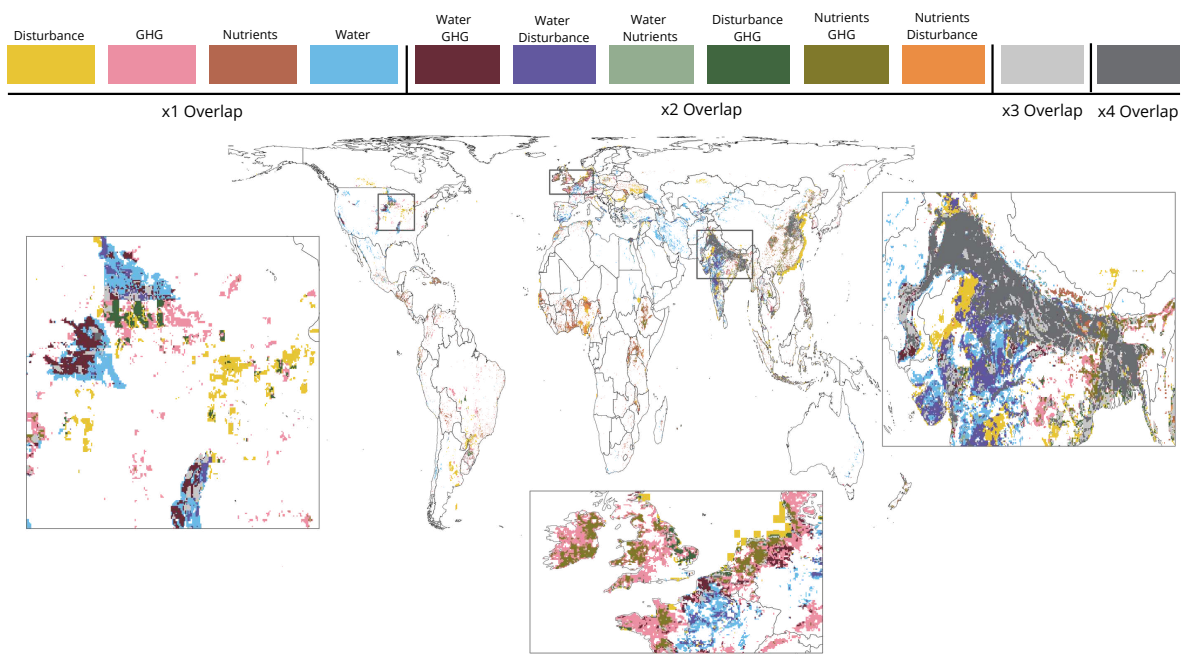
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842 Figure 2

