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Article *in* Integrated Environmental Assessment and Management · July 2019

DOI: 10.1002/ieam.4187

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Integrated Environmental Assessment and Management — Volume 00, Number 00—pp. 1–12
Received: 12 September 2018 | Returned for Revision: 4 December 2018 | Accepted: 26 June 2019

Critical Review

Sustainable Seafood and Vegetable Production: Aquaponics as a Potential Opportunity in Urban Areas

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ABSTRACT

Global population growth will increase pressures on current food systems in order to supply adequate protein and produce to the increasingly urban world population. The environmental impact of food production is a critical area of study as it influences water and air quality, ecosystem functions, and energy consumption. Aquaponics (in which seafood and vegetables are grown in a closed-loop system) has the potential to reduce the environmental impact of food production. A review of the current environmental and economic considerations is provided in order to identify current research gaps. Research gaps exist with respect to 1) diversity of aquatic and plant species studied; 2) inconsistent bounds, scope, and lifetime across studies; 3) diverse allocation of the environmental and economic impacts to the coproducts; 4) scale of systems considered; 5) transportation of produced food; and 6) presence of heavy metals, pests, and pathogens with human health implications. These aspects require increased attention to close the existing gaps prior to widescale deployment of these systems for increased sustainable food production toward satisficing human needs. *Integr Environ Assess Manag* 2019;00:1–12. © 2019 SETAC

Keywords: Aquaponics Sustainability Food–energy–water nexus Life cycle assessment Seafood

INTRODUCTION

The world population is projected to increase to 9.8 billion people in 2050, intensifying pressures on current food systems to feed an ever-growing population (UN 2017). In order to feed this increased population, which is predominantly expected to inhabit urban areas, shifts in consumption along with the adoption of new food production methods must occur (Barbosa et al. 2015). The average person in the United States consumes approximately 16 lb (7.3 kg) of seafood (containing 1.37 to 2.22 kg of protein) annually (White 2016). Meanwhile, the United States Department of Agriculture (USDA) recommends that individuals consume about 5 oz (142 g) of protein per day, or about 114 lb (51.8 kg) per year (USDA 2017). Shifting protein consumption from terrestrial animals to fish and plant sources can provide human health and environmental benefits, given that seafood is a less environmentally costly method of meeting society's protein demand. With respect to global warming potential (kilograms of carbon dioxide equivalents [CO_2E] per kilogram of food produced), fish in general have a lower impact than conventional protein sources. On a mass basis, salmon and tuna, for example, generate 3.3 kg of CO_2E and 2.6 kg CO_2E per kilogram of food produced, respectively, compared to ground beef (29 kg CO_2E/kg), lamb (26 kg CO_2E/kg), pork (8.2 kg CO_2E/kg), and chicken (4.8 kg CO_2E/kg) (Heller et al. 2013). Nijdam et al. (2012) evaluated the range of environmental impacts (using kilograms CO_2E and land usage) of protein production through a metaanalysis of life cycle assessment (LCA) studies, including 15 studies for beef production, 4 studies for sheep meat, 12 studies for milk and cheese, 8 studies for pork, 5 studies for poultry, 16 studies for seafood including freshwater fish, 1 study for meat generally, and 3 studies for vegetables (Figure 1). Their work suggests that the global warming potential for fish produced in aquaculture is in general lower than that of terrestrially raised animal sources (with the exception of chicken and pork).

Aquaculture systems, in which freshwater and saltwater fish, crustaceans, and mollusks are grown in captivity, can reduce the distance that seafood travels prior to reaching the consumer if located near areas of consumption (Tlusty and Legueux 2009). These systems have the potential to increase fish consumption, conserve wild fish stocks, reduce food waste, and reinvigorate local economies. However, aquaculture represents diverse activities with an equally diverse array of environmental impacts. Aquaculture systems may require large inputs of water and feed, including feed made with ocean fish species, and may

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Published 12 July 2019 on wileyonlinelibrary.com/journal/ieam.

