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Review article

Environmental health impacts of feeding crops to farmed fish

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A B S T R A C T

Half of the seafood consumed globally now comes from aquaculture, or farmed seafood. Aquaculture therefore plays an increasingly important role in the global food system, the environment, and human health. Traditionally, aquaculture feed has contained high levels of wild fish, which is unsustainable for ocean ecosystems as demand grows. The aquaculture industry is shifting to crop-based feed ingredients, such as soy, to replace wild fish as a feed source and allow for continued industry growth. This shift fundamentally links seafood production to terrestrial agriculture, and multidisciplinary research is needed to understand the ecological and environmental health implications. We provide basic estimates of the agricultural resource use associated with producing the top five crops used in commercial aquaculture feed. Aquaculture's environmental footprint may now include nutrient and pesticide runoff from industrial crop production, and depending on where and how feed crops are produced, could be indirectly linked to associated negative health outcomes. We summarize key environmental health research on health effects associated with exposure to air, water, and soil contaminated by industrial crop production. Our review also finds that changes in the nutritional content of farmed seafood products due to altered feed composition could impact human nutrition. Based on our literature reviews and estimates of resource use, we present a conceptual framework describing the potential links between increasing use of crop-based ingredients in aquaculture and human health. Additional data and geographic sourcing information for crop-based ingredients are needed to fully assess the environmental health implications of this trend. This is especially critical in the context of a food system that is using both aquatic and terrestrial resources at unsustainable rates.

Contents

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1. Introduction

The global food system faces significant stressors in population growth, limited land and water resources, rising demand for animal products, overreliance on fossil fuels, and a changing climate (Foley et al., 2011, Neff et al., 2011). In addition, seafood production has changed substantially over the last few decades. Half of seafood consumed globally currently comes from aquaculture, or farmed seafood, which is increasing at a faster rate than any other animal production sector (UNFAO, 2014a). In the past, seafood production and consumption primarily raised concerns related to overfishing, habitat destruction, and food safety (Botsford et al., 1997, Rasmussen et al., 2005, Feldhusen, 2000). Now, we also need to consider the implications and externalities of farming half of our seafood.

Aquaculture is a diverse sector. Different species of aquatic animals have different nutritional needs and are raised using widely divergent methods (e.g., raised in ponds, rivers, open water net-pens, or land-based tanks). About two-thirds of farmed aquatic animal production requires feed (UNFAO, 2014a). Some species, like tilapia or grass carp, are herbivorous and can consume 100% vegetarian feed made from crops and other food and agricultural byproducts. Historically, many herbivorous fish were raised in extensive systems, where no feed was administered. However, farmers are intensifying production and using farm-made or commercial feeds, some of which contain fish or animal proteins and fats. Other species, such as Atlantic salmon, rainbow trout, and cod, are carnivorous and have always been fed fish or animal protein and/or lipids as part of their diet. Fishmeal (FM) is a common source of protein in aquaculture feeds, although some farms are replacing FM with animal byproducts such as poultry byproduct meal or vegetable protein such as soybean meal. Fish oil (FO) is commonly used as a fat source, but rendered animal fats and vegetable oils are increasingly used in place of (or in combination with) FO.

Aquaculture feed is made by grinding or mixing plant and animal-based ingredients together. In industrialized settings, the mixture of ingredients is passed through an extruder to create bite-sized feed pellets. In commercial feedmills, these extruded pellets resemble pet food kibble and are dried and stored in containers to increase shelf-life. Commercial feeds are considered a "complete feed" that contains necessary amounts of protein, fats, carbohydrates, vitamins, and trace minerals. Aquaculture animals raised on commercial or farm-made feeds reach harvest weight more quickly than animals raised on forage (i.e., in extensive aquaculture where no feed is administered) (Hasan et al., 2007). Therefore, farmers may be motivated to switch from extensive systems to semi or fully intensive systems due to productivity gains. Farmers are unlikely to shift from extensive systems to intensive systems at once; they often follow iterative steps to increase efficiency such as increased fertilization, aeration, pumping, the use of farm-made feed, and finally purchasing commercial feed. The global trend toward increased production and efficiency has dramatically expanded the use of commercial aquaculture feed.

To calculate total commercial aquaculture feed use globally, Tacon and Metian (2015) multiplied aquaculture production for each species by the percent of each species on commercial feed and the efficiency that fish convert feed into mass (i.e., feed conversion ratio). We have reproduced these data in Fig. 1 for the top five species groups to show the different rates of change for each variable within different sectors. More granular data are difficult to obtain and are needed to explain trends within sectors, such as transitioning from extensive methods to semi-intensive and intensive methods, transitions from farm-made feed to commercial feed, and increasing terrestrial feed use. For each type of aquaculture, it would be useful to know if an increase in terrestrial ingredients was due to expansion in overall production and/or substitution of ingredients, such as replacing FM/FO with terrestrial proteins and oils. The global use of non-commercial aquaculture feeds (i.e., farm-made and direct feeding of low-value fish to farmed fish) is estimated to be between 18 and 36 million metric tons (MMT); importantly, the data used in our review focus on commercial aquaculture feeds because the types and amounts of feed

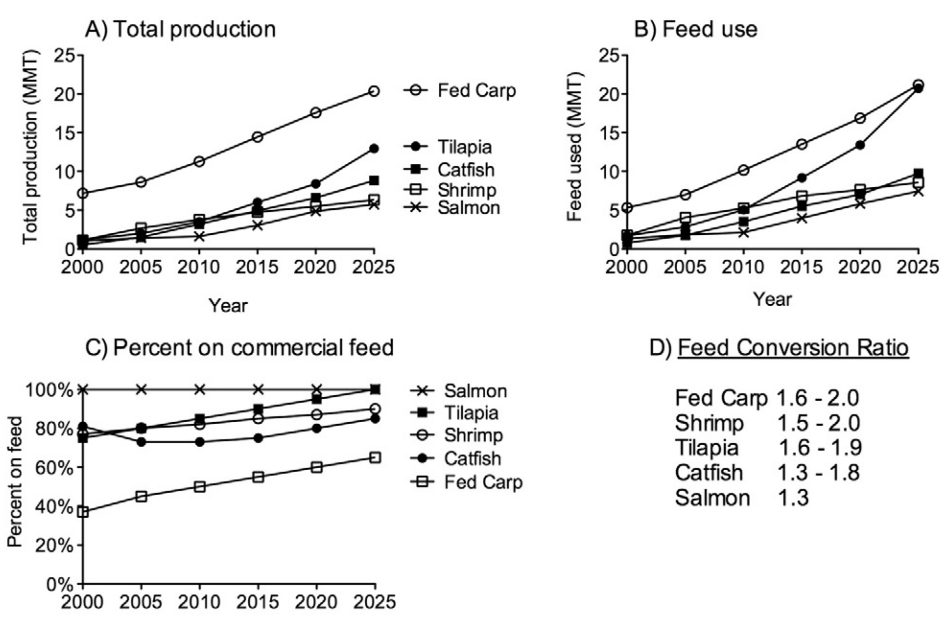

Fig. 1. Estimated A) production, B) commercial feed use, and C) percent commercial feed use 2000–2025 for the top-5 species groups (based on 2015 production data). D) Estimated feed conversion ratios for selected species. Data from Tacon and Metian, 2015.

ingredients used in other aquaculture feeds have not been quantified (Tacon and Metian, 2015).

To meet new demand as more farmed aquatic animals are raised using aquaculture feed, global production of commercial aquaculture feed increased 106% from 2000 to 2008, and is projected to increase 124% between 2008 and 2020 (Tacon and Metian, 2015, Tacon et al., 2011). Important components of aquaculture feed are FM and FO, which are primarily made using wild-caught forage fish (Shepherd and Jackson, 2013). Aquaculture is the largest consumer of FM and FO, which are mostly fed to a few key species: marine shrimp, marine fish, and salmon (Tacon et al., 2011). Using forage fish and low-value “trash” fish to feed a growing aquaculture industry raises concern of overfishing, disruption to aquatic food webs, food insecurity, and a potential net loss of seafood available for human consumption (Cao et al., 2015, Naylor et al., 2009). The absolute amount of FM and FO used in commercial aquaculture feed has remained relatively flat, a trend that is likely to persist, and therefore, result in sustained demand for FM and FO (Fig. 2) (Tacon et al., 2011). The aquaculture industry has made a substantial effort to lower proportions of FM and FO in formulated feeds (Tacon et al., 2011, Naylor et al., 2009). Continued progress is needed, however, in China, the global leader in aquaculture production (Cao et al., 2015). Alternative ingredients, such as those derived from commodity agricultural crops, are increasingly used to meet most of the new demand for aquaculture feed (Tacon et al., 2011). Terrestrial crops are the focus of this paper because they have been used in aquaculture feed more than other types of alternative ingredients (Tacon et al., 2011).

