

The environmental cost of animal source foods

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We reviewed 148 assessments of animal source food (ASF) production for livestock, aquaculture, and capture fisheries that measured four metrics of environmental impact (energy use, greenhouse-gas emissions, release of nutrients, and acidifying compounds) and standardized these per unit of protein production. We also examined 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, depending on the production method being used. The lowest impact production methods were small pelagic fisheries and mollusk aquaculture, whereas the highest impact production methods were beef production and catfish aquaculture. Many production methods have not been evaluated, limiting our analysis to the range of studies that have been published. Regulatory restrictions on ASF production methods, as well as consumer guidance, should consider the relative environmental impact of these systems, since, currently, there appears to be little relationship between regulatory restrictions and impact in most developed countries.

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Animal source food (ASF) production is one of the most dynamic elements of the world food system. Livestock production has been increasing at an average of 2.46% per year from 1993 to 2013 (data obtained from FAOSTAT; www.fao.org/faostat/en/#data/CL) and aquaculture, which increased at an average of 5.79% per year from 2009 to 2014 (FAO 2016), more than compensated for the slight (0.3% per year) decline in production from capture fisheries over the same period (FAO 2010, 2012). Both production and demand for ASFs is expected to continue to rise (Godfray *et al.* 2010), driven by world population growth and rising incomes in many countries (Hazel and Wood 2008).

The environmental consequences of ASF production have received considerable scientific and public attention (Tilman *et al.* 2001; Steinfeld *et al.* 2006; Smith *et al.* 2010; Herrero *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 influenced (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 must have greater access to more standardized information across a range of metrics about the relative environmental costs of alternative production methods when attempting to meet rising demand.

There is a large and growing source of literature documenting the environmental impacts of different ASFs (eg Steinfeld *et al.* 2006; Pelletier *et al.* 2011). With the exception of energy use, however, there are no systematic comparisons of environmental costs across the different types of ASFs. Global and national agricultural policies, trade agreements, and environmental regulations guide decisions on expanding food production, and the ability to make systematic comparisons between different ASFs would allow these decisions to be better informed.

The environmental impacts of food production can be considered from many perspectives, including the inputs (eg energy, fresh water, fertilizer, pesticides, antibiotics) and the consequences (eg greenhouse-gas [GHG] emissions, water use, water quality, biodiversity loss, habitat destruction) of food production methods. Many of these consequences were considered in the planning documents for the Millennium Ecosystem Assessment (WRI 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.

We identified 148 individual LCAs for ASFs that evaluated major production methods in an effort to collate and systematize our understanding of the environmental impacts across the range of animal production methods. Of these studies, 48 were for livestock (meat), 29 were for capture fisheries, and 71 were for aquaculture. We also reviewed the literature for data

In a nutshell:

- All food production has environmental costs, which differ greatly between different types of animal protein
- Most of the environmental costs derive from fertilizer used in feed production, fuel for fishing boats, and circulation of water in aquaculture
- The lowest impact forms of animal protein come from species that feed naturally in the ocean and that can be harvested with low fuel requirements
- Public policy should explicitly consider the relative environmental costs of food production when regulations are being developed

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about other impacts not widely assessed by LCA approaches, including water use, pesticides, antibiotics, and soil erosion.

■ Methods

All LCAs of livestock, aquaculture, and capture fisheries that could be found using keyword searches in Web of Science and Google Scholar were tabulated (search terms used are listed in WebTable 1). We completed this search in April 2017 and identified a total of 324 LCAs. We removed studies of specialized production methods that are not representative of global production, including small-scale production, “new innovative” production or trial production methods, and organic farming. As such, only studies that focused on “conventional” production (ie long-standing, industrial, mass-production) were included in our analysis. We further filtered the LCAs by including only those studies in which impacts up to the farm gate, aquaculture facility, or vessel landing site were assessed. If the assessment went beyond these stages, we used estimates of the subsystem up to the desired life-cycle stage, if available. All livestock and aquaculture LCAs included feed production. After filtering, 148 LCAs remained for further analysis. More detailed explorations of how the production methods affected impacts within a type of ASF are included in WebPanel 1 and WebFigures 2–9.