 DOI: 10.1002/ieam.4187

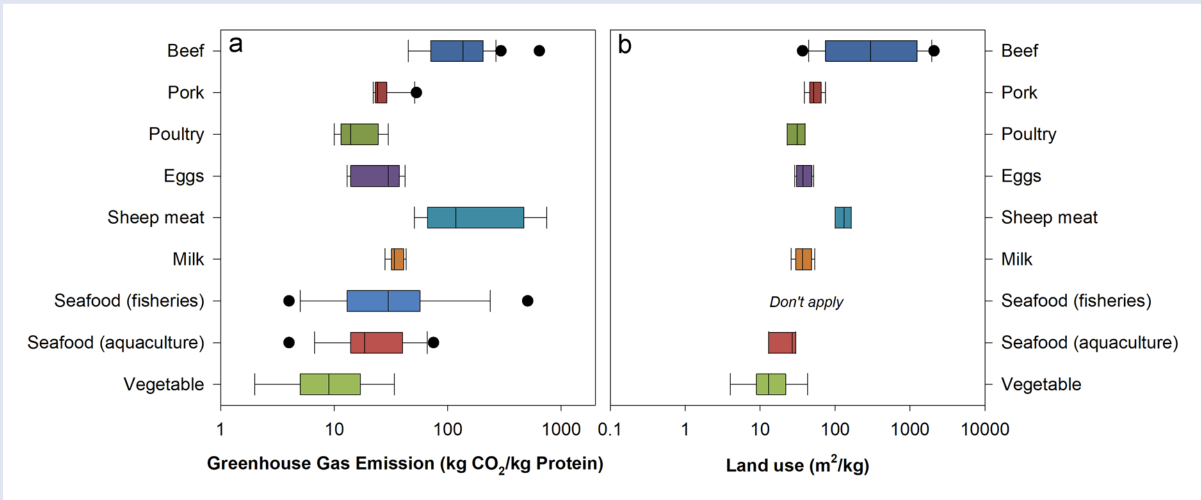

Figure 1. Environmental impact of protein production across different sources, adapted from Nijdam et al. 2012 utilizing data from Sheenan et al. 1998; Hass et al. 2001; Phetteplace et al. 2001; Berlin 2002; Silvenius and Gronroos 2003; Ziegler et al. 2003, 2011; Cederberg and Flysjo 2004; Zhu and Van Ierland 2004; Basset-Mens and van der Werf 2005; Eriksson et al. 2005; Nempecek et al. 2005; Casey and Holden 2006; Mollenhorst et al. 2006; Weiske et al. 2006; Williams et al. 2006; Katajajuuri 2007; Ogino et al. 2007; Verge et al. 2007, 2008, 2009; Blonk et al. 2008; Hirschfeld et al. 2008; Thomassen et al. 2008; Ziegler and Valentinsson 2008; Aubin et al. 2009; Blonk et al. 2009; Cederberg, Flysjo et al. 2009; Cederberg, Meyer et al. 2009; Edward-Jones et al. 2009; Ellingsen et al. 2009; Flachowsky and Hachenberg 2009; Pelletier et al. 2009; Peters et al. 2009; FAO 2010; Iribarren, Hospido et al. 2010; Iribarren,Vazquez-Rowe et al. 2010; Nyugen et al. 2010; Pelletier and Tyedmers 2010; Ponsioen et al. 2010; Vazquez-Rowe et al. 2010, 2011, 2012; Sheane et al. 2011; Ramos et al. 2011; Svanes et al. 2011.

have significant environmental impacts, such as biodiversity loss, land use change, and eutrophication (Naylor et al. 2000). Different fish species require large amounts of fish-based protein for their growth (although animal by-products are also used), in ratios from less than 1 unit of wild fish required per unit of farmed fish (<1:1), such as tilapia, to more than 5:1 for large predatory fish such as salmon raised in aquaculture (Naylor et al. 2000). Multiple studies have worked to quantify the environmental impact of fish produced in aquaculture systems, particularly with respect to the changes in environmental impact compared to wild caught fish (Ayer and Tyedmers 2009; Bosma et al. 2011; Henriksson et al. 2012; Liu et al. 2016). Other issues with respect to the environmental impact of aquaculture systems have been investigated, such as impacts due to different types of fish feed (Papatryphon et al. 2004), species of fish, feedstocks of the system, waste management practices (Cao et al. 2007), system energy consumption, and water characteristics (Aubin et al. 2009).

Aquaponics presents an innovation in conventional aquaculture systems by combining aquaculture with hydroponic plant growth. In these systems fish grow in conjunction with plants using closed-loop, typically recirculating, water systems and can potentially reduce the environmental concerns associated with both conventional aquaculture and agriculture (Figure 2). Plants take up the required N and P, which are produced and converted as a result of fish metabolism and bacterial activities and which are essential nutrients for plant growth (Grozea and Blidariu 2011). The recirculation of the water also potentially reduces the environmental impact of the system by reducing water consumption. An additional advantage of these systems is that conventional soil contaminants are not relevant to the crops; however, there are concerns about different types of contamination, such as the spread of microbial pathogens through fish waste in water. Challenges also exist with respect to scaling the fish and crop production together due to differences in growth rates, the effectiveness of N uptake for different crops, cost, and energy requirements (Lin 2014). These systems have been suggested as being suitable for urban areas in that they can be housed on rooftops or in other nonconventional areas. With respect to the fish products, tilapia are the most commonly farmed species; however, other species such as cod and shrimp are also raised (Grozea and Blidariu 2011; Tyson et al. 2011). There is more diversity in the types of crops grown, including tomato, bean, cucumber, lettuce, basil, okra, and pepper (Love et al. 2015). Aquaponic protein and plant production present an opportunity to reduce the environmental impact of food production, the distance that food travels, and the corresponding food, energy, and water impacts that will be incurred to feed an increasingly large urban world population. Although they hold incredible promise for sustainable food production, these systems have not yet been widely adopted (Goddek et al. 2015).

