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Commercial aquaponics production and profitability: Findings from an international survey

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ABSTRACT

Aquaponics is the integration of aquaculture and hydroponics. There is expanding interest in aquaponics as a form of aquaculture that can be used to produce food closer to urban centers. Commercial aquaponics uses methods and equipment from both the hydroponics and aquaculture industries. There have been few studies of commercial-scale aquaponics production, and the purpose of this research was to document the production methods, crop and fish yields, and profitability of commercial aquaponics in the United States (US) and internationally. An online survey was used for data collection, and 257 respondents met the inclusion criteria for the study. Eighty-one percent of respondents lived in the US, and the remaining respondents were from 22 other countries. The median year that respondents had begun practicing aquaponics was 2010. A total of 538 full-time workers, 242 part-time workers, and 1720 unpaid workers or volunteers were employed at surveyed organizations. The most commonly raised aquatic animals by percent were tilapia (69%), ornamental fish (43%), catfish (25%), other aquatic animals (18%), perch (16%), bluegill (15%), trout (10%), and bass (7%). Production statistics, gross sales revenue, investments, and sales outlets for operations are reported and compared to other fields of aquaculture and agriculture. A multivariable logistic regression model was used to study which factors were associated with profitability (as a binary outcome) in the past 12 months. Several factors were significantly associated with profitability: aquaponics as the respondents' primary source of income ($p < 0.01$; Odds Ratio: 5.79; 95% Confidence Interval: 3.8–9.0), location in US Department of Agriculture plant hardiness zones 7–13 ($p < 0.01$; OR: 4.17; 95% CI: 3.2–5.5), gross sales revenue ≥$5000 ($p < 0.01$; OR: 3.58; 95% CI: 2.2–5.8), greater aquaponics knowledge ($p < 0.01$; OR: 2.37; 95% CI: 2.0–2.9), and sales of non-food products (e.g., supplies, materials, consulting services, workshops, and agrotourism) ($p = 0.028$; OR: 2.13; 95% CI: 1.1–4.2). Our survey findings provide a better understanding of the business of aquaponics, which may enhance future commercial operations.

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1. Introduction

Aquaponics is the integration of aquaculture and hydroponics, a soilless system for crop production. The recirculating aquaculture research community introduced the idea of aquaponics in the mid-1970s (Lewis et al., 1978; Naegel, 1977; Sneed et al., 1975). In their studies, edible plants were used to remove waste products from recirculating aquaculture systems. Today, commercial aquaponics production exists primarily in controlled environments, such as greenhouses or outdoor locations with favorable climates, using methods and equipment that draw from both the hydroponics and aquaculture industries.

A handful of studies have documented the productivity of research-scale aquaponics operations (Rakocy, 2012; Rakocy et al., 2006; Watten and Busch, 1984), and in 2013 the United States Department of Agriculture (USDA) began collecting aquaponics production data as part of the Census of Aquaculture, which was last published in 2006 (USDA, 2006). Results from research facilities and other factors, such as expanding interest in sustainable agriculture and producing food closer to urban centers, have stimulated interest and involvement from a small but growing aquaponics industry. However, little research has been conducted on commercial-scale aquaponics production. The purpose of

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this study was to document the production methods, crop and fish yields, and profitability of commercial aquaponics in the United States (US) and internationally.

2. Materials and methods

2.1. Survey

We created and implemented an online survey as previously described (Love et al., 2014). The study was reviewed by Johns Hopkins University School of Public Health Institutional Review Board (IRB No: 00005088).

We collected 1084 complete responses between June 25, 2013 and October 1, 2013. Summary findings from the total survey population (which mostly included hobbist gardeners, but also included educators, non-profit organization staff and commercial operators) were published elsewhere (Love et al., 2014). Survey respondents who sold aquaponics-related food or non-food products and services in the previous 12 months were administered additional survey questions; the data collected during this sub-survey are reported here.

2.2. Data analysis

Data from the survey software (Qualtrics, Provo, UT, USA) were exported and analyzed in Excel (Microsoft, Redmond, WA, USA), STATA (StataCorp, College Station, TX, USA) and Prism (v5, GraphPad, La Jolla, CA, USA). T-tests were used to compare the means of two groups by factors such as farm size and aquaculture system volume. A Kruskal–Wallis test was used to compare groups of three or more when the data was not normally distributed, and a Dunn multiple comparison post-test was used for intergroup comparisons.