Some potential consequences of using crop-based feeds for aquaculture have recently been explored. Belton et al. (2010) criticized a sustainability certification standard for farmed tilapia in part because the soy used in the feed was associated with negative consequences of expanding soy production in general (Belton et al., 2010). In addition, some life cycle analyses have compared environmental implications of feed formulations with high and low proportions of fish-based ingredients (Boissy et al., 2011), but this research has not assessed the cumulative global effects of shifting to crop-based aquaculture feed. Troell et al. (2014) examined whether aquaculture adds to the resilience of the global food system, with feed inputs and resilience through diversification being primary considerations (Troell et al., 2014). The authors noted that aquaculture will increasingly compete with terrestrial animal agriculture for feed from crops and other sources (Troell et al., 2014). Most recently, Pahlow et al. (2015) modeled the water footprint of various feed formulations to compare species and estimate the global freshwater footprint of commercial aquaculture feed. The geographic source regions for the feed crops are unknown, so the authors used global averages of water use. The authors estimated that between 31 and 35 km^3 of water were used to grow crops for commercial aquaculture feed in 2008, and showed that the water footprint associated with aquaculture feed increases with the use of terrestrial crop-based ingredients (Pahlow et al., 2015). This research highlights seafood's changing environmental footprint, or the resource use and waste generation associated with a product or industry. Environmental impacts can also affect human health, and environmental health is a discipline within public health that focuses on human exposures to physical, chemical, and biological factors that directly or indirectly affect human health. We build on previous research by including potential environmental and human health effects of increasing use of crops for aquaculture feed.—

There are potential human nutrition implications of using crop-based aquaculture feeds. The use of vegetable oils (e.g., soy, corn, canola, palm, sunflower oils) in place of FO may interfere with nutritional properties of farmed seafood by reducing the levels of certain omega-3 fatty acids (Turchini et al., 2009). Seafood is the primary source of two omega-3 long-chain polyunsaturated fatty acids (PUFA) in the human diet. PUFAs are fats with multiple C—C double bonds, and eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are two types of PUFAs. They are sometimes called the “marine omega-3 s” because of their origin in the marine environment. Moderate intake of EPA/DHA in seafood has been linked to positive health outcomes including improved cardiovascular health and neurodevelopment (Lee et al., 2009, Larqué et al., 2012). In the wild, EPA and DHA are transferred through the aquatic food chain, beginning with phytoplankton as the primary producer (Salem and Eggersdorfer, 2015). People can also consume FO and algae supplements containing EPA/DHA, and there is a growing trend to fortify food with EPA/DHA (Ganesan et al., 2014). Humans and fish can bioconvert other omega-3 PUFAs found in plants to EPA and DHA (Brenna et al., 2009, Lazzarotto et al., 2015), but conversion rates are low and typical Western diets have low levels of most omega-3 PUFAs (Simopoulos, 2002). The World Health Organization (WHO) recommends consuming moderate levels of seafood, in large part for EPA and DHA intake (World Health Organization, 2010), as do the U.S. Departments of Agriculture (USDA) and Health and Human Services (HHS). The USDA and HHS recommend replacing some meat with seafood to increase intake of EPA and DHA, and specifically replacing some red meat with seafood to decrease intake of saturated fat (USDA and HHS, 2010, 2016). None of these bodies differentiate between farmed and wild caught fish in their dietary recommendations, and it is important to understand how levels of EPA/DHA in farmed seafood are impacted when vegetable oils are used in place of or in combination with FO.

Here, we examine some of the potential environmental health and resource use implications arising from the increasing demand and changing composition of commercial aquaculture feed. We consider uncertainty and knowledge gaps surrounding increasing terrestrial resource use, environmental degradation, and exposure to deleterious compounds used in industrial crop production, as well as possible

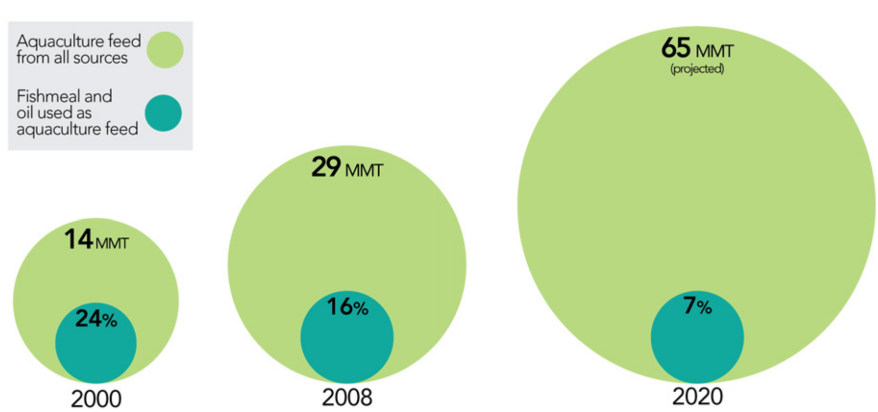

Fig. 2. Growth of commercial aquaculture feed use. As the production of commercial aquaculture feed increases, shown here as actual and projected production from 2000 to 2020, overall use of FM and FO remains the same but the proportion of feed made from fish has and will continue to decline (Tacon and Metian, 2015, Tacon et al., 2011).

implications for human nutrition. We use the term *industrial crop production* to refer to a form of food production characterized by large, specialized operations that typically rely on chemical fertilizer and pesticide inputs to support intensive production of one or two crops.

2. Material and methods

We identified resources for analysis using a combination of methods to examine specific aspects of increasing use of crop-based feed ingredients in aquaculture production. First, we analyzed crop production data to develop estimates of global resources used to produce the main aquaculture feed crops. We conducted two literature reviews to explore 1) the environmental health impacts linked to industrial crop production and 2) potential changes in nutritional content of farmed seafood. Finally, we developed a conceptual framework to highlight knowledge gaps and visually communicate our results on the potential direct and indirect relationships between trends in feed ingredients and resource use, environmental health, and human nutrition.

2.1. Resource use dimensions of crop production for aquaculture feed

Relatively little is known about the implications of using crop-based aquaculture feeds for resource use in terrestrial agriculture (but see Pahlow et al., 2015, described above). To quantify key aspects of and the potential uncertainty surrounding the land and freshwater resources consumed in commercial aquaculture feed production, we extracted estimates of primary-equivalent crop quantities used in global aquaculture feed from Troell et al. (2014) with GraphGrabber (Quintessa, Oxfordshire, UK). To conduct our analyses, we used these quantities, United Nations FAOSTAT production and trade, and global land use and management values from West et al. (2014) combined with different assumptions about the composition and geographic sourcing of aquaculture feeds (described below). Our analyses are centered on the year 2008 for consistency with the latest estimates of commercial aquaculture feed use (Tacon et al., 2011).

The top five crops used in commercial aquaculture feed on a production basis by weight are: rapeseed/canola (~26% of plant-equivalent aquaculture feed crop production), soybean (~26%), maize (~13%), nuts (~12%), and wheat (~9%) (Troell et al., 2014). To illustrate the range in potential global resource consumption and excess fertilizer nutrient use associated with producing these top five crops, we multiplied estimated primary-equivalent crop demand for aquaculture feed by nationally-weighted data for resource use per kilogram of each crop from West et al. (2014). Because the source countries producing crop-based aquaculture feeds are presently unknown or not publicly available, we used two scenarios to illustrate the range in uncertainty: (1) by assuming global sourcing, where total crop-based aquafeed production is simply weighted by crop production in each country globally (i.e., assuming that aquafeed production is proportional to total crop production) and (2) by assuming that all crop-based aquafeed production is sourced from the top three exporting countries for each crop (weighted by the total crop mass exported). These basic scenarios are therefore intended to reflect the range in *potential* resource use globally, providing comparison among the five crops, rather than absolute resource use per se.

After processing, crop-based ingredients for commercial aquaculture feeds emphasize soybean meal as the largest crop-based ingredient. Soybean meal accounts for ~23% of the processed crop-based ingredients used in aquaculture feed, while rapeseed meal accounts for ~19% (Tacon et al., 2011). We therefore use a deeper analysis of global soybean production and trade circa 2008 (the latest estimate of external feed inputs to global aquaculture from Tacon et al., 2011) in order to compare key land use and management efficiency metrics across major producing and exporting countries (based on nationally-weighted data from Foley et al., 2011 and West et al., 2014). We use these data to illustrate the potential range in resource-use efficiency associated with commercial aquaculture feed derived from soy in different regions. Bilateral trade statistics for soybean and soy meal are from FAOSTAT (2013) based on importing-country reported trade flows (metric tons). Harvested area may be lower than the actual physical land area due to multiple harvesting of the same land in a given year.