The aim of the present work is to explore the sustainability and suitability of aquaponic food production to feed an increasing urban population. The present review paper is structured to analyze the current state of knowledge of each facet individually: *Environmental Implications*, *Economic Implications*, and *Human Health Implications*.

ENVIRONMENTAL IMPLICATIONS

Life cycle assessment is a systematic tool for determining the environmental impact of a product or process across its entire life cycle or a portion of interest (Klopffer 1997;

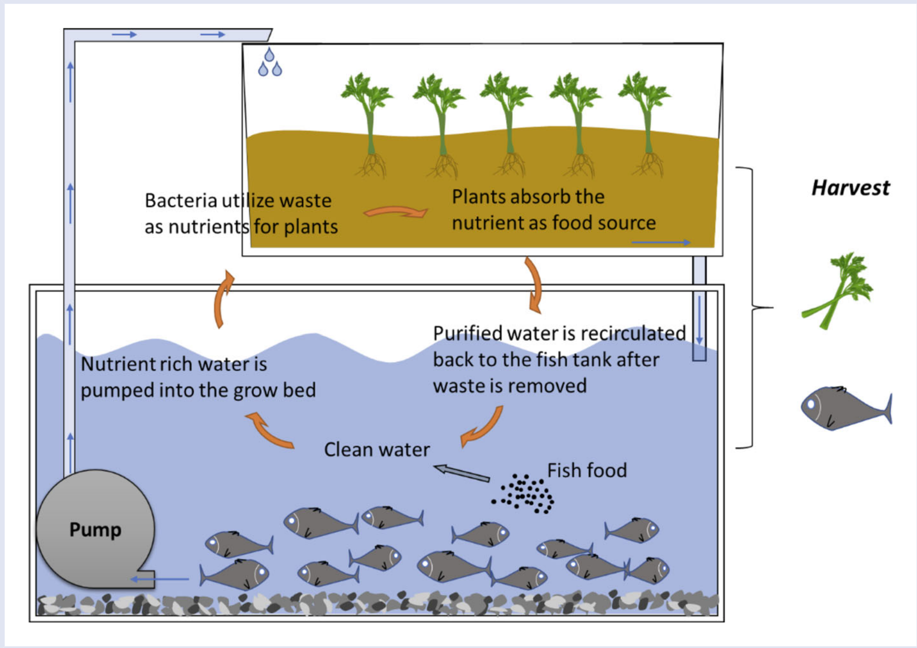

Figure 2. Simplified aquaponics system.

Finnveden et al. 2009). Typical life cycle stages include raw materials acquisition, manufacturing, use, and end of life. In the context of agriculture products, the growing cycle could be considered the manufacturing surrogate stage. In the context of aquaponics, few comprehensive LCAs exist, and those that do have focused mainly on tilapia and basil production (Junge et al. 2017). Boxman et al. (2017) evaluated tilapia and basil cultivated together at the commercial scale, with tilapia as the targeted end product, and found an environmental impact of 8.5 kg CO_2E per 1 kg of fish produced (2.1 kg CO_2E when construction and electricity impacts are excluded). Xie and Rosentrater (2015) found a range dependent on the size of the production facility of 3.3 to 18 kg CO_2E per kilogram of fish produced, with the larger scale facility having a smaller environmental impact per unit mass of produced fish. Cohen et al. (2018) also investigated large-scale lettuce and tilapia production, finding a reduction in environmental impacts across all of the impact categories of at least 40% compared to conventional aquaculture practices. Other studies have not performed full and comparable LCA studies; however, they have considered water and nutrient consumption, finding that aquaponics systems in general consumed less material-based inputs than conventional production systems (Love et al. 2015; Xie and Rosentrater 2015; Delaide et al. 2017; Forchino et al. 2017; Maucieri et al. 2018). Although energy consumption is considered the major contributor to the environmental impact throughout the aquaponics' life cycle, limited study makes it inconclusive when compared with conventional aquaculture or wild fisheries production systems. A selection of the current body of knowledge based on LCA studies is presented in Table 1, in order to show the large range of CO_2E values found. Bohnes and Laurent (2019) present a critical review of the LCA of aquaculture in general, and thus the present work will be limited to aquaponics.