Although our search captured a broad range of impact categories calculated in the form of LCAs, our analysis was restricted to the most common: energy intensity (megajoules [MJ]; 86 studies), GHG production (CO₂-equivalent [-eq] released; 120 studies), eutrophication potential (PO₄-eq released; 96 studies), and acidification potential (SO₂-eq released; 94 studies). WebTable 2 lists each LCA study included in the analysis, the product being analyzed, and the published LCA results per 40 g of protein produced for each of the impact categories. The conversion rates we used, from total production through weight of edible product to weight of protein, are shown in WebTable 3. In all cases we calculated impacts for a standardized serving of 40 g of protein. This is slightly below the US Department of Agriculture’s recommended minimum daily requirement for a healthy adult (46 g for females, 52 g for males) and corresponds to roughly 200 g of meat or fish (plant source foods are also a source of protein).

■ Results

Results of LCA review

We classified each product into one of 14 categories, which were combined into three major groups (aquaculture, capture fisheries, and livestock) and then separated by taxonomic group. Carp, catfish, shrimp, salmon, mollusks and tilapia are all high-volume aquaculture products and were given their own category. Capture fisheries were divided according to whether they harvested invertebrates, large pelagic fish, small

pelagic fish, shrimp, or whitefish. Livestock was divided into pork, beef, and chicken. We found a small number of studies for milk, eggs, and lamb but these were excluded due to insufficient 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, GHG production, eutrophication potential, and acidification potential. An overall comparison of aquaculture, livestock, and capture fisheries across all impact categories is shown in Figure 2. In the LCA studies, the median values across all impact categories of capture fisheries were lower than those for livestock and aquaculture; Figure 2b–d shows the range of values within aquaculture, livestock, and capture fisheries.

Energy used

The amount of energy used in the production of 40-g protein portions (Figure 1a) varied greatly among food production methods, ranging from a low median value of 0.94 MJ per portion of protein for small pelagic fisheries to a high median value of 75.6 MJ per protein portion for catfish aquaculture. Overall, livestock production required lower inputs of energy than aquaculture or capture fisheries, with the exception of mollusk aquaculture and small pelagic fisheries (results of pairwise significance tests are shown in WebTable 4). Small pelagic fisheries required less energy than catfish, shrimp, and tilapia aquaculture, as well as invertebrate fisheries; pork production required less energy than catfish, shrimp, and tilapia aquaculture; beef production required less energy than shrimp aquaculture; mollusk aquaculture required less energy than catfish, shrimp, and tilapia aquaculture; and salmon aquaculture required less energy than shrimp aquaculture.

Greenhouse gases

GHG production per portion protein (Figure 1b) was lowest for mollusk aquaculture and small pelagic fisheries, with salmon aquaculture, chicken production, and large pelagic and whitefish fisheries also emitting less than 1.0 kg CO₂-eq per 40 g of protein. GHG emissions generated by catfish aquaculture and beef production were more than 20 times as high (results of pairwise significance testing are shown in WebTable 5). GHG emissions generated by small pelagic and whitefish fisheries were significantly lower than those generated by catfish, shrimp, and tilapia aquaculture, beef production, and invertebrate and shrimp fisheries; emissions generated by mollusk and salmon aquaculture were significantly lower than those generated by catfish and shrimp aquaculture, beef production, and invertebrate fisheries; and emissions generated by mollusk aquaculture were lower than tilapia aquaculture and shrimp fisheries.

Eutrophication

Eutrophication potential (Figure 1c) differed greatly among production methods. We found that although most production