2.2. Environmental health impacts of crop production for aquaculture feed

The purpose of this literature review was to identify and summarize the links between industrial crop production and human health risks. We searched the peer-reviewed literature, using the Google Scholar and PubMed databases, to identify key primary research articles and reviews that report findings relevant to the exposure pathways and environmental health impacts of industrial crop production. We searched the databases for literature up to August 2015 using the following search terms in various combinations: agriculture, birth outcomes, crop production, exposure, farmworkers, health, human health, nutrient, pesticide, public health, occupational, pollution, and water. Journal articles were identified in the following fields: *environmental health*, *occupational safety and health*, and *environmental sciences*. We focused on fertilizer and pesticide use; these topics were selected based on previous knowledge of food systems and public health. Our review of the literature is not meant to be systematic, given the breadth of topics included in this paper. Instead, we prioritized journal articles that review the literature on one aspect of human health and industrial agriculture (e.g., pesticides and cancer) and primary research articles with a large sample size and/or that utilized rigorous study design/methods. Studies were excluded from our review if the findings were similar to one or two more recent or rigorous articles we included.

2.3. Implications for human nutrition

Intensively farmed fish get their nutrients exclusively from feed ingredients, and different feed ingredients can produce edible fish meat with varying nutritional content. To quantify long-term trends in seafood availability and its relationship to global diets, we extracted data from United Nations FAOSTAT (FAO, 2016) from 1960 to 2012 for the global and regional seafood supply (in million metric tons), and components of seafood related to nutrition (in grams/capita/day). To investigate the potential relationship between changing aquaculture feeds and human nutrition, we searched the relevant peer-reviewed literature using Google Scholar and PubMed until August 2015 using the following search terms: *aquaculture*, *seafood*, *fish*, *nutrition*, *feed*, *and fish oil*. We also looked for relevant articles and reports that were cited in papers found through searching (commonly described as snowball sampling). We extracted fish nutrition information from the USDA National Nutrient Database for Standard Reference for fatty acid profiles (USDA, 2015). The articles and reports used in this review cover human nutrition, food chemistry, and/or aquaculture.

2.4. Development of a conceptual framework

Based on the findings of our two literature reviews and estimates of potential agricultural resource use directed to production of crop-based commercial aquaculture feeds, we propose a conceptual framework to help guide further research in this area. Our conceptual framework, presented in the Discussion Section, illustrates potential linkages and implications of the increasing use of crops for aquaculture feed with a focus on environmental health and human nutrition.

3. Results

3.1. Resource use dimensions of crop production for aquaculture feed

Following our two simple scenarios of global crop-based commercial aquaculture feed sourcing (Table 1), we estimate that production of the

Table 1
Top producing and exporting countries by crop, mean of 2007–2009.

Global production	Top-5 countries (percentage)
Rapeseed/canola	China (21%), Canada (20%), India (12%), Germany (10%), France (9%)
Soybeans	USA (36%), Brazil (26%), Argentina (19%), China (6%), India (5%)
Maize	USA (40%), China (20%), Brazil (7%), Mexico (3%), Argentina (2%)
Nuts (groundnuts)	China (37%), India (19%), Nigeria (8%), USA (5%), Indonesia (4%)
Wheat	China (17%), India (12%), USA (9%), Russia (9%), France (6%)
Global exports	**Top-3 countries (percentage)**
Rapeseed/canola	Canada (44%), France (12%), Ukraine (11%)
Soybeans	USA (44%), Brazil (32%), Argentina (12%)
Soybean meal[a]	Argentina (40%), Brazil (21%), USA (12%)
Maize	USA (50%), Argentina (12%), Brazil (8%)
Nuts (groundnuts)	China (25%), Argentina (20%), India (14%)
Wheat	USA (19%), Canada (11%), France (11%)

[a] Soybean meal differs from soybean exports (as a grain) due to processing and trade.

top five major aquaculture feed crops required ~99,000–104,000 km^2 of harvested cropland area in 2008—comparable to the land area of Iceland. We estimate that rapeseed requires the most harvested area (~38,000–40,000 km^2) and results in the highest excess nitrogen fertilizer use of the five major crops in both scenarios (Fig. 3). Groundnut production for aquaculture feed requires the most irrigation water under both scenarios (global production versus major exporting country production), despite being a much smaller absolute feed source by mass, while irrigation water consumption for wheat and rapeseed is sensitive to assumptions about source regions (Fig. 3). We focus on irrigation water here, instead of total water consumption that includes rainwater, as irrigation is the directly managed fraction of water consumption that is closely related to the availability of fresh surface and groundwater (Hoekstra et al., 2011). Soybean and groundnut have comparable excess nitrogen and phosphorus fertilizer use based on our two scenarios, while the excess phosphorus fertilizer use for rapeseed also illustrates strong sensitivity to sourcing assumptions.

We further assessed production and trade in soybean. Nearly twice the amount of soybean meal was used as a commercial aquaculture feed ingredient compared to FM in 2008 (6.8 MMT soybean meal versus 3.7 MMT FM) (Tacon et al., 2011). China was by far the largest importer of soybean worldwide (>70% of its soy consumption imported) (FAO, 2015), embodying diverse irrigation water consumption, excess nitrogen, and excess phosphorus per unit of soybean imported. Collectively, the United States (28%), Brazil (27%), and Argentina (25%) contributed >80% of global soybean exports (average of the period 2007–2009) when considering both soybean grain and soybean meal (FAO, 2015). Although major soy producing countries have similar land requirements per unit of production (Fig. 4), rapid soy expansion in Brazil had additional ecological costs from land clearing during the 2000s (Macedo et al., 2012). We estimate that ~8.5% of U.S. soybean was produced in irrigated systems, reflecting larger irrigation water consumption per unit of production than the average for the rest of the world (West et al., 2014). Brazil and Argentina produce soybean almost entirely in rainfed systems (Siebert and Döll, 2010, West et al., 2014), with less nitrogen fertilizer but dramatically different impacts on soil fertility and the consumption of scarce global phosphorus fertilizers (Fig. 4). Soybean production is an important contributor to fertilizer nutrient use, representing ~8% of excess nitrogen and phosphorus use globally (West et al., 2014)—however, the relative over-application of nitrogen and phosphorus varies across major producing countries (Fig. 4).

3.2. Environmental health risks of industrial crop production

As demonstrated above, crop production is now a major component of the environmental footprint of aquaculture. Through our literature

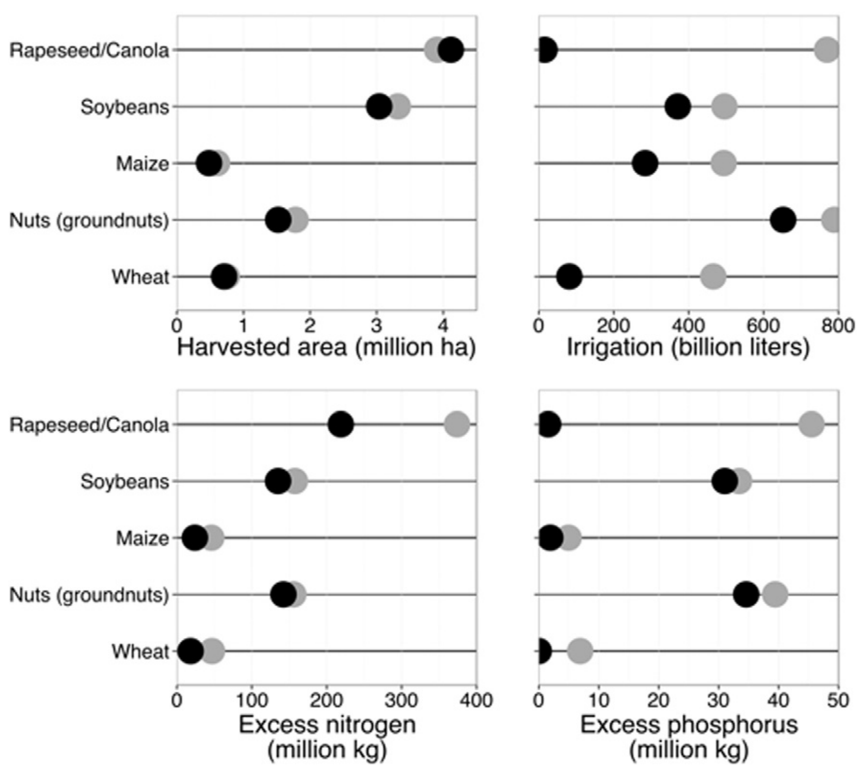

Fig. 3. Estimated resource use associated with the estimated harvested area for the top five aquaculture feed crops circa 2008. The grey points represent the 'global' production scenario. The black points represent the 'exporting country' scenario, where production is assumed to take place in the top three exporting countries. Comparison among the five crops in terms of potential cropland harvested area (hectares), irrigation water consumption (liters), excess nitrogen (N), and excess phosphorus (P) are shown.

