1 **Title: The environmental cost of animal source foods**

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18

19 **Abstract**

20 We conducted a review of 148 assessments of animal source foods (ASF) production for
21 livestock, aquaculture and capture fisheries that measured four metrics of environmental impact
22 (energy use, greenhouse gas emissions, release of nutrients and release of acidifying compounds
23 into ecosystems) and standardized these per protein production. We also reviewed additional
24 literature on freshwater demand, pesticide use and antibiotic use. There are up to 100 fold
25 differences in impacts between specific products and in some cases for the same product; the
26 lowest impact production technologies were capture fisheries for small pelagics and aquaculture
27 for molluscs. The highest impact methods were industrial beef production and catfish
28 aquaculture. Many production technologies have not been evaluated and our analysis was limited
29 by the range of studies that have been conducted. Regulatory restrictions on ASF production
30 methods, as well as consumer guidance, should consider their relative environmental impact, and
31 currently there appears to be little relationship between regulatory restrictions and impact in most
32 developed countries.

33

34 **Introduction**

35 Animal source food (ASF) production is one of the most dynamic elements of the world
36 food system. Meat production has been increasing at 2.7% per year from 1995 to 2007 (FAO
37 2009), and aquaculture, which increased at 5.7% per year from 2004 to 2011, more than

38 compensated for the slight (0.3% per year) decline in production from capture fisheries during
39 the same period (FAO 2010; 2012). Both production and demand for ASFs is expected to
40 continue to rise (Godfray *et al.* 2010), driven both by world population growth and rising
41 incomes in many countries (Hazel and Wood 2008).

42 The environmental consequences of ASF production have received significant scientific
43 and public attention (Smith *et al.* 2010; Steinfeld *et al.* 2006; Tilman *et al.* 2001; Worm *et al.*
44 2009; Eschel *et al.* 2014; Hererro *et al.* 2015) both with respect to the sustainability of
45 production and the environmental consequences of alternative practices. A broad range of policy
46 choices have, and will continue to, influence the relative rate and location of growth of different
47 forms of animal production. To make these choices, policy makers, retailers and consumers
48 need more standardized information, across a range of metrics, on the relative environmental
49 costs of alternative production methods for meeting rising demand.

50 There is a large and growing source of literature documenting the environmental impacts
51 of different ASF (e.g. (Pelletier *et al.* 2011; Steinfeld *et al.* 2006)). With the exception of energy
52 use, however, there are no systematic comparisons of environmental costs across animal food
53 types. Globally and nationally, choices are and will continue to be made about how food
54 production is expanded through agricultural policies, trade agreements and environmental
55 regulations. To support such choices there is a pressing need for systematic comparisons.

56 The environmental impact of food production can be measured in many dimensions,
57 including the inputs (e.g., energy, freshwater, fertilizer, pesticides and antibiotics) as well as
58 environmental consequences (e.g., greenhouse gas emissions, water use, water quality,

59 biodiversity and habitat impacts) of food production systems. Many of these consequences were
60 considered in the planning documents for the Millennium Ecosystem Assessment (World
61 Resources Institute 2003) and some have been estimated for a wide range of production methods
62 using Life Cycle Assessment (LCA), the established method for measuring multiple
63 environmental impacts.

64 Here, we found 148 individual LCAs for ASF that evaluated major production
65 technologies in an effort to collate and systematize our understanding of the environmental
66 impacts across the range of animal production systems. Of these studies, 48 were for livestock
67 (meat), 29 were for capture fisheries and 71 were for aquaculture. Further, we reviewed the
68 literature on other impacts not widely assessed by LCA approaches, including water use,
69 pesticides, antibiotics, and soil erosion.