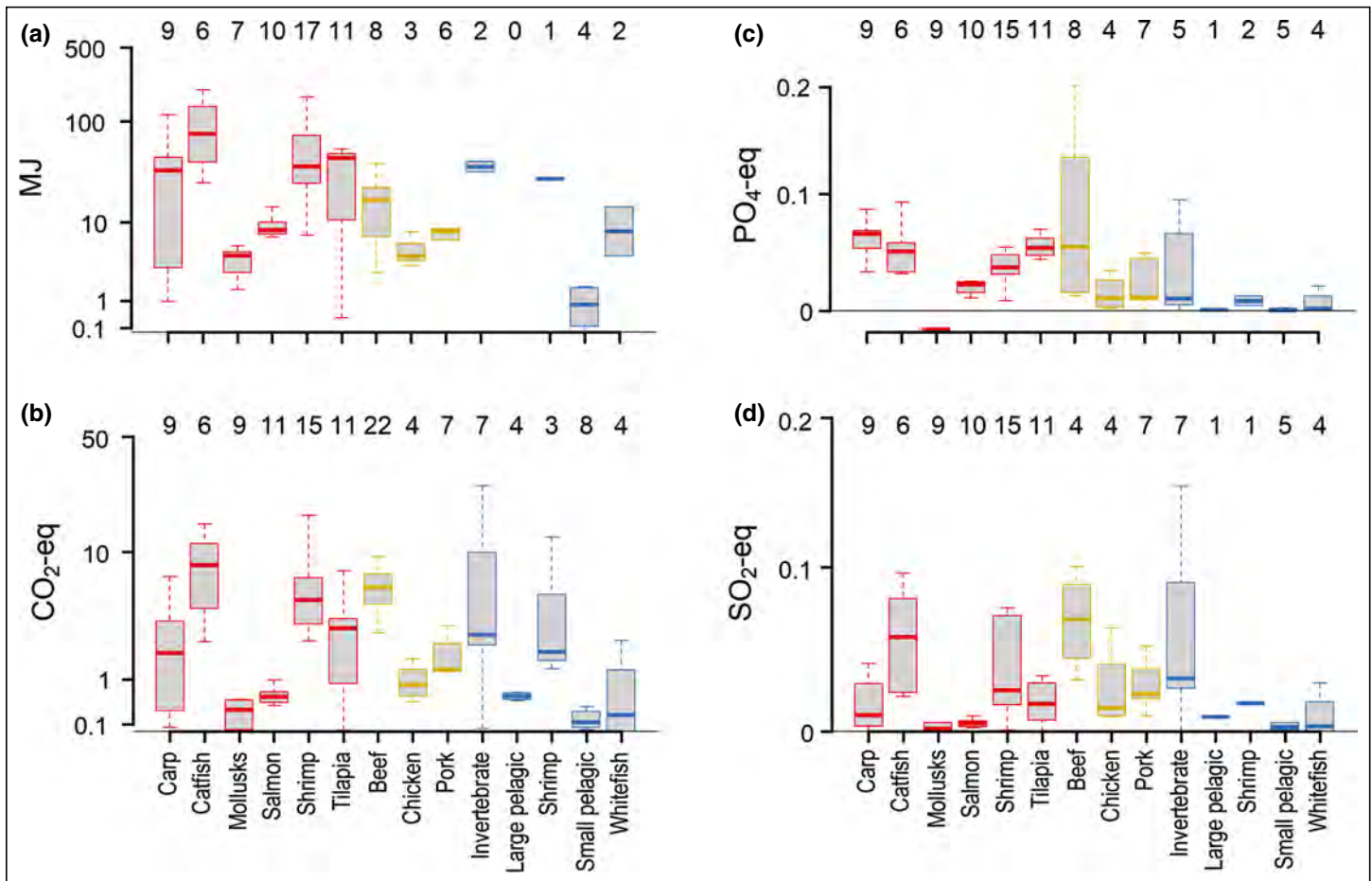


Figure 1. (a) Energy used (MJ), (b) GHG emissions ($\text{CO}_2\text{-eq}$), (c) eutrophication potential ($\text{PO}_4\text{-eq}$), and (d) acidification potential ($\text{SO}_2\text{-eq}$) associated with different production methods per 40-g protein produced. Aquaculture production methods are represented in red, livestock in yellow, and capture fisheries in blue. The thick horizontal line in the 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 the number of studies included in each product category. Y-axis spacing is in log-modulus scale, but the labels are not.

methods release nutrients, mollusk aquaculture actually absorbs nutrients. Because capture fisheries do not rely on fertilizer, they consistently scored lower than both aquaculture and livestock production. Beef production exhibited the broadest range of eutrophication impacts, and had the highest median impact among livestock. Pairwise significant tests (WebTable 6) indicated that nutrient impacts of mollusk aquaculture are significantly lower (negative) than those of beef production, invertebrate fisheries, and all other aquaculture methods except salmon. Chicken production, pork production, small pelagic fisheries, and whitefish fisheries all released fewer nutrients than tilapia aquaculture, and small pelagic fisheries had a smaller impact than shrimp aquaculture.