In addition, a multivariable logistic regression model was used to identify factors that were associated with profitability, using profitability in the past 12 months as the binary outcome. These regression models controlled for potential within-cluster correlation by estimating robust standard errors that clustered respondents by country groups. These groups were defined as follows: 1) US and Canada, 2) Latin America (including Mexico) and the Caribbean, 3) Asia, 4) Australia and New Zealand, 5) Europe, and 6) Africa.

3. Results and discussion

3.1. Survey responses and frame

Two hundred and fifty-seven respondents met the inclusion criteria for the study. Ninety-five respondents sold only aquaponics-grown fish or plants, 69 respondents sold only aquaponics-related materials or services, and 93 respondents sold both aquaponics-grown fish or plants and aquaponics-related materials or services. A total of 188 respondents sold aquaponics-grown fish or plants, which we refer to as “commercial producers.” A total of 162 respondents sold aquaponics-related materials or services, which could include the sale of supplies and equipment, consulting fees for design or construction of aquaponics facilities, and fees associated with workshops, classes, public speaking, or agro-tourism.

3.2. Demographics

Demographics from respondents are presented in Table 1. Respondents ranged in age from 18 to 72 years of age, and the mean age was 47 ± 13 years old. Most respondents were male (77%). Most survey participants (93%) had more than a high school level of education, and over a quarter of respondents (27%) had a graduate degree. The median year that respondents had begun practicing aquaponics was 2010. Less than 10% of respondents had practiced aquaponics for 10 or more years. These findings indicate that commercial aquaponics is a growing field, yet there may be a collective lack of experience among producers.

The majority of respondents (81%; n = 198) lived in the US, which was expected since the survey was in English and originated from

Table 1
Demographics of survey respondents engaged commerce.

Demographics	Number of respondents (%)			
	Total	Sold both	Sold fish or plants only	Sold materials or services only
Overall	257	93	95	69
Gender				
Male	199 (77)	75 (81)	68 (72)	56 (81)
Female	50 (19)	16 (17)	24 (25)	10 (15)
Not specified	8 (3)	2 (2)	3 (3)	3 (4)
Age, yr				
18–29	36 (14)	21 (23)	7 (7)	8 (12)
30–39	39 (15)	16 (17)	12 (13)	11 (16)
40–49	54 (21)	17 (18)	20 (21)	17 (25)
50–59	81 (32)	26 (28)	34 (36)	21 (30)
60–69	36 (14)	8 (9)	18 (19)	10 (15)
70+	11 (4)	5 (5)	4 (4)	2 (3)
Education				
Graduate degree	67 (27)	22 (24)	31 (33)	14 (21)
College degree or college classes	168 (66)	64 (70)	55 (59)	49 (72)
High school, GED, or some high school	18 (7)	6 (6)	7 (8)	5 (7)
Country				
United States	196 (81)	73 (82)	72 (82)	51 (77)
Role in organization				
Owner or operator	92 (33)	41 (44)	31 (33)	20 (29)
CEO	18 (7)	6 (7)	7 (7)	5 (7)
Executive director	15 (5)	7 (8)	5 (5)	3 (4)
School official	5 (2)	3 (3)	2 (2)	–
Farm manager	38 (14)	19 (20)	18 (19)	1 (2)
Educator	40 (14)	18 (19)	15 (16)	7 (10)
Employee	18 (7)	6 (7)	9 (10)	3 (4)
Consultant	28 (10)	15 (16)	8 (8)	5 (7)
Volunteer	11 (4)	2 (2)	8 (8)	1 (2)
Other	12 (4)	3 (3)	5 (5)	4 (6)

the US. A handful of respondents lived in Australia (5%; n = 12), Canada (4%; n = 10), the United Kingdom (1%; n = 3), and the Philippines (1%; n = 2). A single response was recorded from 18 other countries (Belize, Brazil, China, Ghana, Hungary, India, Israel, Italy, Japan, Malaysia, Malta, Mauritius, Oman, Portugal, South Africa, Trinidad, Turks and Caicos, and Uganda).

Roughly half (49%) of respondents had a leadership role in their operation (e.g., owner, operator, CEO, or executive director), and the remainder had other roles in their organization such as farm manager, educator, consultant, or employee. We requested one response per organization to avoid duplication.

