Title: The environmental cost of animal source foods

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Abstract

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

Introduction

Animal source food (ASF) production is one of the most dynamic elements of the world food system. Meat production has been increasing at 2.7% per year from 1995 to 2007 (FAO 2009), and aquaculture, which increased at 5.7% per year from 2004 to 2011, more than compensated for the slight (0.3% per year) decline in production from capture fisheries during the same period (FAO 2010; 2012). Both production and demand for ASFs is expected to continue to rise (Godfray *et al.* 2010), driven both by world population growth and rising incomes in many countries (Hazel and Wood 2008).

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

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

The environmental impact of food production can be measured in many dimensions, including the inputs (e.g., energy, freshwater, fertilizer, pesticides and antibiotics) as well as environmental consequences (e.g., greenhouse gas emissions, water use, water quality, biodiversity and habitat impacts) of food production systems. Many of these consequences were considered in the planning documents for the Millennium Ecosystem Assessment (World Resources Institute 2003) and some have been estimated for a wide range of production methods using Life Cycle Assessment (LCA), the established method for measuring multiple environmental impacts.

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

Methods

All life cycle assessments of livestock, aquaculture and capture fisheries that could be found using key word searches in the Web of Science and Google Scholar were tabulated. Search terms included are given in Table S1. We finished this search in April 2017 and found a total of 324 LCAs. We removed studies of production systems that were not representative of global production. This included small-scale production, “new innovative” production or trial production, or organic farming. Therefore we have only used “conventional” production in our analysis - long-standing, industrial, mass-production. We further filtered the LCA assessments by only using those studies estimating impacts up to the farm gate, aquaculture facility or vessel landing. If the assessment went beyond these stages, we used estimates of the sub-system up to the desired life-cycle stage if available. All livestock and aquaculture LCAs included the feed production. After filtering, 148 LCA assessments remained for further analysis. In the supplemental materials we do explore the wider range of studies in an analysis of how the production method affected impacts within a type of ASF. To standardize our analysis, all production data were standardized by converting to impacts per 40 g of protein.

While there is a broad range of impact categories calculated in LCAs, our analysis was restricted to the most common: energy intensity (MJ; 86 studies), greenhouse gas production (CO_2-eq released; 120 studies), eutrophication potential (PO_4-eq released; 96 studies), and acidification potential (SO_2-eq released; 94 studies). Table S2 shows all the LCA studies we used, the product, and the published LCA results per 40 g of protein produced for each of the impact categories described above. The conversion rates we used from total production through weight of edible product to weight of protein are shown in Table S3. In all cases we have calculated impacts for a standardized serving of 40 g of protein. This is slightly below the USDA recommended minimum daily requirement for a healthy adult (46g for females 52g for males) and corresponds to roughly 200 g of meat or fish. Protein is also available from plant source foods.

Results

Results of LCA review

We classified each product into one of 14 categories, broken into three major groups (aquaculture, capture fisheries, and livestock) and then separated by taxonomic group. Carp, 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.

Greenhouse gasses

Greenhouse gas (GHG) production per portion protein (Figure 1b) is lowest for mollusc aquaculture and small pelagic capture fisheries with salmonid aquaculture, chicken production, and large pelagic and whitefish capture fisheries also under 1.0 kg CO_2-eq per 40 g of protein. Catfish aquaculture and beef produce more than 20 times as much. Table S5 shows pairwise significance testing. Small pelagic and whitefish fisheries emit significantly less GHG than catfish, shrimp and tilapia aquaculture, beef production, and invertebrate and shrimp capture fisheries. Mollusc and salmon aquaculture emits significantly less GHG than catfish and shrimp culture, beef production and invertebrate fisheries; mollusc culture also emits less than tilapia culture and shrimp fisheries.

Eutrophication

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

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

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

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

Other Impacts

In addition to the environmental impacts summarized in the LCA synthesis, there are a range of other environmental impacts including water demand, pesticide use, antibiotic use, soil erosion and biodiversity impacts. While some life cycle assessments do include a wider range of impacts such as toxicity potential (herbicides and pesticides), water dependency and primary productivity demand, there is not a large enough sample size from LCAs across food production categories to provide any summary from a review. Nevertheless, there are major differences in the impacts depending on animal production system. In the following sections we summarize results from a range of sources. In most cases we have attempted to convert the estimates to the amount used per 40 g of protein. Table S8 shows the data we were able to assemble for water and antibiotic use.