70 **Methods**

71 All life cycle assessments of livestock, aquaculture and capture fisheries that could be
72 found using key word searches in the Web of Science and Google Scholar were tabulated.
73 Search terms included are given in Table S1. We finished this search in April 2017 and found a
74 total of 324 LCAs. We removed studies of production systems that were not representative of
75 global production. This included small-scale production, “new innovative” production or trial
76 production, or organic farming. Therefore we have only used “conventional” production in our
77 analysis - long-standing, industrial, mass-production. We further filtered the LCA assessments
78 by only using those studies estimating impacts up to the farm gate, aquaculture facility or vessel
79 landing. If the assessment went beyond these stages, we used estimates of the sub-system up to

80 the desired life-cycle stage if available. All livestock and aquaculture LCAs included the feed
81 production. After filtering, 148 LCA assessments remained for further analysis. In the
82 supplemental materials we do explore the wider range of studies in an analysis of how the
83 production method affected impacts within a type of ASF. To standardize our analysis, all
84 production data were standardized by converting to impacts per 40 g of protein.

85 While there is a broad range of impact categories calculated in LCAs, our analysis was
86 restricted to the most common: energy intensity (MJ; 86 studies), greenhouse gas production
87 (CO₂-eq released; 120 studies), eutrophication potential (PO₄-eq released; 96 studies), and
88 acidification potential (SO₂-eq released; 94 studies). Table S2 shows all the LCA studies we
89 used, the product, and the published LCA results per 40 g of protein produced for each of the
90 impact categories described above. The conversion rates we used from total production through
91 weight of edible product to weight of protein are shown in Table S3. In all cases we have
92 calculated impacts for a standardized serving of 40 g of protein. This is slightly below the
93 USDA recommended minimum daily requirement for a healthy adult (46g for females 52g for
94 males) and corresponds to roughly 200 g of meat or fish. Protein is also available from plant
95 source foods.

96 **Results**

97 **Results of LCA review**

98 We classified each product into one of 14 categories, broken into three major groups
99 (aquaculture, capture fisheries, and livestock) and then separated by taxonomic group. Carp,
100 catfish, shrimp, salmon and tilapia are all high volume aquaculture products and given their own

category; molluscs are assigned to an additional category. Capture fisheries are divided into invertebrates, large pelagics, small pelagics, shrimp, and whitefish. Livestock is divided into pork, beef and chicken. We found a small number of studies for milk, eggs and lamb but excluded these because of the small sample size. Figure 1 shows the distribution of impacts of the four measures that were found in a large number of the LCA studies: energy demand, greenhouse gas production, eutrophication potential and acidification potential. Figure 2 shows an overall comparison of aquaculture, livestock and capture fisheries across all impact categories. In the LCA studies, the median values across all impact categories of capture fisheries are lower than those for livestock and aquaculture. Panels 2b-2d show the range of values within aquaculture, livestock and capture fisheries.

Energy used

Energy used in production of 40 g protein portions (Figure 1a) is highly variable among food production systems, ranging from a median value as low as 0.94 MJ per portion of protein for small pelagic fisheries to as high as 75.6 MJ per protein portion for catfish aquaculture. Overall, livestock production has lower energy inputs than aquaculture or capture fisheries with the exception of mollusc aquaculture and small pelagic fisheries. Table S4 shows pair-wise significance tests with small pelagic fisheries using less energy than catfish, shrimp and tilapia aquaculture as well as invertebrate capture fisheries; pork farming using less energy than catfish tilapia and shrimp aquaculture; beef farming using less energy than shrimp culture; mollusc aquaculture using less energy than catfish, shrimp and tilapia aquaculture. Salmon culture uses less energy than shrimp culture.

122 **Greenhouse gasses**

123 Greenhouse gas (GHG) production per portion protein (Figure 1b) is lowest for mollusc
124 aquaculture and small pelagic capture fisheries with salmonid aquaculture, chicken production,
125 and large pelagic and whitefish capture fisheries also under 1.0 kg CO₂-eq per 40 g of protein.
126 Catfish aquaculture and beef produce more than 20 times as much. Table S5 shows pairwise
127 significance testing. Small pelagic and whitefish fisheries emit significantly less GHG than
128 catfish, shrimp and tilapia aquaculture, beef production, and invertebrate and shrimp capture
129 fisheries. Mollusc and salmon aquaculture emits significantly less GHG than catfish and shrimp
130 culture, beef production and invertebrate fisheries; mollusc culture also emits less than tilapia
131 culture and shrimp fisheries.