3.3. Operation location

Fish and plants have different environmental tolerances and many respondents (46%) used multiple settings for production (Table 2). Greenhouses were the most popular facility for housing aquaponics systems. Forty-one percent of respondents used a greenhouse in combination with another location to grow plants and raise fish. Thirty-one percent of respondents used only a greenhouse (31%), and 4% practiced rooftop farming. These finding are consistent with aquaponics producers that adopt principles of controlled environment agriculture, where greenhouses have long been popular places for crop production (Dalrymple, 1973).

Seventy-four percent of commercial producers owned the property where their aquaponics system was located. Aquaponics systems were located at personal residences for 39% of commercial producers.

3.4. Aquaponics design

Aquaponics systems were primarily designed by the respondent. Seventy-one percent of commercial producers designed their aquaponics system themselves, and the remaining 29% either hired a consultant and/or purchased a kit. In the future, as commercial systems become larger and more complex, we anticipate that engineers and other consultants will play a larger role in system design.

Commercial producers used a variety of methods for plant production within aquaponics (Table 3). Briefly, rafts refer to polystyrene or other materials used for buoyancy to float crops in tanks of water roughly 0.2 to 0.4 m deep. Crops are then planted inside net-pots, which are inserted into holes in the floating rafts. Media beds contain soilless media, such as expanded shale or clay pebbles, and are used to grow crops with a flood-and-drain irrigation method. Wicking beds are similar to media beds, however, wicking beds are filled with an absorptive growing media such as coconut coir. In the nutrient thin film technique (NFT), a fine mist of water is sprayed or dripped onto plant roots in a horizontal gutter or tray design. Vertical towers are similar to NFT, except crops are instead grown in a vertical tray or tube. Dutch buckets are irrigated container planters filled with soilless media. More than two-thirds of respondents (69%) used a combination of two or more methods, and over a third of respondents (34%) used a combination of three or more methods. The most common approach was to use both rafts and media beds together, which was used by about a quarter (26%) of the commercial producers. Among commercial producers, the rank order from most-to-least-used methods was: floating rafts (77%), media beds (76%), nutrient film technique (NFT) (29%), vertical towers (29%), wicking beds (6%), and Dutch buckets (5%). Crop production methods most commonly used by respondents were different than methods used in conventional hydroponics (Jones, 2005; Tyson et al., 2009).

At their facilities, 43% of commercial producers used supplemental lighting for crop production. Some facilities (45%) raised or bred their own fish in a nursery or hatchery. Cooling produce is important for crop preservation to reduce spoilage and prevent wilting (Prusky, 2011), and half of commercial producers did not have on-site cold storage for produce. A recent survey of small and medium size agricultural farms in the US found that 18% of respondents did not cool produce (Harrison et al., 2013), which is a lower rate than found in our survey.

We asked several questions regarding food safety. Eleven percent of aquaponics facilities did not have on-site bathrooms. These findings are much lower than a survey of small and medium size agricultural farms, which found that 33% of respondents lacked onsite bathrooms and hand-washing facilities (Harrison et al., 2013). Among commercial aquaponics producers, 38% lacked a food safety plan, which may indicate an educational need as some producers may lack knowledge regarding best practices to reduce the chance of spreading foodborne diseases.

3.5. Aquaponics size

In our survey, commercial producers had significantly larger operations by system volume ($p < 0.0001$) and facility size ($p < 0.0001$) than respondents who only sold materials or services. The total size of all commercial producers was 8.6 ha (21.1 acres) with a total system volume of 9.8 million L (2.6 million US gallons) of water. One hundred forty-five of the 188 commercial producers lived in the US. These US commercial producers used a total of 7.8 ha (19.3 acres) of land and their aquaponics systems contained 9.6 million L (2.5 million US gallons) of water. The average commercial production site in the US was 0.01 ha (0.03 acres) in size and 10,300 L (2700 US gallons) in volume. By comparison, hydroponic production in Florida, US in 2004 was 29.8 ha (74 acres) (Tyson et al., 2009), which is significantly larger than the total size of operations from respondents in this survey. Appendix A presents graphs of the respondents' facility footprint ($\log_{10}$ m^2) plotted against system volume ($\log_{10}$ L) to show relative relationships between the size and volume of respondents' operations.