Acidification

Acidification potential (Figure 1d) was lowest for mollusk aquaculture, with small pelagic and whitefish fisheries and salmon aquaculture not far behind. Although beef production had the highest median acidification impact, due primarily to the high level of variability among beef studies, no

statistically significant differences were found between beef and other products. The dominant source of acidification potential in aquaculture and capture fisheries was the acidifying compounds released by fuel use, but for livestock it was NH_3 and NO_x emissions, derived largely from the production of manure. Pairwise significance testing revealed that shrimp aquaculture had greater acidification potential than both mollusk and salmon aquaculture, as well as small pelagic and whitefish fisheries (WebTable 7).

How the production system influences impacts

The primary GHG and acidification impacts of capture fisheries depended on fuel use, with correlations exceeding 0.95 (WebFigure 1). Tyedmers (2004) provided one of the first overviews of fisheries energy use, with Parker and Tyedmers (2014) considerably expanding on the available data. Fuel use primarily reflects the extent to which fish can be captured efficiently. Consistent with these studies, we found that small pelagic fishes, which form dense schools, can be captured with the lowest impact regardless of whether they

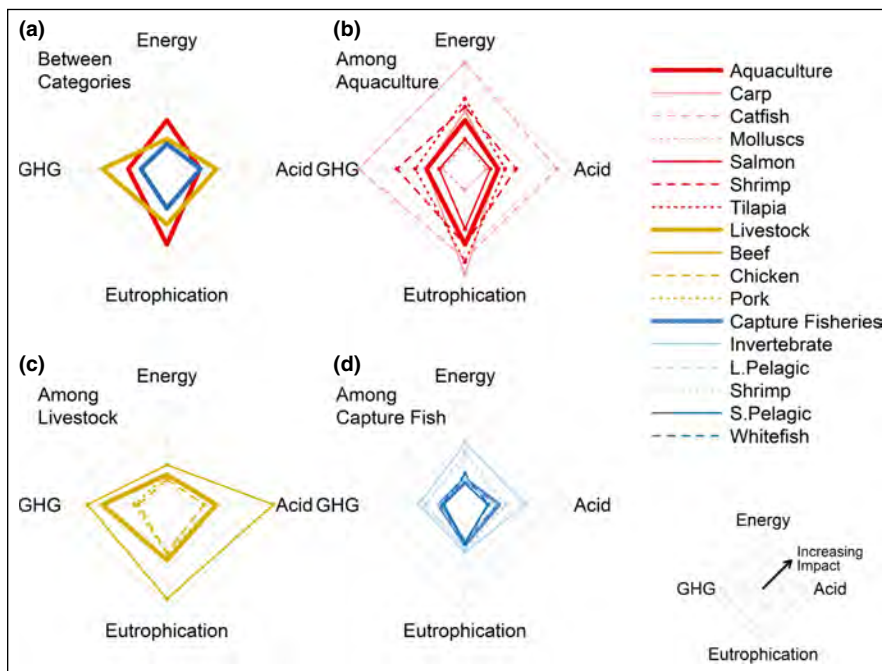


Figure 2. Radar plots comparing environmental impacts (a) between different food production methods, (b) within aquaculture production methods, (c) within livestock production methods, and (d) within capture fisheries across all four impact categories examined (energy demand [MJ], GHG emissions [CO₂-eq],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

were caught by purse seining or midwater trawl; that demersal (bottom-feeding) fish species are intermediate in impact; and that invertebrate species, whether captured by trawl or by pot, had the highest impact (WebFigure 3). The most surprising result was the high fuel use (and thus other impacts) of pot fisheries for invertebrates like lobster, which had been previously noted by Parker and Tyedmers (2014). Trawling involves dragging a net through the water, an activity that involves high energy demands, whereas dropping pots is far less energy intensive. However, as Tyedmers (2004) noted, the commercial value of many marine invertebrates is so high that fishermen will expend a great deal of fuel to catch species such as 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 (2010) 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; the latter two weigh heavily against beef production and at least partly account for the general pattern of beef production having the highest impacts (WebFigure 4). Feed efficiency was lowest for beef production (followed by pork) and was highest for chicken, a pattern consistent with the overall impact of each production system. We found that grass-fed beef generated higher GHG emissions (WebFigure 4).