132 **Eutrophication**

133 Eutrophication potential (Figure 1c) shows very large differences between systems. Most
134 methods release nutrients, while mollusc aquaculture actually absorbs nutrients. Capture
135 fisheries consistently score lower than aquaculture or livestock because no fertilizer is used. Beef
136 production demonstrates the broadest range of eutrophication impacts, and has the highest
137 median impact among livestock. Pairwise significant tests (Table S6) indicate mollusc
138 aquaculture releases less nutrients than beef production, invertebrate fisheries and all other
139 aquaculture methods except salmon. Chicken, pork, and capture fisheries for small pelagics and
140 whitefish all release less nutrients than tilapia aquaculture. Small pelagics also have a lesser
141 impact than shrimp culture.

Acidification

Acidification potential (Figure 1d) is lowest for mollusc aquaculture, with small pelagic and whitefish capture fisheries and salmonid aquaculture not far behind. While beef production has the highest median acidification impact, due to high variability among beef studies, no statistically significant differences are found between beef and other product categories. The dominant source of acidification potential in aquaculture and capture fisheries is the energy used, but for livestock it is NH_3 and NO_x emissions largely from manure. Pairwise significance testing indicates shrimp aquaculture to have greater acidification potential than both mollusc and salmon aquaculture as well as small pelagic and whitefish capture fisheries (Table S7). Mollusc aquaculture also has lower impacts than catfish aquaculture and invertebrate fisheries.

How the production system influences impacts

The primary GHG and acidification impacts of capture fisheries depend on fuel use with correlations in excess of 0.95 (Figure S1). Tyedmers (2004) provided one of the first overviews of fisheries energy use and Parker and Tyedmers (2014) expanded on the data available considerably. Fuel use is primarily related to the extent that fish can be captured efficiently. Consistent with these publications, we found (Figure S3) that small pelagic fishes which form dense schools can be captured with the lowest impact regardless of whether caught by purse seining or midwater trawl, that demersal fish species are intermediate in impact, and invertebrate species, whether captured by trawl or pot the highest impact. The most surprising result is the high fuel use (and thus other impacts) of pot fisheries for invertebrates like lobsters which had been noted by Parker and Tyedmers (2014). Trawling which involves dragging a net through the water demands a great deal of energy, but dropping pots does not. However, as Tyedmers

164 (2004) noted, the value of many invertebrates is so high that fishermen will expend a great deal
165 of fuel to catch a lobster and indeed there is a direct relationship between the price of the product
166 and the amount of fuel expended.

167 De Vries and de Boer suggested that the differences between livestock production
168 methods are due to three major factors, (1) feed efficiency, (2) methane production from
169 ruminants and (3) reproduction rates. Factors 2 and 3 both weigh heavily against beef, and the
170 general pattern of highest impacts associated with beef (Figure S4, supplemental materials) are
171 consistent with this. Feed conversion ratios are lowest for beef, then pork and highest for
172 chickens, which is consistent with their overall impact. We found (supplemental materials) that
173 grass fed beef had higher greenhouse gas emissions but lower fuel use. Data on organic
174 production were insufficient to draw any conclusions.

175 For aquaculture production the primary impacts have been associated with the feed used
176 (or lack of it) and energy used to recirculate water through pumping (Pelletier et al. 2011; Hall
177 et al. 2011) We found both of these to be supported by the LCAs we reviewed. Unfed
178 (extractor) species had consistently lower impacts across all measures, and systems requiring
179 pumping were the highest (Figure S5, Figure S6, Figure S8, Figure S9).