Table 2
Location of commercial aquaponics systems.

Location(s)	Percent of respondents (n = 183) [b]
Greenhouse[a]	31
Outdoors	15
Greenhouse, inside a building	13
Greenhouse, outdoors	13
Greenhouse, outdoors, inside a building	9
Inside a building	7
Outdoors, inside a building	4
Greenhouse, outdoors, rooftop, inside a building	2
Greenhouse, rooftop, inside a building	2
Greenhouse, rooftop	1
Outdoors, rooftop	1

[a] Greenhouse also includes high tunnel and hoophouse.
[b] Data were from respondents who sold aquaponically-raised plants or fish.

Table 3
Methods for hydroponic plant production.

Hydroponic method(s)	Percent of respondents (n = 186)[c]
Raft, media bed	26
Raft	14
Media bed	13
Raft, media bed, NFT[a]	10
Raft, media bed, NFT, vertical tower	9
Raft, media bed, vertical tower	8
Raft, NFT	3
Media bed, vertical tower	3
Vertical tower	3
Raft, media bed, NFT, vertical tower, wicking bed	2
Other combinations of methods[b]	10

[a] NFT = nutrient film technique; a fine mist of water is sprayed or dripped onto plant roots in a horizontal gutter or tray design. Similar to vertical towers except horizontal.
[b] Thirteen other combinations of plant production methods were each performed by two or fewer respondents.
[c] Data from respondents who sold aquaponically-raised plants or fish.

Table 4
Number of full-time, part-time, and unpaid workers at commercial aquaponics organizations.

Group	N	Full-time workers[a]		Part-time workers[b]		Unpaid workers, family members, or volunteers	
		Mean (±st dev)	Total	Mean (±st dev)	Total	Mean (±st dev)	Total
Sold only plants or fish	92	1.4 (±4)	128	0.4 (±1)	41	5.0 (±24)	460
Sold only materials or services	87	0.9 (±3)	78	0.4 (±1)	32	2.0 (±8)	175
Sold both	93	3.6 (±10)	332	1.8 (±3)	169	11.7 (±56)	1085
All groups	272	2.0 (±6)	538	0.9 (±2)	242	6.0 (±36)	1720

[a] ≥150 days/yr.
[b] <150 days/yr.

Our findings can be compared to the 2005 USDA Census of Aquaculture, and in particular the recirculating aquaculture portion. In 2005, the average system volume for recirculating aquaculture operations was nearly identical to the average volume of commercial aquaponics producers in our survey (10,209 L vs 10,300 L) (USDA, 2006). The USDA census identified 415 recirculating aquaculture operations in 45 states, and in the present survey we collected data from 145 commercial producers in 38 states. Aquaponics can be practiced using recirculating aquaculture methods, however, there appears to be very little overlap among the sample population of our survey and the USDA Census of Aquaculture because only 13% of US commercial producers in our survey were practicing aquaponics on or before 2005. Additional comparisons can be made to the recently published 2013 USDA Census of Aquaculture, which identified 71 commercial aquaponics operations. Appendix B presents a comparison of US commercial aquaponics operations by state in the present study and in the 2013 Census of Aquaculture.

3.6. Employment

In the previous 12 months, a total of 538 full-time workers and 242 part-time workers were employed by the operations responding to the survey (Table 4). The average facility employed one or two full-time workers and one part-time worker. Operations that only sold materials or services had fewer employees than operations that sold both material or service and fish or plants ($p < 0.0001$). Similarly, operations that only sold fish or plants had fewer employees than operations that sold both material or service and fish or plants ($p < 0.0001$). A large number of unpaid workers, family members, and volunteers ($n = 1720$) were working at operations with an average of 6 unpaid workers per facility. Operations that sold plants or fish and materials or services used a similar number of unpaid workers as operations that sold only plants or fish ($p > 0.05$). Operations that only sold materials or services relied on significantly fewer unpaid workers compared to the other two types of operations ($p < 0.001$ for each).

Among all aquaculture operations responding to the US Census of Aquaculture, operators employed 5600 full-time workers at 1105 farms, 4800 part-time workers at 1789 farms, and 3600 unpaid workers at 1935 farms (USDA, 2006). It appears that aquaponics operations in this survey employ fewer staff, on average, than other types of aquaculture operations. This could be due to the smaller average size of aquaponics operations compared to other aquaculture operations.