The current body of literature for LCAs of aquaponic seafood production is somewhat limited. With respect to the species of seafood considered, in aquaponic studies tilapia, carp, and rainbow trout are the 3 most studied species (Hollmann 2013; Hindelang et al. 2014; Love et al. 2015; Xie and Rosentrater 2015; Boxman et al. 2017; Fang et al. 2017; Cohen et al. 2018; Maucieri et al. 2018; Silva et al. 2018). With respect to aquaponics, multiple products are generated, including both plants and seafood, and the allocation of the environmental impacts in literature is inconsistent. This ranges from allocating the total environmental impacts to fish (Boxman et al. 2017), vegetables (Forchino et al. 2017), combined mass produced (Hindelang et al. 2014), and time period of operation (Fang et al. 2017; Silva et al. 2018). These inconsistent allocation methods and functional units make it challenging to compare the relative environmental impacts of food produced in these systems. Leafy greens have been the predominantly studied product in aquaponic production (such as basil, lettuce, pak choi, and kale) (Hirschfeld et al. 2008; Xie and Rosentrater 2015; Delaide et al. 2016; Boxman et al. 2017; Fang et al. 2017; Forchino et al. 2017; Cohen et al. 2018; Maucieri et al. 2018; Silva et al. 2018), although more exotic crops such as tomatoes have also been studied (Hindelang et al. 2014; Love et al. 2015; Schmautz et al. 2017). This relatively few diversity of seafood and produce species studied limits the quantity and quality of insights that may be drawn.

Based on the published literature, general insights may be drawn as to the environmental impacts of aquaponic systems. Boxman et al. (2017) found fish food and electrcity consumption to be 2 of the major contributions to the environmental impact of their aquaponics system, across

Table 1. Summary of environmental impacts of aquaponic fish and produce production

Fish product	Impact (kg CO_2E/kg of fish)	Plant product	Impact (kg CO_2E/kg of vegetable production)	Bounds/Allocation	Study
Rainbow trout (*Oncorhynchus mykiss*)	—	Lettuce (*Lactuca sativa*)	—	1 kg lettuce	Forchino et al. 2017
Tilapia (Nile and red, live-weight)	10	Basil (wet weight)	3	1 ton live weight fish	Boxman et al. 2017
Tilapia (*Oreochromis niloticus*)	804	Basil (*Ocimum basilicum*)	1350	1 kg tilapia, 1 kg basil	Xie and Rosentrater 2015
Tilapia (*O. niloticus*)	405	Basil (*O. basilicum*)	671	1 kg tilapia, 1 kg basil	Xie and Rosentrater 2015
Tilapia (*O. niloticus*)	144	Basil (*O. basilicum*)	241	1 kg tilapia, 1 kg basil	Xie and Rosentrater 2015
Ornamental fish (*Carassius auratus* L.)	—	Lettuce, Rocket salad	480	1-y system operation	Maucieri et al. 2018
Tilapia	11	Lettuce	2	1 ton tilapia and 5 ton lettuce (combined mass)	Cohen et al. 2018
Nile tilapia	14	Varying (morning glory, kale, tomato, basil, etc.)	3	Fish, vegetable, sludge (combined mass)	Hindelang et al. 2014
Carp (common carp)	—	Lettuce (oak leaf and Batavia)	6	52 d of system operation and 1 kg of lettuce	Jaeger et al. 2018
Tilapia (*O. niloticus*)	—	Pak choi (*Brassica chinensis*)	—	32 d of system operation	Silva et al. 2018
Tilapia and hybrid striped bass	9	Varying lettuce	4	1 kg fish, 1 kg lettuce	Hollmann 2013

multiple impact categories. This finding is reinforced elsewhere in the current literature (Hollmann 2013; Hindelang et al. 2014; Forchino et al. 2017; Cohen et al. 2018; Mauceiri et al. 2018; Jaeger et al. 2019). Forchino et al. (2017) also included the enviornmental impact of the aquaponics infrastructure, which contributed significantly to the overall environmental impact. Regionality has the potential to influence electricity and heat usage, where in warmer climates less heat and electricity for supplemental lighting must be utilized compared to colder and darker locations. The relative contribution of aquafeed is also relevant to the environmental impacts, particularly because there is a current thrust to develop fish meal and oil-free aquafeed alternatives due to decreasing forage fish populations and increasing prices (Tacon and Metian 2008; Naylor et al. 2009; Froehlich et al. 2018). These feeds commonly utilize fish alternatives such as terrestrial animal by-products, plant-based proteins and lipids, seafood by-products, insects, and single-cell oils (Naylor et al. 2009; Oliva-Teles et al. 2015; Basto-Silva et al. 2019; Le Feon et al. 2019). Changes to and shifts in feed ingredients and electricity usage are 2 potential methods to reduce the environmental impacts of aquaponic food production.