180

181 **Other Impacts**

182 In addition to the environmental impacts summarized in the LCA synthesis, there are a
183 range of other environmental impacts including water demand, pesticide use, antibiotic use, soil
184 erosion and biodiversity impacts. While some life cycle assessments do include a wider range of

185 impacts such as toxicity potential (herbicides and pesticides), water dependency and primary
186 productivity demand, there is not a large enough sample size from LCAs across food production
187 categories to provide any summary from a review. Nevertheless, there are major differences in
188 the impacts depending on animal production system. In the following sections we summarize
189 results from a range of sources. In most cases we have attempted to convert the estimates to the
190 amount used per 40 g of protein. Table S8 shows the data we were able to assemble for water
191 and antibiotic use.

192 Fresh water use differs greatly across production methods. Irrigated crops as inputs to
193 livestock and aquaculture are the most intensive uses while livestock that is raised by grazing on
194 a non-irrigated pasture uses far less. Capture fisheries and mollusc aquaculture use almost no
195 fresh water. Aquaculture in freshwater is more difficult to evaluate and has been rarely studied
196 (Gephart *et al.* 2017); while the fish are certainly present in freshwater, there may be little
197 consumptive use.

198 Antibiotic use is particularly interesting because of the differences in use within the
199 farmed salmon production category, as well as the large differences between all livestock and
200 most farmed salmon. Capture fisheries and mollusc culture use no antibiotics.

201 **Discussion**

202 This is the first comparison of a range of environmental impacts across livestock,
203 aquaculture and capture fisheries. There are striking differences regarding the environmental
204 impacts of different animal source food production systems (Figure 3). The range of variability
205 is quite high and any proposed policy needs to consider the specific species and production

206 system. We showed the high variability in some aquaculture and capture fisheries is due to
207 major differences in the production method. For aquaculture, the differences are due to (1)
208 whether the fish are fed and (2) whether the system requires power for circulating water. For
209 capture fisheries the impacts are primarily due to the amount of fuel used. Overall, mollusc
210 culture and small pelagic and whitefish capture fisheries consistently stand out as lowest impact
211 across categories.

212 A LCA is useful in determining impacts of ASFs globally, but it is important to consider
213 local effects. Though greenhouse gas emissions may act globally, eutrophication and water use
214 issues may be felt stronger at the local level. For example, one ton of eutrophication potential in
215 the form of nitrogen waste may have a stronger impact on a freshwater lake or stream, than on
216 the open ocean. Further, freshwater systems with different underlying geology will have
217 differing capacities to buffer acidification impacts. Similarly, the environmental impact of water
218 use may be strikingly different between places with an excess of fresh water compared to
219 locations faced with water shortage.

220 **Weaknesses in our analysis**

221 We have relied on a wide range of published (peer-reviewed or reports) life cycle
222 assessments that often used different methods and made different assumptions. We have not
223 made an attempt to evaluate the differences between assumptions nor to evaluate the quality of
224 the work in the individual LCAs. Our primary filter was to not use LCAs that examined small
225 experimental production systems or systems not making a significant contribution to total
226 production. Hall et al. (2011) examined by far the greatest number of aquaculture systems, but
227 the analysis of the inputs to aquaculture was not done at as fine a geographic scale as many other

228 LCAs. However, the Hall study does greatly increase the sample size and given the difference
229 between production technologies are over an order of magnitude, we felt that including the
230 studies would contribute to our analysis. In some cases, our sample size for any individual
231 production method is small and it could well turn out that a larger more representative sample of
232 that production method would change the results. However, we found many significant
233 differences in the pair-wise tests.

234 While many LCA studies were available, not all of the various production methods are
235 included, and the data available are heavily biased towards production in the developed world for
236 both livestock and capture fisheries. The aquaculture data are much more representative of
237 world production as Asia dominates aquaculture production and is well represented in the LCAs
238 available. As more LCAs are performed it will be possible to assess these more subtle
239 differences.

240 Our analysis only included impacts of the production method and delivery of the product
241 to the farm gate, the aquaculture facility, or the fishing port. There are few studies available of
242 the environmental impacts of processing, transport, retail and consumption.