3.7. Production

The average respondent raised two species of aquatic animals, and 30% of respondents raised three or more species of aquatic animals. The most commonly raised aquatic animals by percent were tilapia (*Tilapia* spp., 69% of respondents), ornamental fish (43%), catfish (order Siluriformes, 25%), other aquatic animals (18%), perch (*Perca* spp., 16%), bluegill (*Lepomis macrochirus*, 15%), trout (*Oncorhynchus* spp., *Salmo* spp., *Salvenlius* spp., 10%), and bass (*Micropterus* spp., *Morone* spp., 7%). The "other" category included animals such as shrimp and prawns (suborder Dendrobranchiata), crayfish (*Astacoidea* and *Parastacoidea* Families), minnows, carp (*Cyprinidae* Family), pacu (*Colossoma* spp., *Piaractus* spp., etc.), barramundi (*Lates calcarifer*), pangasius (*Pangasius* spp.), and other fish. Ornamental fish were twice as likely to be raised by respondents who were engaged in the sale of aquaponics materials and services compared to respondents who only sold aquaponics plants or fish.

Commercial producers reported fish and plant harvests from the previous 12 months (Table 5). The median quantity of fish harvested by respondents was 23 to 45 kg/yr (50 to 99 lb/yr). Nearly a quarter (24%) of respondents did not harvest any fish in the previous 12 months, presumably because these were new operations. Based on the median of the range of production values reported by each respondent, we estimate 86,000 kg (190,000 lb) of fish were harvested by respondents in the previous 12 months. To compare the scale of commercial aquaponics to other industries, the farmed tilapia industry in the US harvested 10 million kg (22 million lb) of fish in 2011, the latest year with available data (NMFS, 2013).

The most frequently raised plants among commercial producers were as follows: basil (*Ocimum basilicum*, 81% of respondents), salad greens (76%), non-basil herbs (73%), tomatoes (*Solanum lycopersicum*, 68%), head lettuce (*Lactuca sativa*, 68%), kale (*Brassica oleracea*, 56%), chard (*Beta vulgaris* subspecies *cicla*, 55%), bok choi (*Brassica rapa* subspecies *chinensis*, 51%), peppers (*Capsicum annuum*, 48%), and cucumbers (*Cucumis sativus*, 45%). The median quantity of plants harvested by respondents was 45 to 226 kg/yr (100 to 499 lb/yr). Ten percent of respondents harvested >4536 kg/yr (>10,000 lb/yr) and two respondents harvested >45,359 kg/yr (>100,000 lb/yr). Based on the median of the range of production values reported by each respondent, we estimate that 452,000 kg (997,000 lb) of plants was harvested by respondents in the previous 12 months. By pairing plant and fish harvests by respondent, we observed that production was skewed towards plants (Appendix C). There appears to be an economic and a biological basis for the focus on plant production. Crops, such as herbs and salad greens have a higher farm gate price than fish, such as tilapia. Crops can reach harvestable size sooner than fish, allowing for multiple plantings in the same year. In addition, the biomass conversion ratio for crops is better than fish; as much as 9 kg of lettuce can be grown using fish manure

Table 5
Weight of commercial fish and plant harvests in the previous 12 months.

Amount (kg)[a]	Percent of respondents[c]	
	Fish harvest ($n = 185$)	Plant harvest ($n = 184$)
0	24	2
0.45–22	19	14
23–45	12	15
46–226	15	21
227–453	14	16
453–2268	8	18
2269–4536	2	4
4537–22,679	5[b]	7
22,680–45,359	–	2
>45,360	–	2

[a] Originally in the survey categories were reported in units of pounds, and were later converted into kilograms.
[b] These fish harvests were reported in the survey as >4537 kg.
[c] Data from respondents who sold aquaponically-raised plants or fish.

from 1 kg of fish feed (personal communication, Ryan Chatterson, Chatterson Farms, Florida), while feed conversation ratios for fish are closer to 1:1.