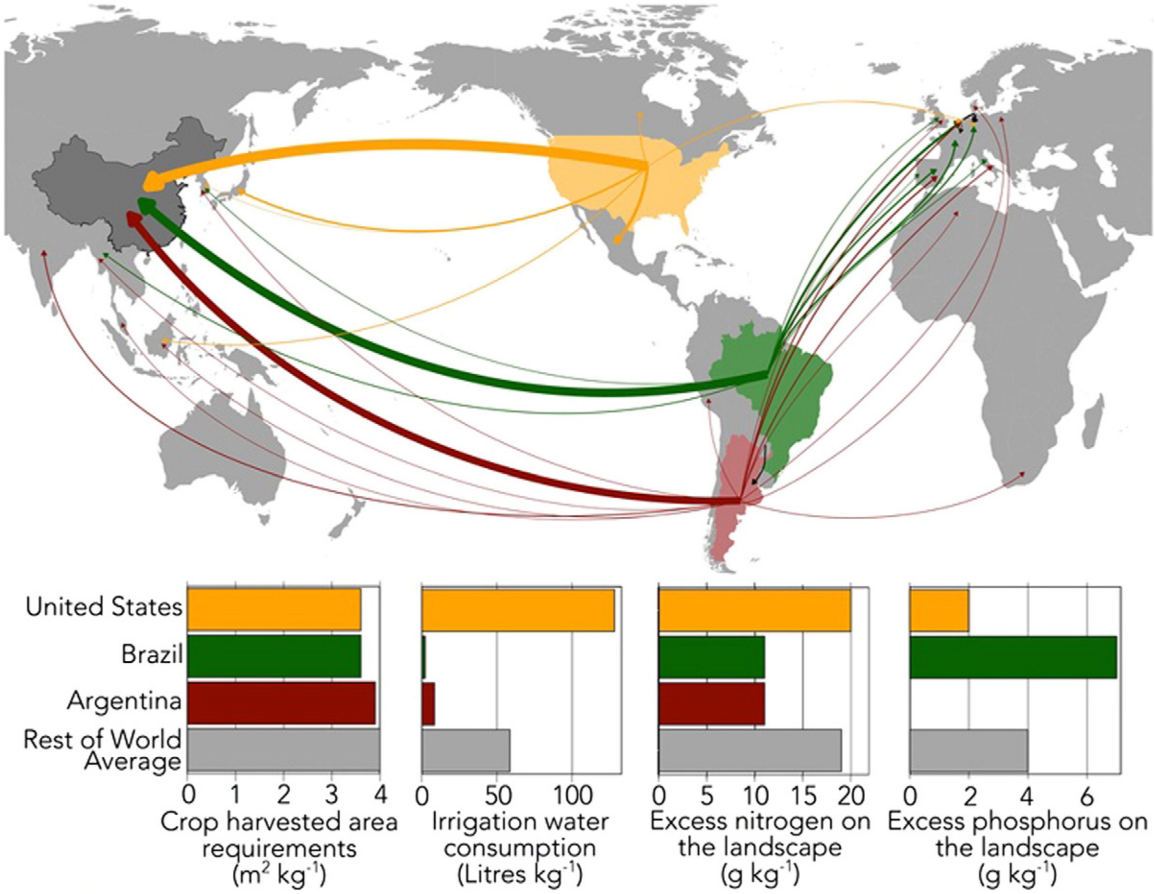

Fig. 4. Global soybean production and trade circa 2008. The United States (28%), Brazil (27%), and Argentina (25%) contributed >80% of global soybean exports (FAO, 2015). China is the largest importer of soybean worldwide, embodying diverse irrigation water consumption, excess nitrogen, and excess phosphorus per unit of soybean imported.

search, we identified 13 primary research and review articles on environmental health impacts of industrial crop production. The findings are summarized below. Additional detail on the study design, pollution source, primary exposure route, and health impacts are presented in Supporting Information Table S1. Due to the lack of data on geographic sourcing of crops used in aquaculture feeds and specific production methods, this review is by necessity not specific to crops grown for commercial aquaculture feed. We therefore highlight the need for new data and tracking mechanisms in order to quantify the environmental implications of crop-based feed ingredient production.

Crop production involves use (and potentially overuse) of fertilizer nutrients, including nitrogen and phosphorus, and these fertilizers, both synthetic and from animal manures, can degrade the quality of surface and groundwater used by humans for recreation, fishing, or drinking (Graham and Nachman, 2010). This can impact human health in many ways. A U.S.-based case–control epidemiologic study using data from the National Birth Defects Prevention Study found a positive association between prenatal consumption of drinking water with higher levels of nitrates and cases of spina bifida, limb deficiency, cleft palate, and cleft lip (Brender et al., 2013). Case descriptions by Knobeloch et al. (2000) describe the development of methemoglobinemia (i.e., blue baby syndrome), a condition that reduces the oxygen-carrying capacity of an infant's blood, in households that rely on private well water and are located near heavy agricultural activity. Gulis et al. (2002) conducted an ecological epidemiologic study in Slovakia and found higher incidences of some cancers among people who rely on drinking water contaminated with nitrates. The researchers found higher nitrate levels were associated with more cases of stomach cancer, colorectal cancer, non-Hodgkin lymphoma, and overall cancer for women, and more colorectal cancer and non-Hodgkin lymphoma in men (Gulis et al., 2002). In addition to nitrates in drinking water, Graham and Nachman (2010) reviewed the relevant literature and showed that animal waste used as fertilizer often contains agricultural chemicals, including non-metabolized veterinary drugs, hormones, and pesticides, which can contribute to harmful exposures in persons who rely on impacted groundwater for consumption and other household uses.

Chemical pesticides are used in agriculture to control insects and weeds with the goal of improving crop quantity and/or quality. Use of chemical pesticides can impact human health on and off agricultural operations. An analysis of multiple, passive surveillance systems focused on acute pesticide-related illness or injury among U.S. agricultural workers found over 3000 cases reported between 1998 and 2005 (Calvert et al., 2008). The symptoms reported involved the eyes, skin, and nervous, digestive, respiratory and cardiovascular systems. The U.S. Environmental Protection Agency recognizes the limitations of passive surveillance systems, and estimates that 10,000–20,000 physician-diagnosed pesticide poisonings occur annually among agricultural workers in the U.S. (Reigart and Roberts, 1999). Regarding long-term health impacts, researchers in Turkey compared blood samples from agricultural workers who use pesticides and non-agricultural workers and found significantly increased oxidative stress among agricultural workers, which can lead to the development of cancer (Ogut et al., 2014). A meta-analysis of 89 cohort and case–control epidemiologic studies focused on agricultural workers found a significant association between occupational exposure to pesticides and development of Parkinson's Disease (Pezzoli and Cereda, 2013). In addition, a literature review examining cancer, pesticides, and people working in agriculture found that occupational exposure to pesticides was linked to prostate cancer, non-Hodgkin lymphoma, leukemia, and multiple myeloma

(Alavanja et al., 2013). Researchers conducted a prospective cohort epidemiologic study in the U.S. using the large Agricultural Health Study dataset, which includes almost 2000 cases of prostate cancer and 1000 cases of aggressive prostate cancer, and found that use of four specific pesticides among licensed applicators was associated with an increased incidence of aggressive prostate cancer (Koutros et al., 2013). The results of a 25-year longitudinal cohort study in the Netherlands concluded that high occupational exposure to pesticides was associated with rapid declines in lung function, especially among individuals who had never smoked, and the researchers note that low lung function is linked to respiratory conditions including chronic obstructive pulmonary disease (COPD) (de Jong et al., 2014). Lastly, a cross-sectional epidemiologic study in Egypt surveyed mothers and sampled meconium (first feces) from 190 newborns. The results of the study showed that babies who tested positive for prenatal exposure to pesticides had mothers who were four times more likely to work in agriculture and were more likely to have a low birth weight, which is associated with increased infant mortality and childhood morbidity (El-Baz et al., 2015).