The bounds and scope of the different studies vary considerably, along with the scale of the systems, including the allocation of capital equipment, postproduction processing, and transportation. This inconsistency makes it challenging to compare different studies in a rigorous manner. The size of the aquaponic product systems also varies greatly, from a research scale (Hindelang et al. 2014; Cohen et al. 2018) to a commercial scale (Boxman et al. 2017), which has the potential to greatly influence the environmental impacts. Despite the challenges of comparing different studies, Xie and Rosentrater (2015) have shown that economies of scale do occur in aquaponic systems, with reduced production costs and environmental impacts as the production volume increases.

The use of multiple impact categories to relate the environmental impacts to the systems and production volumes is critical to achieve a comprehensive assessment of systems' environmental impacts. A large percentage of currently published studies use greenhouse gas emissions (CO_2E) as the sole comparable environmental impact category considered, while also quantifying considerations such as energy and water consumption. Table 1 is presented in CO_2E for the sake of comparability. Although a portion of the literature includes other impact categories, such as acidification, eutrophication, and abiotic depletion (fossil fuels) (Hindelang et al. 2014; Cohen et al. 2018; Maucieri et al. 2018). Bohnes and Laurent (2019) reviewed LCAs of aquaculture studies and found that in 98% of the studies CO_2E was utilized as an impact category, whereas abiotic depletion was applied in only 22% of the studies published. Questions have also been raised as to whether the currently utilized suites of impact categories capture critical aspects of seafood production, such as resource depletion due to overfishing for forage fish (Froehlich et al. 2018). This suggests that a broader suite of impact categories must be considered going forward. Expanding the investigated environmental impacts associated with pollutant emissions (e.g., photochemical smog, carcinogenics, ecotoxicity) as well as the environmental impact associated with biotic resource use (e.g., marine seafood) is necessary to achieve a holistic assessment of aquaponics' environmental impacts.

TRANSPORTATION

In the United States, the local food movement has been gaining momentum over the last several years (Romero 2015; Erbentraut 2017; Marolf 2017). The goal of the movement is for food to be consumed in the same geographic area that it is produced, generally but not exclusively defined as within a 100-mile radius (Romero 2015). Although this has been found to be feasible in some areas, in general it is not feasible in large urban areas with dense populations, where the majority of population growth is expected to occur in the future (Cohen 2006; Montgomery 2008; McDonald et al., 2011; Sexton 2011; Romero 2015). From an overall environmental perspective, the relative contribution of transportation to the environmental impact of food is fairly small (about 15%) for most food groups (Weber and Matthews 2008; Wakeland et al. 2011). However, in particular instances when the food travels a significant distance, the environmental impact of transportation makes a significant contribution (Jones 2002; Plawecki et al. 2013; Grant and Hicks 2018). This is relevant because the distance that seafood travels to consumers has increased over time (Watson et al. 2015).

The relative contribution of transportation to the environmental impact of seafood has been studied in particular scenarios and case studies. Ziegler et al. (2012) analyzed aquaculture and wild caught fish production in Norway and found that for most scenarios, with the exception of air freight, the C footprint of transportation was not significant. They also suggested that food miles (how far food travels) is not a good metric for quantifying the sustainability of food production and travel. Ziegler (2007) in his LCA of capture fisheries found that, for caught seafood products, the majority of transportation environmental impacts were due to the actual fishing itself and the quantity of fuel utilized. Farmery et al. (2014) studied the life cycle environmental impacts of wild caught Tanzanian southern rock lobster and found that the international air freight of the live lobsters contributed significantly to both the global warming potential and total environmental impacts. Tlusty and Legueux (2009) made the point in their work that multiple modes are often used to distribute seafood, such as ships, trucks, and airplanes, which have different energy intensities. Seafood with a low environmental impact from production which travels a great distance, may ultimately be more environmentally costly than a seafood product which is intensive to produce, but only travels a short distance. This suggests that the transportation of seafood may be significant environmentally (utilizing the impact category of energy

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consumption), and that it has the potential to shift which products are favorable environmentally, based on geography and modes of transportation. It has also been suggested that the profit margins on aquaponically produced food will likely increase if the distribution chain is short (Goddek et al. 2015). These findings indicate that potentially locating aquaponic food production in urban areas, where there is a current lack of agriculture and food production, may reduce the environmental impact of the transportation of the food due to fewer modes utilized and shorter distances traveled. Consequently, leading to a lower food production overall environmental impacts.