3.8. Sales outlets

Commercial producers sold plants and fish through a variety of direct and indirect markets. Direct markets include famers markets, farm stands, and community supported agriculture (CSA); indirect markets include grocery stores, restaurants, institutions, and wholesalers. The rank order of outlets for plants and fish raised in aquaponics systems is presented in Fig. 1. Commercial producers who also sold materials or services used more sales outlets for their crops (mean = 3 outlets) compared to commercial producers that did not sell materials and services (mean = 2 outlets), which suggests that respondents with diversified business models may be more willing to try new markets. Commercial producers who sold plants to indirect markets had significantly larger operations than producers that only sold plants to direct markets ($p = 0.002$). The same relationship between sale of fish to indirect versus direct markets and average farm size was not observed ($p = 0.7$).

Almost half of commercial aquaponics producers (47%) sold other agricultural products in addition to aquaponics crops, although the survey did not ask what products were sold or where they were marketed.

Results of the survey were compared to findings from a USDA Economic Research Service (ERS) report examining typical local food sales outlets for farms in the US (Low and Vogel, 2011) (Table 6). The average commercial aquaponics producer sold products at more sales outlets than other farms in the ERS report. The percentage of commercial aquaponics producers that sold their products at their own farm or facility was significantly higher than comparable-sized farms' direct sales on the farm premises. A larger proportion of commercial aquaponics producers also sold products at farmers markets, which are niche markets where producers can find higher prices and gain valuable exposure to new customers. This information could indicate location as an important driver for commercial aquaponics profitability, as sales could be correlated with the accessibility of the farm/facility to customers.

3.9. Income and profitability

We asked a series of questions about respondents' income and profitability in the previous 12 months (Fig. 2). Aquaponics was the primary source of income for 30% of respondents. These numbers are comparable with small-scale farmers; in 2012, about 37% of operators on farms generating less than \$50,000 in gross revenue indicated that farming was their primary occupation (USDA, 2012). Commercial producers who also sold aquaponics materials and services were more likely than other groups to have an aquaponics-related job as their primary source of income (Fig. 2A).

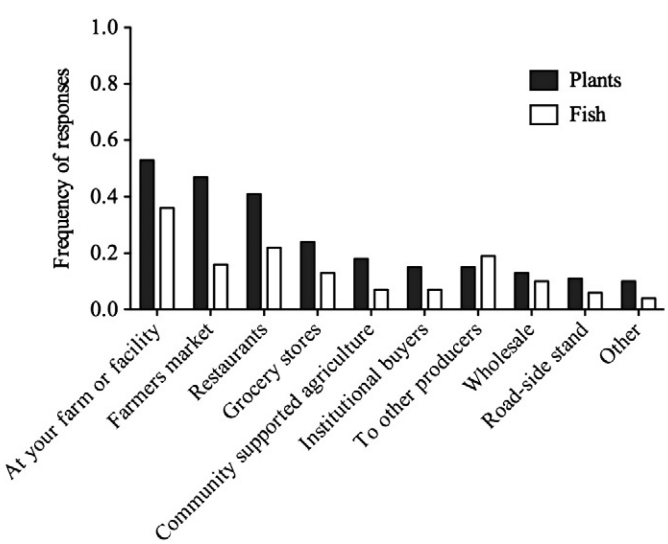

Fig. 1. Markets for plants and fish raised in commercial aquaponics systems used by respondents (n = 188).

Thirty-one percent of respondents reported that their operation was profitable in the previous 12 months (Fig. 2B). Over half (55%) predicted profitability in the next 12 months and nearly three-quarters of respondents predicted that they would be profitable in 36 months. Commercial producers who also sold aquaponics materials and services were the most profitable group (Fig. 2B). Producers who only sold crops were more optimistic about future profitability than other groups (Fig. 2D).

3.10. Gross sales revenue

Respondents reported their aquaponics-related gross sales revenue in the previous 12 months (Fig. 3). The median respondent received \$1000 to \$4999 (US dollars) in the previous 12 months (Fig. 3A), with 10% of respondents receiving >\$50,000. Commercial producers with diversified revenue streams had larger gross sales revenue than respondents that only sold plants and fish or respondents that only sold materials and services (Fig. 3B). The point at which most respondents typically reported profitability was >\$50,000 per year in gross sales revenue (Fig. 3C).