Beyond occupational exposure to pesticides, research has also focused on communities residing on the fence-line or downwind of spray sites. Lu et al. (2000) assessed exposure to pesticides among children living at varying distances from agricultural sites and with parents who did and did not have occupational exposure. The researchers analyzed hand swipes, household dust, and urine samples and found higher concentrations of pesticides and levels of metabolites with closer proximity to pesticide-treated crops and/or if the parents worked in agriculture (Lu et al., 2000). A study by Toccalino et al. (2014) was based on large-scale environmental sampling in the U.S. and involved testing of more than 1200 wells, which were sampled twice between seven and fourteen years apart. The research found that the percentage of samples with one or more pesticide compounds was highest for wells in agricultural areas (Toccalino et al., 2014). The scientific evidence summarized here demonstrates the potential environmental health impacts of industrial crop production, especially related to drinking water contaminated by fertilizers and exposure to pesticides through occupational activities, having a parent with occupational exposure and/or living in proximity to heavy agricultural areas.

3.3. Implications for human nutrition

In this section we looked at seafood consumption at the macro-level using global trends in food supply and at the farm-level by exploring the effects of feeding practices on the nutritional properties of fish. Available FAO data were used to examine global food production, food supply, and supply of protein and fats. Importantly, “food supply” is reported by the FAO as domestic production plus imports minus exports. The data does not account for all loss and waste throughout the supply chain and during consumption, so it should be considered an overestimate and not the actual amount eaten.

In 2012, humans captured and farm-raised 158 million metric tons of aquatic animals (Fig. 5a). About half of all seafood consumed by humans comes from aquaculture, and that fraction is expected to increase over time (UNFAO, 2014a). Most aquatic animals (86%) were fed to people, with a per capita global supply of 52 g/capita/d (Fig. 5b,c). The remaining 14% of seafood harvests, mainly small fish and trimmings, were used as feed for farmed fish, livestock, domestic pets, or as fertilizer. Fish, seafood, and other aquatic products represent 3% of the global food supply and 6% of the global protein supply (Tables S2–S4). Cereals (32%), meat (25%), and milk (14%) provide more protein to the world's population (Table S4). Fish and seafood are not large contributors to the global fat supply, just 1% (Table S5), partly because fish are lean sources of meat with lower levels of saturated fats, especially compared to red meat.

Among all regions, Asia has the largest supply of edible seafood (Fig. 5d), mostly due to China being both the leading producer and consumer of seafood globally (UNFAO, 2014a). Fish, seafood, and aquatic products account for 5% of the food supply in Asia, 4% in Oceania, 3% in Europe, and 2% in Africa and the Americas (Table S2). On a per capita basis, Europe and Oceania have the highest supply of protein and fats derived from seafood (Fig. 5e, f), however, these findings must be put in the context of their overall food supply and affluence. Europe, Oceania, and the Americas consume more protein from animal sources (mainly meat, dairy, and eggs) than plant sources, and more animal protein per capita than other regions (Table S4). In Africa and Asia, plants are the dominant source of protein, providing 77% and 66% of protein respectively. However, when animal protein is consumed, relative to other regions, more comes from aquatic sources than land-based sources. A similar situation exists regarding consumption of fats from plant and animal sources by region (Table S5). Taken together, these findings suggest that Asia and Africa are important regions for aquaculture and health stakeholders to focus on, in Asia because of high production and utilization and in Africa due to nutritional needs for protein and fat in the diet.

In addition to global food supply trends, human nutrition is affected by commercial feed formulations and decisions made at the farm-level. Aquacultured species may or may not be nutritionally similar to wild caught counterparts, depending upon what feed ingredients are used. Feeding trial studies from the aquaculture literature provide the most robust comparisons of nutrients in farmed fish. Feeding trials are grow-out studies that compare feed formulations and look for equivalence in fish growth rates, feed conversion, and/or tissue nutrient profiles. We focused on fatty acids in farmed fish feeding trials, which include saturated fatty acids (SFA, or saturated fat), monounsaturated fatty acids (MUFA), and polyunsaturated fatty acids (PUFA). There are associations between consuming certain PUFAs and a decreased risk of heart disease and improved neurological development (Lee et al., 2009, Larqué et al., 2012, Greene et al., 2013), however, there is some controversy over the strength of these associations. Western diets have low ratios of omega-3 to omega-6 PUFA, and a handful of studies indicate that these low ratios are less healthy than diets with higher ratios of omega-3 to omega-6 PUFA (Simopoulos, 2002, Wijendran and Hayes, 2004, Williams et al., 2011). For these reasons, the fatty acid content and fatty acid profile of farmed fish is of considerable interest to the nutrition and medical communities.

We reanalyzed data from 10 studies identified by Turchini and colleagues as well as 12 more recent studies comparing fish diets with varying levels of FO and vegetable oil (Turchini et al., 2009) (Table 2). Vegetable oils were corn, palm, peanut, rapeseed, soybean, sunflower, and vegetable oil blends. The general trend was fish receiving vegetable oils have lower relative fractions of omega-3s in fillets compared to fish oil fed fish. There were also higher relative fractions of MUFA, omega-6 PUFA and total PUFA (omega-3 + omega-6) in vegetable oil fed fish fillets compared to fish oil fed fish. Most studies report fatty acid fractions in relative amounts (relative to the total amount of fatty acids in a sample), however, there were a handful of studies that reported the absolute amounts of fatty acids in fish in addition to relative amounts of fatty acids. These studies found that some fish (rainbow trout, barramundi, jade perch and murray cod) fed vegetable oil have higher overall amounts of total PUFAs than fish fed FO, mainly due to higher omega-6 levels. Future feeding trials should report absolute and relative amounts of fatty acids to allow for nutritional comparisons. There are clear merits to evaluating omega-3 PUFA content in farmed seafood in addition to total PUFA (sum of omega-3 and omega-6 fatty acids) because high omega-6 PUFA levels can mask lower omega-3 PUFA levels in fish raised on vegetable oil.

We also identified 14 farmed/wild species comparisons (from 7 studies) in the nutrition and food chemistry literature that compare farmed and wild species (Table 3). These studies were not focused on evaluating changes in the nutritional profile of fish fed alternative (i.e., plant-based) feeds, but were merely product comparisons. In all products, PUFA concentrations ranged from 0.5 to 4 g per 100 g fish