ECONOMIC IMPLICATIONS

The economic implications of aquaponic food production systems are critical to consider when assessing the potential broad-scale use of these systems. Goddek et al. (2015) found a lack of comprehensive quantitative data to support the development of economically feasible aquaponics systems. An early study by Adler et al. (2000a) indicates that the integration of fish and plant production systems produces economic cost savings over either system alone. Although there has been tremendous interest in aquaponics production, there are only about 250 commercially viable operations in the United States that sell fish, plants, and/or aquaponics equipment and systems (Love et al. 2014). The majority of these operations in the United States are located in the southern, northeastern, and west coast areas of the country (Love et al. 2014). However, the majority of current literature focuses on the southern portions of the country and warm weather aquaponics.

The economic implications of aquaponic food production have historically been investigated more often than have the environmental impacts (Adler et al. 2000a, 2000b; Liu et al. 2016; Bosma et al. 2017; Asciuto et al. 2019). Adler et al. (2000a) valued the cost to produce rainbow trout at US $5.09/kg and lettuce at $0.58 per head. Accounting for inflation, in 2019 it would cost $7.43/kg of rainbow trout produced; at the 2018 European market price of rainbow trout ($5.75–$8.32/kg) this would be potentially be profitable (CoinNewsMediaGroup 2018; FAO 2018). Lui et al. (2016) determined the cost to produce Atlantic salmon at $5.60/kg, which is profitable at 2018 market prices. However, the majority of income for aquaponics producers is from the sale of vegetables because they mature more quickly and are brought to market at more frequent intervals than is the seafood. Accounting for inflation, it would cost $0.85 to produce each head of lettuce (Adler et al. 2000b). The Produce Price Index records both the price a farmer is paid and the retail price of selected commodities (Western Growers 2019). The average price paid to a farmer in 2018 for a head of iceberg lettuce was $0.60 (ranging from $0.31 to $1.29 per head of lettuce), which would not be profitable. In a study of commercial aquaponics producers in the United States, less than one-third of respondents indicated that their operations were profitable in the previous 12 mo. A second contributing factor may be the initial capital cost for the aquaponic production equipment. More work needs to be done to better understand the challenges experienced by aquaponic producers in striving for profitability.

In general, production scale, much like in conventional agriculture, influences the environmental and economic impacts of the production systems. Xie and Rosentrater (2015) compared 3 different scales of an aquaponics facility that produces both basil and tilapia (Figure 3a). They found a sharp decrease in the cost to produce the tilapia and basil as the size of the facility increased. This finding suggests that, from an economics perspective, large-scale