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

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

Discussion

This is the first comparison of a range of environmental impacts across livestock, aquaculture and capture fisheries. There are striking differences regarding the environmental impacts of different animal source food production systems (Figure 3). The range of variability is quite high and any proposed policy needs to consider the specific species and production system. We showed the high variability in some aquaculture and capture fisheries is due to major differences in the production method. For aquaculture, the differences are due to (1) whether the fish are fed and (2) whether the system requires power for circulating water. For capture fisheries the impacts are primarily due to the amount of fuel used. Overall, mollusc culture and small pelagic and whitefish capture fisheries consistently stand out as lowest impact across categories.

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

Weaknesses in our analysis

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

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

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

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

Comparing environmental impacts

Notwithstanding the limitations outlined above, we have provided a first comparison of a range of environmental impacts across the various elements of the animal source food system. We find that the impacts can differ markedly and, depending upon which particular environmental issue is considered most important, the relative ranking of different production 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 (trawlshttp://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 (CO_2-eq), (c) eutrophication potential (PO_4-eq), and (d) acidification potential (SO_2-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.

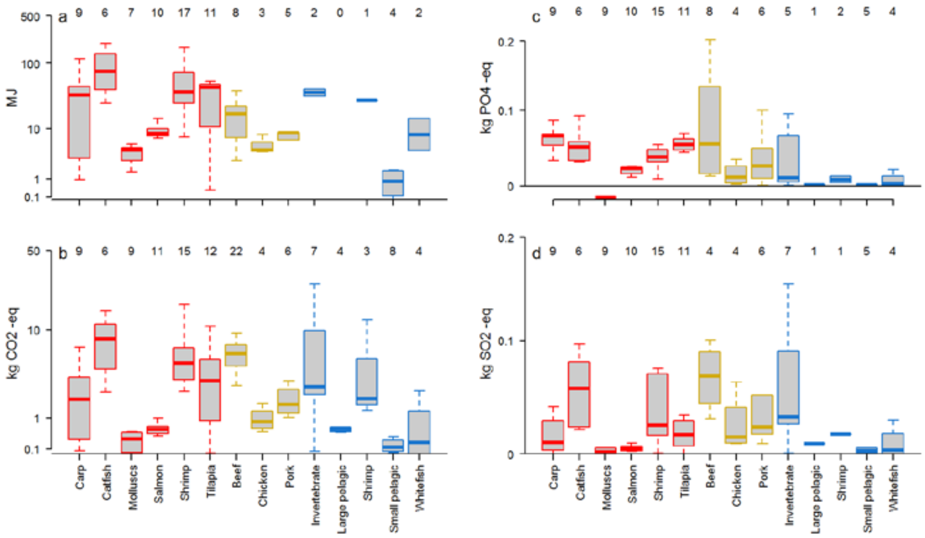

Figure 2. Radar plots comparing environmental impacts (a) between different food production systems, (b) within aquaculture production systems, (c) within livestock production systems, and (d) within capture fisheries across all four impact categories examined (Energy demand (MJ), GHG emissions (CO_2-eq), eutrophication potential (PO_4-eq), and acidification potential (SO_2-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).

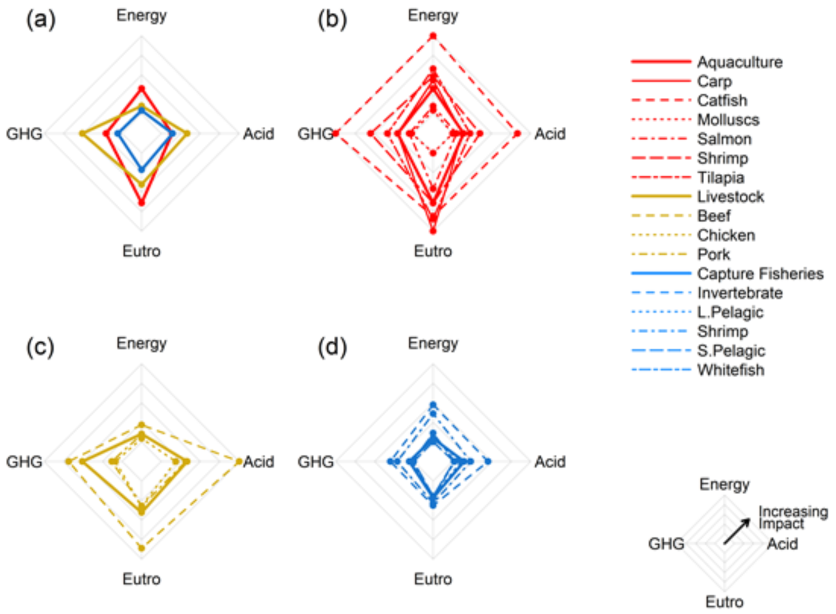

Figure 3. Animal source foods come from a wide variety of production methods.