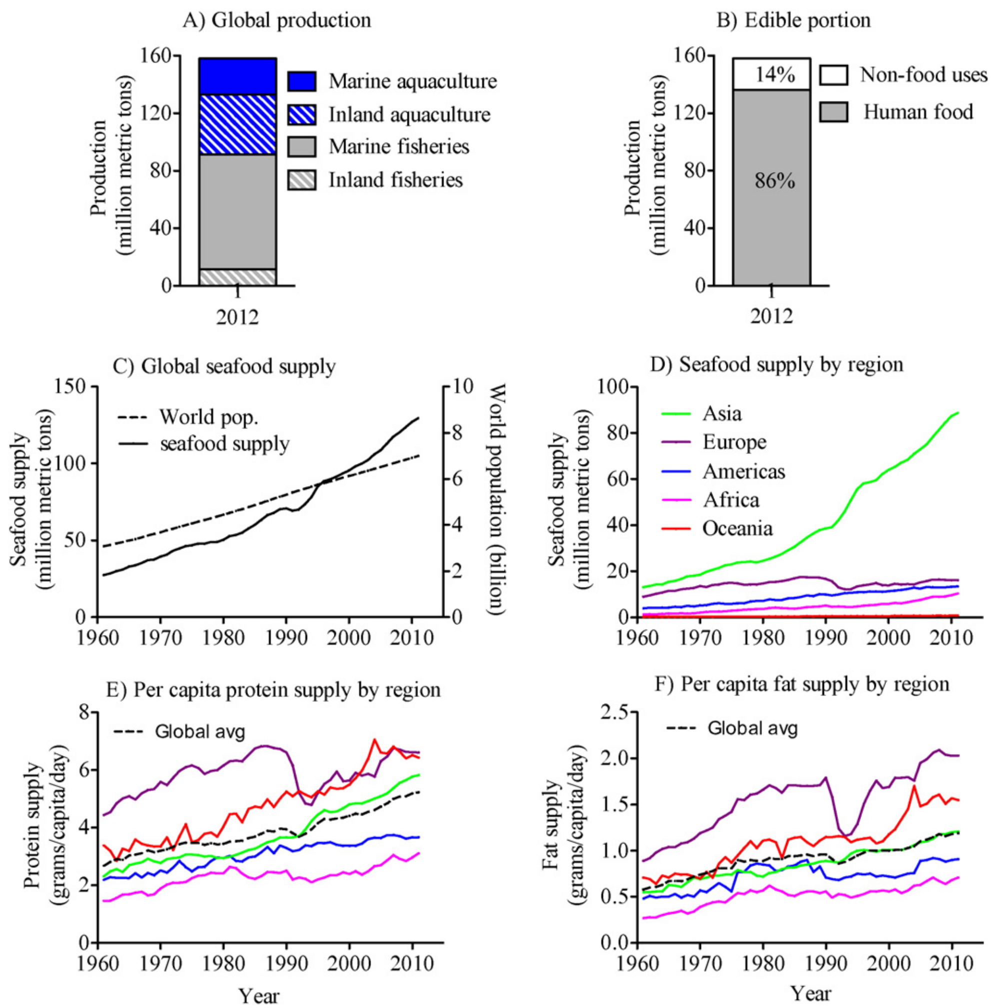

Fig. 5. Global seafood production and per capita consumption. a) Global fisheries and aquaculture production and b) the human edible fraction of seafood in 2012 (UNFAO, 2014a). Edible fisheries and aquaculture c) total supply, d) supply by region, e) per capita protein supply by region, and f) per capita fat supply by region (1961–2011) (FAO, 2016).

tissue and were highest in Atlantic salmon. Across all species, there were no clear trends in SFA, MUFA, and total PUFA ratios in farmed and wild pairs of fish. For example, PUFA fractions in farmed Atlantic salmon were higher than wild Atlantic salmon in one case, but lower in another study. However, for rainbow trout, two sources found higher PUFA fractions in wild compared to farmed trout. The articles we reviewed did not report aquaculture feed ingredients, so we were unable to determine how feed composition impacted PUFA fractions in farmed fish. PUFAs were separated into omega-3 and omega-6 fatty acid fractions in 8 of 14 comparisons, which showed weak evidence for a decrease in omega-6 PUFA fractions and increase in omega-3 PUFA fractions in farmed fish. Where data was available, absolute fatty acid content (for fatty acids: SFA, MUFA, and omega-3 and omega-6 PUFAs) was higher in farmed fish compared to wild species (Atlantic salmon, coho salmon, rainbow trout, channel catfish, tilapia). Together, the data from feeding trials and farmed/wild comparison studies indicate that farmed fish can be nutritionally similar to wild fish and can have higher levels of PUFAs, but nutritional content depends on feed, and vegetable oil fed fish may have PUFA ratios skewed toward omega-6 PUFAs.

4. Discussion

We reviewed potential direct and indirect environmental and public health impacts related to the changing composition of aquaculture feed. Our results show that producing the types of crops used in commercial aquaculture feed uses significant amounts of land, water, and fertilizer, which contributes to and could compound environmental issues related to agricultural production in general. Our analyses show the need for geographic sourcing information of crops for more precise estimates on actual resource use linked to a growing aquaculture industry given their high uncertainty. We considered human health impacts of industrial crop production as an indirect effect of growing crops for commercial aquaculture feed by summarizing key research on human health effects associated with nutrient runoff and pesticide use. This literature provides strong evidence that agricultural workers, their families, and residents living near heavy agricultural activity are at increased risk of health problems caused by exposure to nutrients and/or chemical pesticides. In addition, feeding carnivorous farmed fish increasingly plant-based diets can alter the nutritional profiles of these products, which could affect human nutrition and health in general. Due to the constraints facing our aquatic and terrestrial systems, it is critical to understand the changing ecological footprint and environmental health impacts of aquaculture's increasing reliance on crop-based feed so policy makers, businesses, and consumers can make informed decisions regarding resource use, food production methods, and dietary patterns. Our analysis shows large discrepancies in the per unit and global estimates of resource use embodied in commercial aquaculture feed depending on which nation these crops are sourced from worldwide, especially for water consumption and excess fertilizer (Fig. 3). These excess nutrients are a key driver of water quality degradation locally and in downstream coastal areas, especially in major crop exporting countries like the U.S. The ranges in our estimates highlight the need

Table 2
Relative changes in fatty acid[a] profiles in farmed fish fed vegetable oil diets compared to a control diet of fish oil.

Species	Trophic level[b]	Oil type	SFA	MUFA	Omega-3 PUFA	Omega-6 PUFA	Omega-3/6 PUFA	Total PUFA	References
Atlantic salmon	4.5	Camelina oil	↓	↑	↓	↑	↓	↑	(Hixson et al., 2014)
Atlantic salmon	4.5	Vegetable oil blend	↓	=	↓	↑	↓	↑	(Torstensen et al., 2005)
Hybrid striped bass	4.4	Corn oil	↓	↑	=	↑	↓	↑	(Lane et al., 2006)
Murray cod	4.2	Linseed oil	↓	↓	↑	↑	↓	↑	(Turchini et al., 2011)
Yellowtail amberjack	4.2	Canola oil	↓	↑	↓	↑	↓	↓	(Bowyer et al., 2012)
Atlantic cod	4.1	Camelina oil	↓	↑	↓	↑	↓	↑	(Hixson et al., 2014)
Atlantic cod	4.1	Peanut oil	=	↑	↓	↑	↓	↓	(Lie et al., 1986)
Rainbow trout	4.1	Linseed, sunflower oil	↓	↓	↓	↑	↓	↑	(Thanuthong et al., 2011)
Rainbow trout	4.1	Vegetable oil blend	=	=	↓	↑	↓	=	(Caballero et al., 2002)
Barramundi	3.8	Rapeseed oil	↓	↑	↓	↑	↓	↑	(Alhazzaa et al., 2011)
African catfish	3.7	Sunflower oil	↓	↓	↓	↑	↓	↑	(Ng et al., 2003)
Gilthead sea bream	3.7	Soybean oil	↓	↓	↓	↑	↓	↑	(Fountoulaki et al., 2009)
Gilthead sea bream	3.7	Soybean oil	↓	↓	↓	↑	↓	↑	(Izquierdo et al., 2005)
Red sea bream	3.7	Rapeseed oil	↓	↑	↓	↑	↓	↑	(Huang et al., 2007)
European seabass	3.5	Soybean oil	↓	=	↓	↑	↓	↑	(Montero et al., 2005)
Senegalese sole	3.3	Vegetable oil blend	↓	↑	↓	↑	↓	↑	(Reis et al., 2014)
Senegalese sole	3.3	Soybean oil	↓	↓	↓	↑	↓	↑	(Benitez-Dorta et al., 2013)
Sharpsnout seabream	3.2	Soybean oil	↓	↓	↓	↑	↓	↑	(Piedecausa et al., 2007)
Turbot	3.1	Soybean oil	↑	↓	↓	↑	↓	na[c]	(Regost et al., 2003)
Jade Perch	2.7	Linseed oil	↓	↑	↑	↑	↓	↑	(Van Hoestenberghe et al., 2013)
Hybrid tilapia	2.2	Crude palm oil	↑	↑	↓	↑	↓	↓	(Bahurmiz and Ng, 2007)
Grass carp	2.0	Vegetable oil blend	=	↓	↓	↑	↓	↑	(Du et al., 2008)
Percent of studies with a relative decrease in fatty acids			77%	41%	86%	0%	100%	14%	

[a] SFA = saturated fatty acids; MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids; omega-6 PUFA is also known as omega-6 fatty acid; omega-3 PUFA is also known as omega-3 fatty acid; omega-6/omega-3 is the ratio of omega-6 to omega-3 PUFA.
[b] Trophic level from Fish Base (http://www.fishbase.org/).
[c] na = not available.

for geographic sourcing information for crops used in aquaculture. Pahlow et al. (2015) were limited by the same information gap; they conducted an in-depth analysis of the water footprint of different aquaculture species, and used global averages to estimate water use for feed crops due to the lack of sourcing information. A benefit of the Pahlow study was constructing species-specific diets as a preliminary step to developing water use estimates by species, while our study looked at top crops used in commercial aquaculture feed and did not differentiate by species. A benefit to studying trends by species is that herbivorous/omnivorous fish are more likely to receive terrestrial crops in feed, which may result in different environmental impacts. Carnivorous species consume fewer terrestrial crops but feed companies are beginning to replace FM/FO with terrestrial crops as FM/FO supplies diminish and costs increase. Different rates of growth in production of herbivorous/omnivorous versus carnivorous aquatic species will impact demand for various types of crops due to different nutritional needs (i.e., levels of lipids, protein, and carbohydrates in optimal feeds); this should be explored in future research.