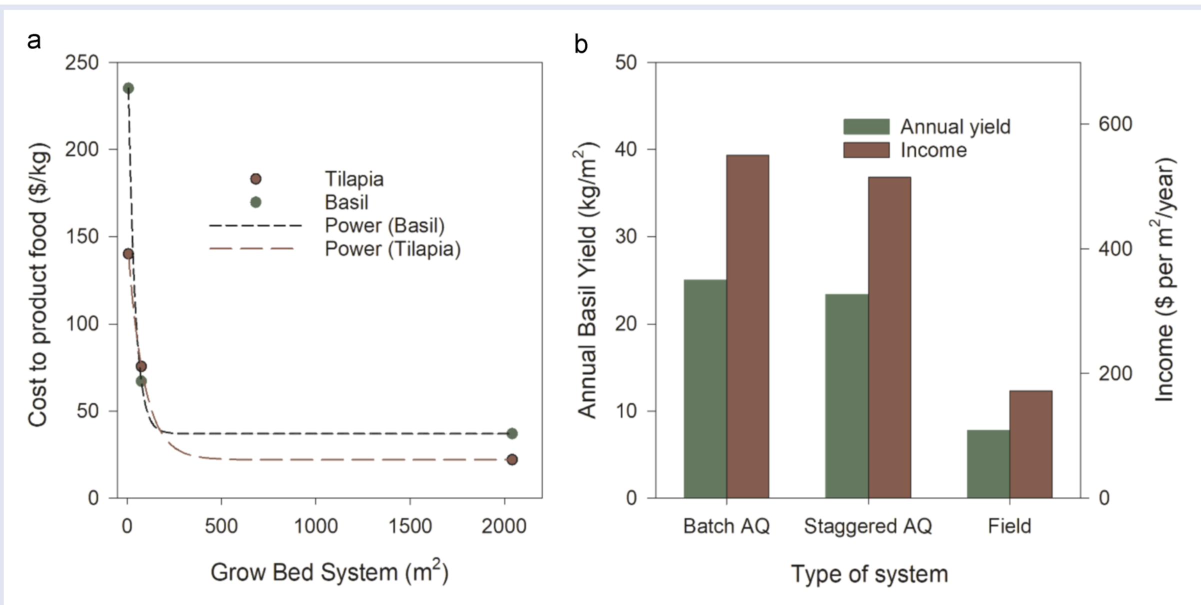

Figure 3. Cost to produce aquaponic tilapia and basil as a function of facility scale (using data from Xie and Rosentrater 2015) (a) and annual yield and income per unit produced by basil in 3 different cropping systems (adapted from Rakocy et al. 2003) (b). AQ = aquaponics.

aquaponics facilities will likely be more profitable than will small-scale versions. In addition, Rakocy et al. (2003) suggest that both batch and staggered aquaponics produce higher yield and generate more economic gains over field cropping systems for basil production (Figure 3b). They also recommend staggered aquaponics over batch aquaponics due to the more substantial fish output and the potential nutrient deficiency that occurs in crops grown in batch aquaponics systems.

HUMAN HEALTH IMPLICATIONS

Consumption of fish is considered to be part of a healthy diet (Willett et al. 1995; Kris-Etherton et al. 2002; Zampelas et al. 2005; Domingo et al. 2007). At the same time, there is a risk of consuming heavy metals (such as Hg) and other contaminants (such as PCBs and dioxins) when consuming fish, due to the bioaccumulation and biomagnification of these contaminants through the food chain (Egeland and Middaugh 1997; Foran et al. 2004; Hites et al. 2004). Similarly, vegetables provide key nutrients to humans (Slavin and Lloyd 2012; Di Noia 2014), but the current concern about vegetables as a pathway to spread pathogens and disease (Berger et al. 2010) could be amplified by closed-loop fish and plant production systems.

HEAVY METAL CONTAMINATION

Mercury is a relevant concern with respect to fish consumption, and a large body of literature weighs the human health benefits of fish consumption with the potential detriments of Hg consumption (Egeland and Middaugh 1997; Jardine 2003; Sakamoto et al. 2004; Arnold et al. 2005; Verbeke et al. 2005; Domingo et al. 2007; Castro-Gonzalez and Mendez-Armenta 2008; Burger and Gochfelf 2009; Ginsberg and Toal 2009; Gladyshev et al. 2009; Copat et al. 2013).

Salmon, in particular, has been well studied with respect to heavy metals and other contaminants in both a wild caught and an aquaculture setting, although not in an aquaponic setting specifically (Sunderland 2007). In general, no difference has been found in the Hg levels between farmed and wild salmon (Foran et al. 2004). However, differences have been found with respect to higher organic As concentrations in farmed salmon, and Co, Cu, and Cd at higher concentrations in wild salmon (Foran et al. 2004). These differences are thought to be largely a result of the salmon feed and the concentrations of the metals in the water that the salmon are raised in. At the same time, another study found that farmed salmon had higher concentrations of PCBs, dioxins, and dieldrin than did their wild counterparts (Hites et al. 2004). Salmon farmed in North America have been found to have much lower concentrations than those farmed in Europe, likely due to differences in the salmon feed. This suggests that, if the feed given to aquaponically raised salmon and the water conditions are carefully controlled, the quantity of Hg and other contaminants in the salmon could be reduced or eliminated.

Farmed fish in general have lower concentrations of Hg than do their wild caught counterparts, ranging from a factor of 2 to 12. Karimi et al. (2012) suggest that for farmed fish in general (including aquaculture and aquaponics) this is a much-understudied area, and more species-specific work must be done to generate a holistic view of the metals and other contamination in farmed fish. For most fish considered, including salmon, trout, and walleye, the relationship between the length of the fish and the quantity of metals and other contaminants (particularly Hg and PCBs) is significant and relevant, given that these compounds both bioaccumulate and biomagnify up the food chain (Jardine et al. 2009; Gewurtz et al. 2011). Work by Ward et al. (2010) found that when the fish are grown faster, the concentration of Hg is lower, compared to fish of a similar size. This has critical implications for farmed fish management, particularly with regard to increasing the growth rate of the fish, which again suggests that an aquaponic setting may allow for decreasing or eliminating the contaminants in farmed fish. The relative benefits and risks of seafood consumption are often discussed in the context of heavy metals exposure (Willett et al. 1995; Egeland and Middaugh 1997; Kris-Etherton et al. 2002; Jardine 2003; Sakamoto et al. 2004; Verbeke et al. 2005; Zampelas et al. 2005; Domingo et al. 2007; Castro-Gonzalez and Mendez-Armenta 2008; Burger and Gochfelf 2009; Ginsberg and Toal 2009; Gladyshev et al. 2009; Copat et al. 2013).