The primary impacts of aquaculture production have been linked to the feed used (or lack of it, in the case of unfed [extractor] species) and the energy used to recirculate water through pumping (Hall *et al.* 2011; Pelletier *et al.* 2011); these factors were also commonly identified in the LCAs we reviewed. Unfed species had consistently lower impacts across all measures, and systems requiring water pumping had the highest impacts (WebFigures 5, 6, 8, and 9).

Other impacts

In addition to the environmental impacts summarized in the LCA synthesis, production methods may have a wide range of other impacts, including high water demand, the use of pesticides and antibiotics, soil erosion, and effects on biodiversity. Whereas some LCAs include a wider range of impacts, such as toxicity potential (herbicides and pesticides), water dependency, and primary productivity consumed, the sample size from LCAs across food production categories was insufficient to provide a summary. Nevertheless, there are major differences in the impacts among animal production methods. 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. The data we were able to locate for water and antibiotic use are shown in WebTable 8.

Use of fresh water differed greatly across production methods. Irrigated crops as inputs to livestock production and aquaculture were the most intensive uses, whereas livestock raised by grazing on non-irrigated pastures required far less fresh water, and capture fisheries and mollusk aquaculture required almost no fresh water. Freshwater aquaculture systems are more difficult to evaluate, as they have rarely been studied (Gephart *et al.* 2017); although cultured fish are certainly present in these systems, there may be little consumptive use.

The degree of antibiotic use is particularly interesting because of the differences within salmon aquaculture (eg Norwegian facilities use almost no antibiotics, whereas Chilean facilities use large amounts) as well as between livestock production systems (WebTable 8). No antibiotics are used in capture fisheries and mollusk aquaculture.

Discussion

This is the first comparison of a range of environmental impacts across livestock, aquaculture, and capture fisheries. There are striking differences in terms of the environmental impacts of different ASF production methods (Figure 3).