243 **Comparing environmental impacts**

244 Notwithstanding the limitations outlined above, we have provided a first comparison of a
245 range of environmental impacts across the various elements of the animal source food system.
246 We find that the impacts can differ markedly and, depending upon which particular
247 environmental issue is considered most important, the relative ranking of different production
248 methods can be very different. Small pelagic fisheries and aquaculture for molluscs and salmon

score very well across a range of metrics. Small pelagic fisheries have low impact because they are caught in dense schools require relatively little fuel, aquaculture for molluscs because they are neither fed nor require pumping, and salmon aquaculture because it requires no pumping and feed conversion is quite efficient.

There has been a considerable amount of discussion of the environmental impacts of different food production systems, that has rarely included comparison to the alternatives. The environmental impacts of capture fisheries have received particular attention in high-profile journals (e.g. (Myers and Worm 2003; Pauly *et al.* 1998; Worm *et al.* 2006)) that in turn have often led to front page coverage on major newspapers and film documentaries. Many forms of aquaculture have been criticized (Naylor and Burke 2005; Naylor *et al.* 2009) for their negative environmental impact. Increasingly, active campaigns are underway to limit consumption of particular species and production methods in both domains. Yet there are virtually no systematic assessments of the consequences of restricting production from marine sources on the exploitation of terrestrial sources (or vice versa), despite growing evidence that consumers deprived of one will shift their demand to the other (Brashares *et al.* 2004). A particularly egregious instance of unbalanced/suboptimal regulation seems likely to be occurring between marine and terrestrial sources of animal source foods. For example, numerous NGOs are pushing to have major retailers stop selling fish caught by bottom trawls (<http://www.greenpeace.org/international/en/news/Blogs/makingwaves/7-reasons-bottom-trawling-is-bad-news/blog/56982/>) Our initial results suggest that restrictions on shellfish culture, or small pelagic fisheries that reduce sustainable production from those sectors would

likely have negative overall environmental consequences and any policies that push consumption towards high impact ASF would have negative consequences.

The time is well overdue for the scientific community to construct more comprehensive assessments of the environmental costs of using alternative resource stocks and production methods to meet the growing demand for animal source foods. Our classification of production methods was greatly limited by the data available from life cycle assessments. Far more LCAs are needed for a broader range of production methods in different countries. We need a more robust comparison of organic vs. conventional agriculture, as well as evaluating milk, egg, pork, chicken and beef production in different countries. Far more work is also needed on comparing the biodiversity impacts of different production methods, particularly the biodiversity costs of feed production for livestock. With such assessments in hand, it will become possible for responsible policy advocates to target their efforts not just on the cause of the moment, but on parts of the production system that are the most environmentally damaging.

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Figure 1. (a) Energy used (MJ), (b) GHG emissions (CO₂-eq), (c) eutrophication potential (PO₄-eq), and (d) acidification potential (SO₂-eq) from production of different products per 40 g protein. Aquaculture production systems are represented in red, livestock in yellow, and capture fisheries in blue. Thick line in box represents the median impact, the box bounds the interquartile range (IQR) and the whiskers extend to include all data within 1.5 times the IQR. Outlier data points are not shown. Numbers above each box represent number of studies included in each product category. Y-axis spacing is in log-modulus scale but labels are not.

Figure 2. Radar plots comparing environmental impacts (a) between different food production systems, (b) within aquaculture production systems, (c) within livestock production systems, and (d) within capture fisheries across all four impact categories examined (Energy demand (MJ), GHG emissions (CO₂-eq), eutrophication potential (PO₄-eq), and acidification potential (SO₂-eq)). Solid lines represent median impacts across broad food production system categories (e.g., aquaculture, livestock and capture fisheries), and dashed lines represent median impacts of product subcategories (e.g., salmon aquaculture, beef production).

Figure 3. Animal source foods come from a wide variety of production methods.