PESTS AND PATHOGENS

The spread of potentially harmful materials between species is a significant concern in a closed-loop system such as aquaponics (Sirakov et al. 2016). Microbial communities are essential in closed-loop aquaponic systems because they are responsible for transforming fish waste into nitrites and nitrates that can be utilized by plants (Goddek et al. 2015). As the produced N (in form of ammonia) should be transformed to the usable form (nitrate) for the plants, this is done by microbial communities within the recirculating setup. If not, the excess ammonia may harm vegetable production. However, concentrations of fish waste or microbial pathogens that are too high have the potential to reduce the yield of an aquaponics system, and environmental conditions (e.g., water pH) among fish, bacteria, and plant communities need to be carefully balanced and optimized. Moreover, even the potential presence of human pathogens in aquaponics-grown produce is a major concern for consumers.

There have been relatively few studies on the presence and potential spread of pests and pathogens in aquaponic systems. Pests and pathogens include plant pests (e.g., aphids, spider mites), microorganisms (e.g., bacteria, fungi), fish parasites (e.g., monogenea, cestoda), and viruses (Goddek et al. 2015). In Hawaii, microbial isolation was conducted across 11 different aquaponic farms to identify the presence of 2 bacteria related to pathogenicity in humans. Fox et al. (2012) found very low levels of generic *Escherichia coli* or undetectable *E. coli* O157:H7 and

Salmonella. However, this can analyze only a short range of microbial pathogens, and a deep microbial profile using modern metagenomic approaches is necessary. One study isolated 42 microorganisms that exerted inhibitory effects on plant and fish pathogens in an established aquaponic system and validated the implementation of biological control of pathogens in closed-loop aquaponic systems (Sirakov et al. 2016).

Research is therefore needed to better identify the microbial community composition within aquaponics systems; to determine the optimal growth conditions for plants, fish, and nitrifying bacteria; as well as to control for the potential impact of pathogens during each segment in the system (Goddek et al. 2015). The current options for pest and pathogen control in aquaponics are severely limited, given that control methods for treating plants (e.g., pesticides) are not always compatible with growing fish, and vice versa (e.g., antibiotics are not allowed in systems growing plants) (Chalmers 2004). Treatment with chlorine, ozone, organic acids, temperature, and UV radiation are common methods (CA Commission 2003; Suslow 2004; FAO 2010). However, the microbial and physiochemical quality of process water decreases rapidly due to the continuous recirculation of aquaponic systems. Elumalai et al. (2017) investigated the influence of UV treatment and found that it significantly controlled foodborne pathogens but not the aerobic plate counts and coliform counts, which suggests further improvements are possible when adapting traditional approaches. Good agricultural practices, in particular, related to human handling of fish and plants, may play a critical role in not introducing contaminants into aquatic systems in the first place (Barnhart et al. 2015).

CONCLUSIONS

The needed future research areas can be described in the context of environmental, economic, and health implications.

In order to feed a growing world population and to carefully assess whether aquaponics is the transformative technology that it is anticipated to be, multiple environmental impact (LCA) research gaps must be addressed. Although current sustainability-related data on aquaponic food production are promising, research needs still exist. In regard to the environment, the current environmental impact data are limited in comparability of systems with respect to the bounds, scope, climate, impact categories, functional units, and species of plants and animals considered. Economically, there is a lack of data from large-scale production systems and from the influence of transportation on the economic viability of these operations. Human health is a concern due to potential pathogen transmission and heavy metals contamination, although the relative isolation of these systems may prove them to be more resilient than current food production methods. In order to holistically evaluate the sustainability implications of aquaponic food production systems as a technology, more work must be done to close the current knowledge gaps.

Acknowledgment—The authors declare no conflict of interest with this work. The authors acknowledge that this work would not be possible without outside support. A Hicks and R Ghamkar would like to thank the Wisconsin SeaGrant program for support of this work. This work has not been formally reviewed by the Wisconsin SeaGrant program, and the views expressed in this work are those of the authors.

Data Availability Statement—This work used all publicly available data, which are available upon request from corresponding author Andrea L Hicks (hicks5@wisc.edu).

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