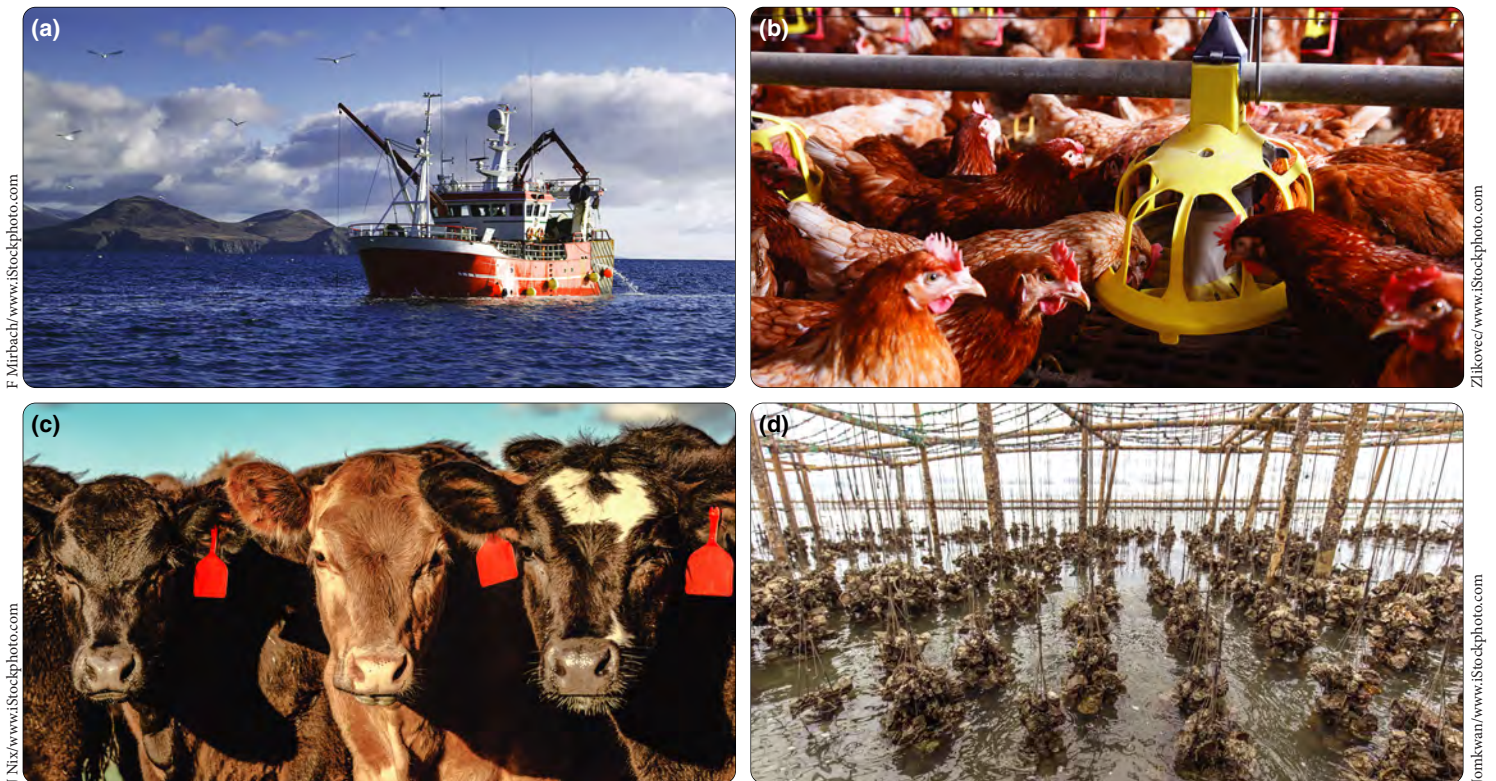


Figure 3. Animal source foods are generated from a wide variety of production methods, including capture fisheries (a), livestock (b and c), and oyster aquaculture (d).

Because the range of variability is quite high, any proposed policy must consider the specific species and production system. We found that the high variability in some aquaculture and capture fisheries can be attributed to major differences in the production method. For aquaculture, the differences are due to whether the fish are fed and whether the production requires energy for water circulation; for capture fisheries, the impacts are primarily associated with the amount of fuel consumed. Overall, mollusk aquaculture and small pelagic and whitefish fisheries consistently stood out as having the lowest impacts across all of the categories included in our analysis.

LCAs are useful in determining the impacts of ASFs globally, but it is also important to consider local effects. Although GHG emissions may have global impacts, eutrophication and water use impacts can be more detrimental at the local level – for example, one ton of eutrophication potential in the form of nitrogen waste will have a more pronounced impact on a freshwater lake or stream than on the ocean. Likewise, freshwater systems with different underlying geology will have differing capacities to buffer acidification impacts, and the environmental impact of water use may differ considerably between areas where fresh water is abundant and locations faced with water shortages.

Weaknesses in our analysis

We relied on a wide range of published LCAs (peer-reviewed literature and reports) that often used different methods

and made different assumptions. We did not attempt to evaluate the differences between assumptions nor to judge the quality of the work in the individual LCAs. Our primary filter was to discard LCAs that examined small experimental production methods, or systems that do not contribute substantially to total production. Hall *et al.* (2011), for example, included many more aquaculture systems in their review, but their analysis of the inputs to aquaculture was performed at a coarser geographic scale than many other LCAs. However, their review greatly increased the available sample size, and given that the differences between production methods exceeded an order of magnitude, we felt that including the studies of Hall *et al.* (2011) would contribute to our analysis. In some cases, the sample sizes for the individual production methods included in our analysis were small, and it is possible that a larger and more representative sample of a given production method would alter the results. Nevertheless, we detected many significant differences using pairwise testing.

Although many LCA studies were available, not all of the various production methods were included in our analysis; moreover, data are often heavily biased, for example toward livestock and capture fisheries production in the developed world. Aquaculture data, in contrast, are much more representative of production worldwide, as Asia dominates global aquaculture production and is well represented in the available LCAs. Assessment of more subtle differences, such as geographic location, will be possible as more LCAs are performed.

Our analysis only included impacts of the production system and delivery of the product to the farm gate, the aquaculture facility, or the fishing port, as there are currently few studies that focus on the environmental impacts of processing, transport, retail, and consumption.