Dominant crop production methods, in addition to using a significant amount of resources, can impact human health. The environmental health impacts of industrial crop production mainly occur through human exposure to air, water, and soil contaminated with nutrients or pesticides. The most vulnerable populations are agricultural workers, their families, and residents living in heavy agricultural areas. Aquaculture operations, feed mills, and feed suppliers that use crop-based feed ingredients may be inadvertently contributing to existing human health risks from industrial crop production. Importantly, human health impacts of feed crop production, similar to resource use and environmental effects, are dependent on where and how feed crops are produced. The ability of the surrounding environment to buffer certain

Table 3
Relative changes in fatty acid[a] profiles in farmed fish compared to wild caught fish. Vegetable or fish oil content of the farmed fish diet was not reported.

Species	Trophic level[b]	SFA	MUFA	Omega-6 PUFA	Omega-3 PUFA	Omega-6/3 PUFA	Total PUFA	References
Atlantic salmon	4.5	↑	↓	na[c]	na	na	↓	(USDA, 2015)
Atlantic salmon	4.5	↑	↓	↑	↑	↑	↑	(Blanchet et al., 2005)
Chinese perch	4.5	↑	=	↓	↑	↓	↑	(Li et al., 2011)
Snakehead	4.4	=	↓	↑	↑	↑	=	(Li et al., 2011)
Coho salmon	4.2	↑	↑	na	na	na	↓	(USDA, 2015)
Channel catfish	4.2	↓	↑	na	na	na	↓	(USDA, 2015)
Rainbow trout	4.1	↑	↑	na	na	na	↓	(USDA, 2015)
Rainbow trout	4.1	↑	↑	↓	↓	↓	↓	(Blanchet et al., 2005)
Gilthead sea bream	3.7	↓	↓	↑	↑	↑	↑	(Bhouri et al., 2010)
Yellow perch	3.7	↑	↓	↓	↑	↓	↑	(Gonzalez et al., 2006)
European seabass	3.5	↓	↑	↓	↓	↓	↓	(Alasalvar et al., 2002)
Bighead carp	2.8	↓	↓	=	↑	↑	↑	(Li et al., 2011)
Tilapia (semi-intensive)	2.2	↓	↑	na	na	na	↑	(Karapanagiotidis et al., 2006)
Tilapia (intensive)	2.2	↓	↑	na	na	na	↓	(Karapanagiotidis et al., 2006)
Percent of studies with a relative decrease in fatty acids		50%	50%	62%	38%	50%	57%	

[a] SFA = saturated fatty acids; MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids; omega-6 PUFA is also known as omega-6 fatty acid; omega-3 PUFA is also known as omega-3 fatty acid; omega-6/omega-3 is the ratio of omega-6 to omega-3 PUFA.
[b] Trophic level from Fish Base (http://www.fishbase.org/).
[c] na = not available.

impacts (e.g., fertilizer nutrients used in excess of crop requirements) and proximity of production sites to communities are important factors that will partly determine the extent of human exposure and resulting health impacts. Environmental impacts of crop production also threaten aquaculture directly, for example the dead zone in the Gulf of Mexico that forms each summer is caused by crop-based nutrient pollution from the Mississippi River, and could impact aquaculture operations in the Gulf region. Including environmental health impacts in multidisciplinary assessments of the footprint of aquaculture production, including sustainability certification programs (e.g., Aquaculture Stewardship Council), could lead to segments of the aquaculture industry choosing crops that have a lower environmental footprint or supporting alternative crop production practices (e.g., organic or agro-ecological growing) in order to market their products as highly sustainable.

Health professionals and the aquaculture industry have communicated the health benefits of seafood for many years. However, farmed fish raised on plant-based diets may not deliver the same amount of omega-3 s in fillets as marine-based feeds. Some feed companies and aquaculture producers have increased efficiency by altering levels of FO in diets, strategically utilizing lower levels during the grow out period and higher levels prior to harvesting to raise EPA/DHA content in the final product (Naylor et al., 2009). The industry is also increasing use of FO made from inedible parts of processed seafood (Shepherd and Jackson, 2013) and researchers have developed genetically modified algae, yeast, and *Camelina sativa* (an oilcrop) to produce EPA/DHA and replace FO (Xue et al., 2013, Hamilton et al., 2014, Betancor et al., 2015, Usher et al., 2015). It will take time and resources for these sources to scale-up, as recent studies cited above indicate their development is currently in a "proof of concept" phase, and they may face opposition from consumers given recent scrutiny of other products containing genetically modified ingredients. Other alternative feed ingredients are under development to provide protein and other macro or micronutrients, such as insects; these products also require time to scale up (Makkar et al., 2014). An analysis of alternative feed ingredients, a potential timeline to bring them to scale, and the resources needed to produce them is beyond the scope of this review. In terms of consumer demand and human nutrition, the importance of maintaining high EPA/DHA levels varies by species. In one analysis, nutrition experts advising the USDA and HHS used nutrient data from fish for sale in the United States and found that farmed carnivorous species had equivalent or higher levels of EPA/DHA compared to their wild counterparts, and herbivorous/omnivorous farmed fish generally had lower levels compared to wild fish (USDA and HHS Advisory Committee, 2015). This finding may be due to the fact that high-value farmed fish prized for their EPA/DHA content (e.g., Atlantic salmon) will be fed FO or EPA/DHA from an alternative source because if farmed salmon were found to have low levels of these omega-3s, consumer demand would likely decrease. If EPA/DHA levels decline in herbivorous/omnivorous fish (e.g., tilapia, catfish, carp), which have lower levels compared to carnivorous species based on their position in the aquatic food web, it is unclear whether there will be human nutrition and public health impacts, and what the nature and severity might be. It depends, in part, on how much EPA/DHA individuals currently get from omnivorous/herbivorous fish, which is determined by how much and which kinds of seafood are consumed and what the fish eat. EPA/DHA levels can be impacted in the short-term by the high cost of FO (~$1500–2500 per ton), and there are long-term questions about the availability of FO (Tallaksen, 2014). If alternative sources of EPA/DHA (e.g., algae, yeast, crops) can be mass-produced for less than the price of FO, we could see faster growth for certain segments of aquaculture, which could also lead to increasing demand for crop-based feed.

4.1. Conceptual framework

We developed a conceptual framework to capture the trends in aquaculture production and use of crop-based feed ingredients and illustrate the potential environmental health and human nutrition impacts included in this review (Fig. 6). As noted above, many of the relationships between factors cannot be fully explored without knowing where and how the feed crops are produced. Nonetheless, it is valuable to develop an initial framework for future research to build upon and clarify. Our proposed framework begins with the left-hand column where we include the two main drivers of increasing aquaculture production, a growing human population and declining fisheries, and the limited supply of FM and FO. These factors result in a growing aquaculture industry that relies on rising amounts of crop-based feed ingredients. A direct impact of a growing aquaculture industry consuming crop-based feeds is an increased production capacity, although some of the farmed seafood may have lower levels of EPA/DHA. Increased availability of farmed seafood could result in health benefits if seafood is eaten in place of some meat (due to lower levels of saturated fat), or if the farmed seafood reaches people suffering from malnutrition or food insecurity. On the other hand, current health benefits associated with consumption of EPA/DHA could be reduced if certain farmed seafood products have lower levels of EPA/DHA due to feed composition. If dietary guidelines are based on reaching weekly EPA/DHA targets from fish, then consumers may need to consume more fish to meet the same targets.

The lower half of the third column shows two direct impacts of the trend of increasing use of crop-based feeds in aquaculture. They are i) the inclusion of land, water, fertilizer, and pesticide use as part of aquaculture's environmental footprint, and ii) a coupling of terrestrial crop and seafood production systems. These shifts may result in indirect public health risks associated with industrial crop production and could also have an effect on the resilience of the global food supply and food security. The relationship between resilience of the global food system and increasing aquaculture production using crop-based feeds was explored in Troell et al. (2014), and more research on these complex factors is needed.