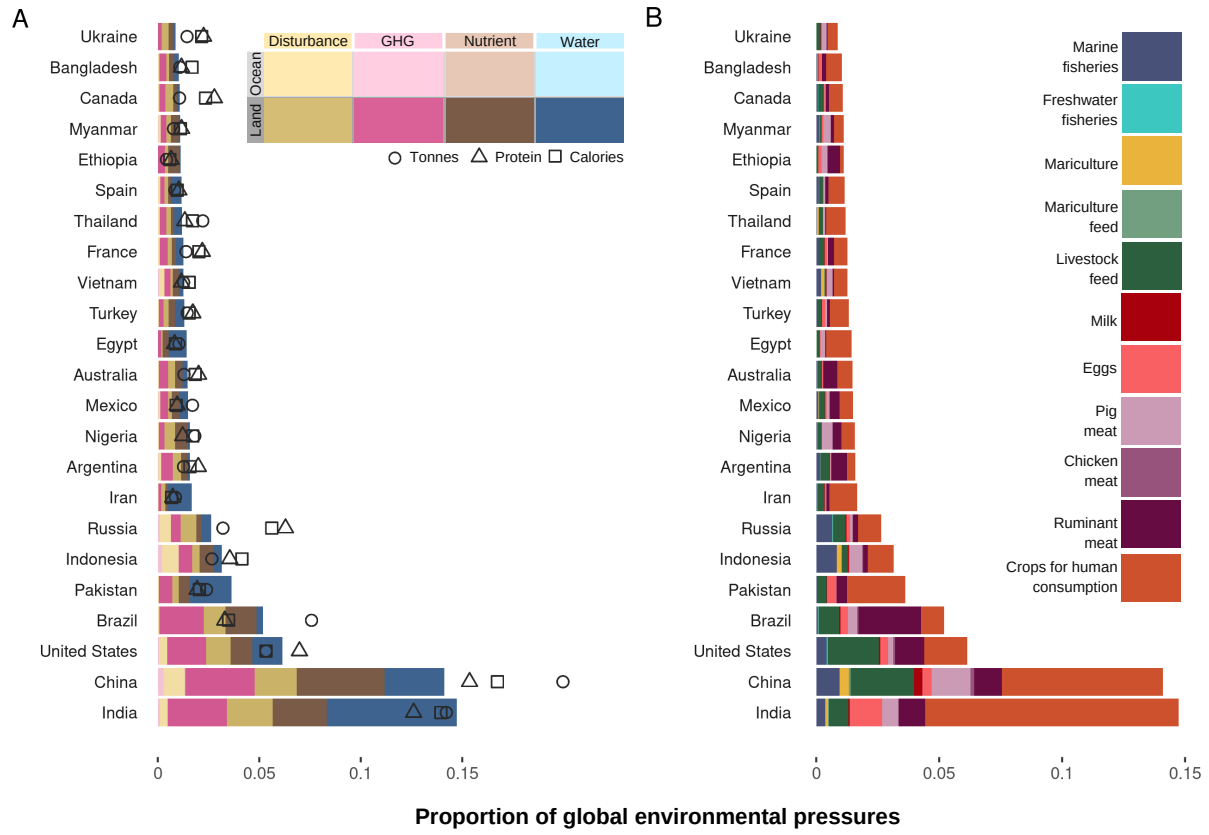


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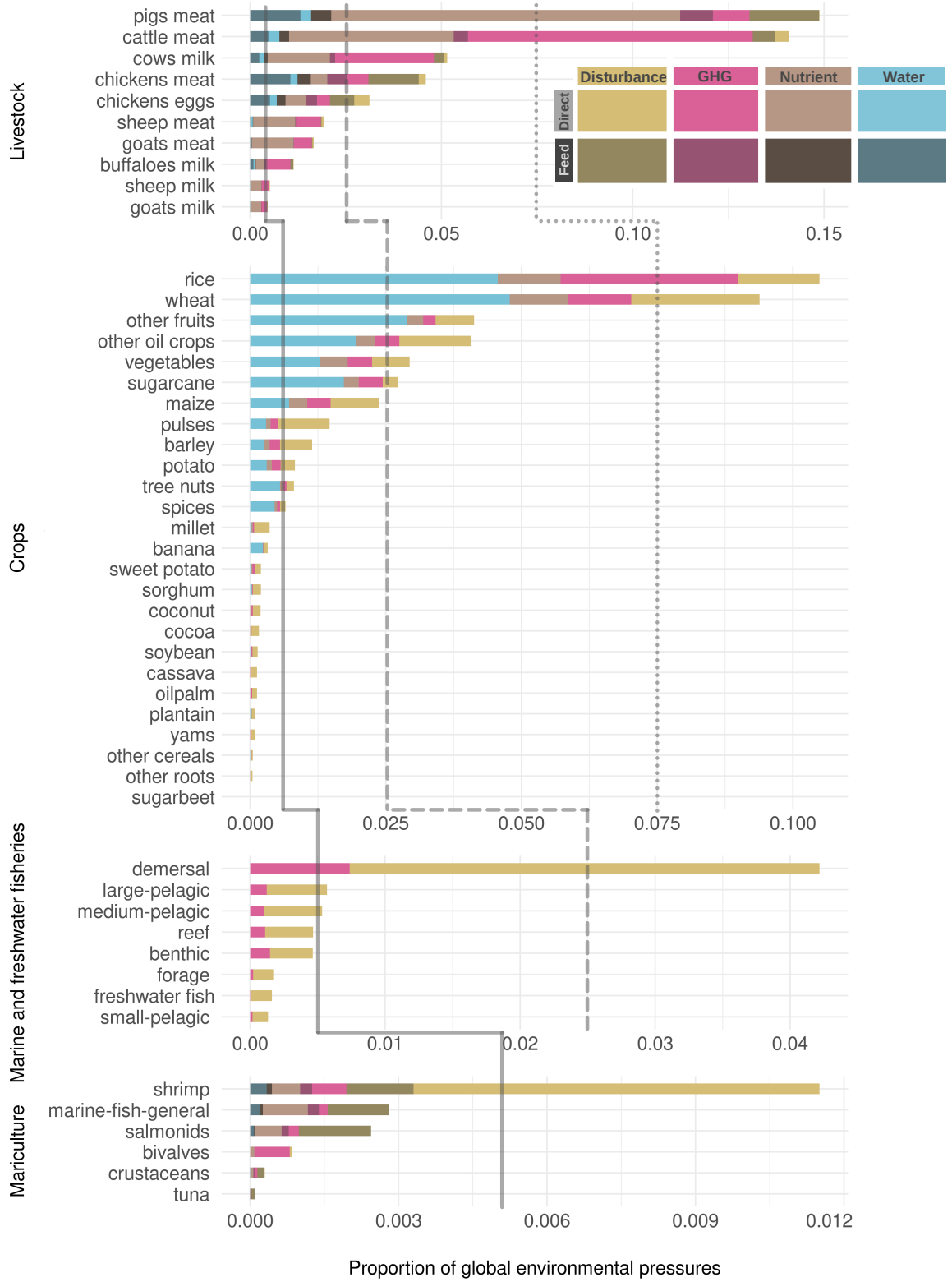
845 Figure 3



847 Figure 4



849 Figure 5



851 Figure 6