Comparing environmental impacts

Despite the limitations outlined above, we have provided the first comparison of a range of environmental impacts across the various elements of the ASF 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 vary greatly. Small pelagic fisheries and mollusk and salmon aquaculture score very well across a range of metrics for several reasons: small pelagic fisheries have a low impact because the fish are caught in dense schools and require relatively little fuel consumption; mollusk aquaculture because cultured mollusks are not fed nor do their pens require water pumping; and salmon aquaculture because salmon pens require no water pumping and feed conversion is quite efficient.

There has been much discussion about the environmental impacts of different food production methods, but rarely have these included comparisons to alternatives. The environmental impacts of capture fisheries, in particular, have received a great deal of attention in high-profile scientific journals (eg Pauly *et al.* 1998; Myers and Worm 2003; Worm *et al.* 2006), which has often led to wider exposure through the popular media. Many forms of aquaculture have been criticized (Naylor and Burke 2005; Naylor *et al.* 2009) for their negative environmental impacts, and active campaigns for limiting consumption of particular species and production methods are increasingly common for both capture fisheries and aquaculture. 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 food source will shift their demand to the other (as seen in Brashares *et al.* 2004). A particularly egregious instance of unbalanced/suboptimal regulation seems to be occurring between marine and terrestrial sources of ASFs; for example, numerous non-governmental organizations are urging major retailers to cease selling fish caught by bottom trawling (Safina 2016). Our initial results suggest that restrictions that reduce sustainable production from shellfish aquaculture or small pelagic fisheries would likely have negative overall environmental consequences, and that policies that steer consumption toward high-impact ASFs would have negative environmental consequences.

The scientific community needs to construct more comprehensive assessments of the environmental costs of using alternative resource stocks and production methods to meet the growing global demand for ASFs. Our classification of production methods was greatly restricted by the limited data availa-

ble from LCAs, demonstrating the need for a far greater number of LCAs that encompass a broad range of production methods in different countries. More robust comparisons of organic versus conventional agriculture are also needed, as are comparative evaluations of milk, egg, pork, chicken, and beef production in different countries. More work should also be done on comparing the impacts of different production methods on biodiversity, particularly for systems associated with livestock feed production. With such assessments available, it will become possible for responsible policy advocates to target their efforts not just on the cause of the moment, but on the elements of food production methods that are the most environmentally damaging.

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■ Supporting Information

Additional, web-only material may be found in the online version of this article at <http://onlinelibrary.wiley.com/doi/10.1002/fee.1822/supinfo>



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A tale of four swallowtails

This family portrait gives a rare side-by-side glimpse of four northeastern North American swallowtail caterpillars. Ranged from left to right are the Eastern tiger swallowtail (*Papilio glaucus*), pipevine swallowtail (*Battus philenor*), Eastern black swallowtail (*Papilio polyxenes*), and the spicebush swallowtail (*Papilio troilus*). Despite being evolutionary relatives with some common features, each has developed its own strategy for survival.

The early-stage larvae of the Eastern tiger, Eastern black, and spicebush swallowtails look like bird droppings to the untrained eye. White and brown or black-banded, these young caterpillars are often able to escape the attention of hungry birds. However, as they mature, both the Eastern tiger and spicebush swallowtail caterpillars transform to mimic green snakes with fake eyespots to scare off predators. To complete this disguise, they also possess a special organ called an osmeterium (found in all swallowtails) that, when threatened, shoots out like a darting snake's tongue. Thrashing around when under duress, these caterpillars can also spray a pungent chemical mix on their attackers. In contrast, their cousin – the Eastern black swallowtail – adopts an alternative strategy: a bold color scheme suggests to predators that it could be poisonous, but it's not. Indeed, this caterpillar is thought to imitate its iconic neighbor: the larva of the poisonous monarch (*Danaus plexippus*). The Eastern black's wardrobe of yellow, black, and green also helps it blend in among plants.

Unlike the others, the pipevine swallowtail caterpillar is truly aposematic. It doesn't need to rely on mimicry because it feeds on toxic pipevines (*Aristolochia* spp), making it distasteful to birds – a trait it carries over into its adult lifestage as a butterfly.

After metamorphosis, the nonpoisonous adult Eastern tiger, Eastern black, and spicebush swallowtails play another trick on their potential foes. They participate in a Batesian mimicry complex in



which they can all mimic the poisonous pipevine swallowtail butterfly to avoid predation and hopefully start the cycle again.

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