Over one third of global crop production is currently used to feed animals, with significant environmental consequences (Foley et al., 2011). Despite this, the shift to crop-based ingredients for aquaculture feed has been presented in the scientific literature and elsewhere as a "sustainable" alternative to fish-based ingredients (Gatlin et al., 2007, Naylor et al., 2009). Likely reasons for this are the relatively small size of the aquaculture industry (which currently consumes ~4% of feed crops (Troell et al., 2014)) and the efficient use of feed inputs compared to terrestrial animal agriculture. Feed is converted to animal biomass more efficiently in aquaculture in part due to the buoyancy provided by the aquatic environment and because farmed aquatic species are mostly ectothermic (i.e., cold blooded) (Naylor et al., 2009, Torrissen et al., 2011). One measure of efficiency in animal agriculture is the feed conversion ratio (FCR), which is defined as the kilograms of animal feed needed per kilogram of added animal body mass. FCRs for farmed fish (1–2.5) are lower than or similar to chicken (2.5), and significantly lower than swine (5) and beef cattle (5–20) (Sampels, 2014, Smil, 2002). Therefore, if global consumption of animal products remained constant and aquaculture replaced significant portions of global livestock production, we would expect a reduction in the total amount of feed needed to produce the same amount of animal protein, and a reduction in the environmental and public health impacts associated with crop production for animal feed. In reality, rising incomes in China, Mexico, South Korea and other countries are leading to increasing global demand for animal protein (Smil, 2002, Tilman et al., 2011). Therefore, an increase in aquaculture production is not likely to lead to a decrease in other forms of land-animal production, and instead may cause further stress on environmental resources. However, it is possible that the rapid growth of aquaculture production over the past few decades contributed to slower growth of terrestrial livestock production than would have otherwise occurred, but this potential relationship has not been studied.

We argue that an increased understanding of relationships and potential impacts of aquaculture's shift to crop-based feed ingredients is

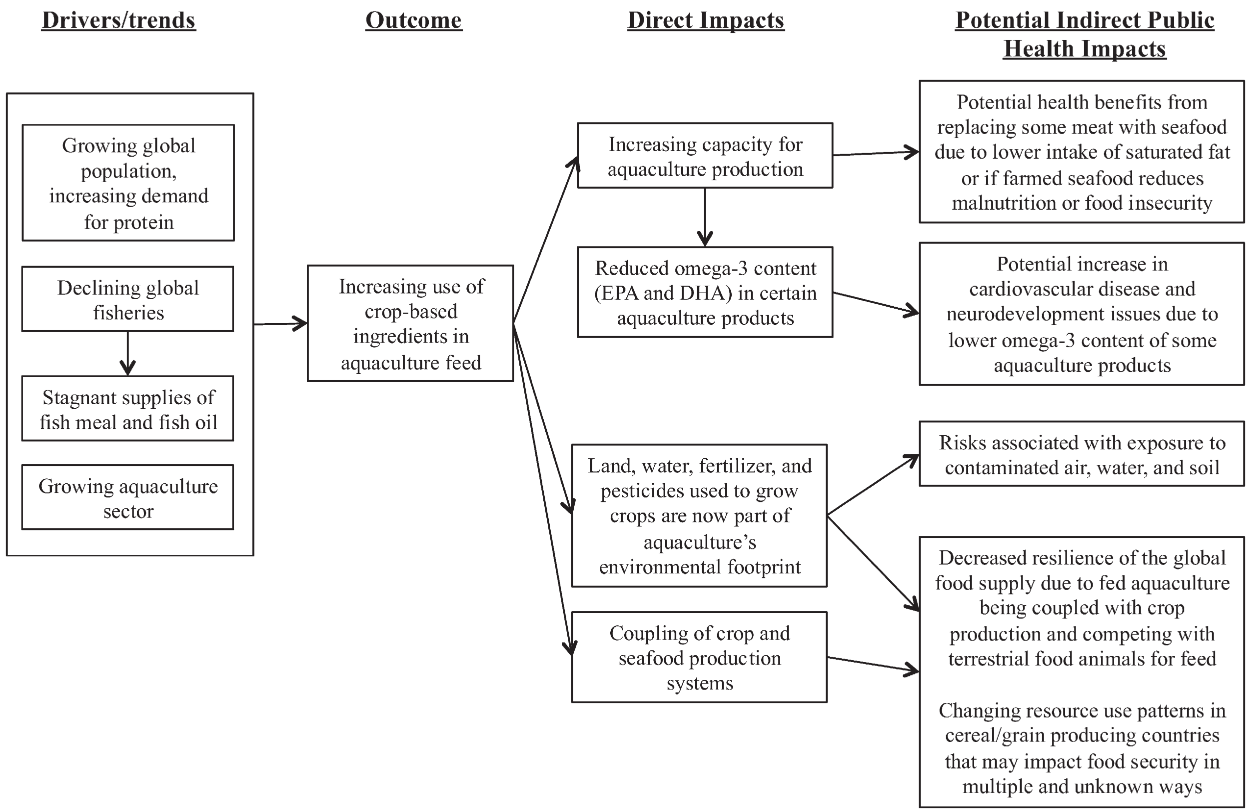

Fig. 6. Conceptual framework depicting potential ecological and environmental health impacts of using more crop-based feed to expand aquaculture production. In response to increasing demand for farmed seafood and limited supplies of FO and FM, the growing aquaculture industry is using more crop-based ingredients in feed. Two direct impacts are increasing capacity for production and potentially reduced content of EPA and DHA in certain aquaculture products due to the limited supply of FO used more sparingly across higher volumes of production. A growing supply of farmed seafood products could have positive human health benefits due to lower consumption of saturated fat if certain types of seafood replace meat in diets and if increased availability reduces malnutrition or food insecurity, but the trends in feed composition could lead to rising cardiovascular and neurodevelopment health issues in populations that consume aquaculture products with reduced levels of EPA and DHA. The other major pathway represented in the framework involves the expanded ecological footprint of global aquaculture production that now includes the resource use and environmental degradation associated with industrial crop production and the coupling of aquaculture and the terrestrial agriculture system. The potential indirect environmental health impacts of this pathway include risks associated with exposure to air, water, and soil contaminated by fertilizers and pesticides. Food security could also be affected by decreased resiliency of the food system due to unsustainable use of resources used to grow crops and altered patterns in crop production due to rising demand for feed crops.

urgently needed, but has been largely overlooked. Here, we provide an interdisciplinary and multifaceted view of the effects of aquaculture on resource use, environmental degradation, environmental health, and human nutrition. We have raised concerns that require short and medium-term solutions to make aquaculture products more nutritious, carry fewer externalities, and more sustainable (i.e., more efficient, economical, and use fewer resources). It is also imperative to work in parallel to develop medium and long-term strategies to build a more resilient, sustainable, and equitable food system. One important strategy is a global dietary shift or 'protein transition' involving an overall reduction in protein consumption among high protein consumers and replacing some meat intake with fish and plant-based protein (Pelletier and Tyedmers, 2010, Kastner et al., 2012, Badgley et al., 2007). Rightsizing animal protein intake is especially important in the U.S. and other high-income countries where animal protein is consumed above recommended levels (Smil, 2002). Aquaculture could play an important role in this transition, and contribute to the dietary protein needs of 800 million people currently undernourished (UNFAO, 2014b), but reversing the trend of growing global demand for animal products and replacing significant meat consumption with more efficient farmed seafood and plant-based protein sources will be difficult.

5. Conclusions

Increasing the use of crop-based ingredients in commercial aquaculture feed is not a panacea—rather, it could carry unanticipated, indirect negative environmental health externalities caused by industrial crop production methods and impact human health through changing nutritional content of aquaculture products. As use of aquaculture feeds with higher proportions of crop-based ingredients grows, aquaculture production will be further decoupled from FM and FO supplies, thus creating a feedback loop and potentially driving demand for additional terrestrial agricultural production even higher than projections based on historical trends (Tilman et al., 2011). Agriculture is already one of the top contributors to global environmental degradation (Foley et al., 2011), and increasing use of terrestrial ingredients in aquaculture feed is unlikely to i) reduce pressure on forage fisheries due to industry expansion, or ii) reduce demand for crop-based feed through increased efficiency compared to terrestrial animal production, due to rising global demand for meat and fish. Additionally, crop yield trends are not on track to meet projected demand (Ray et al., 2013), and climate change will increasingly disrupt crop production, wild fisheries, and aquaculture. These issues highlight the importance of changing global diets and production methods (for crops and animals), not only to promote human health, but also to improve the sustainability and resilience of our food system.

Examination of the potential costs and benefits of increased aquaculture feed production is needed to properly assess the sustainability of the aquaculture industry. To support these analyses, nutritional content should be monitored and the supply and demand of all ingredients used in aquaculture feed, including how and where they are produced, should be systematically tracked. These data are needed to make a full assessment of resources used, potential risks to public health, and agro-environmental tradeoffs associated with increasing land-based feed production. Aquaculture could play an important role in a transition to an efficient, resilient, health-promoting, and just global food system. To accomplish this transition we must promote actions by various stakeholders that account for the resources used to produce feed and the many ways increasing production impacts the environment and human health.

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Appendix A. Supplementary data

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