Similarities exist between commercial aquaponics producers and general farms. Based on data from the 2006 USDA Agricultural Resource Management Survey, farms with gross revenue of less than \$50,000 made up approximately 75% of all farms in the US (USDA, 2009), and in 2008 farms with less than \$50,000 in gross revenue typically sold around \$7800 in local food sales (Low and Vogel, 2011). In both cases, it is clear that a majority of farmers and aquaponics producers tend to operate on a smaller scale. Reasons for this could include limited funding for capital investments, location/space limitations, a lack of desire to expand, or few lucrative sales outlets. Sales revenue in this study were similar to aquaponics organizations responding to the USDA 2013 Census of Aquaculture for (Appendix D).

3.11. Investments

Respondents reported aquaponics-related investments in the previous 12 months (Fig. 4). The median respondent invested \$5000 to \$9999 in the previous 12 months (Fig. 4A). Operators who only sold crops or only sold materials and services tended to invest less money than respondents who sold both types of products (Fig. 4B). There was no association between the amount of money invested in the previous 12 months and self-reported profitability in the same time period (Fig. 4C).

3.12. Modeling factors related to profitability

After examining the univariate association between profitability in the previous 12 months and many factors related to aquaponics farming, we identified several key variables related to profitability. We modeled the outcome of profitability using these variables in multivariable logistic regression models. The final model we selected included type of sales, knowledge, primary source of income, sales revenue, and USDA climate zone (Table 7). The model is adjusted for the respondents' country groups, and can be expressed as:

$$\text{logit}(\pi) = \text{type of sales} + \text{knowledge} + \text{primary source of income} + \text{sales revenue} + \text{USDA climate zone}.$$

Each variable is described below.

3.12.1. Type of sales

The sales of products were separated into three categories: 1) only sold aquaponics-grown fish or plants; 2) only sold aquaponics-related

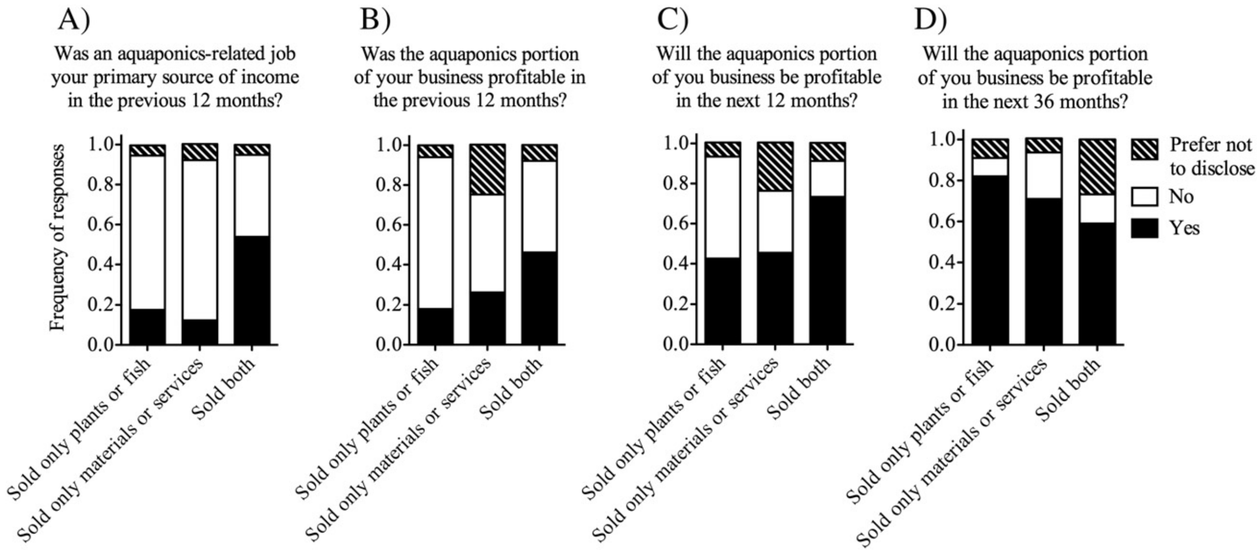

Fig. 2. Respondents views on A) aquaponics-related income, B) profit in the previous 12 months, and projections for C) profit the next 12 months and D) 36 months.

materials and services and 3) sold both aquaponics-raised fish and plants and aquaponics-related materials and services. The model results indicate that people who sold only materials and services were twice as likely to be profitable as people who sold only plants and fish.

3.12.2. Knowledge

Seven survey questions were asked to assess respondents' knowledge and their ability to manage an aquaponics operation. The answers to these questions were used to separate respondents into two groups

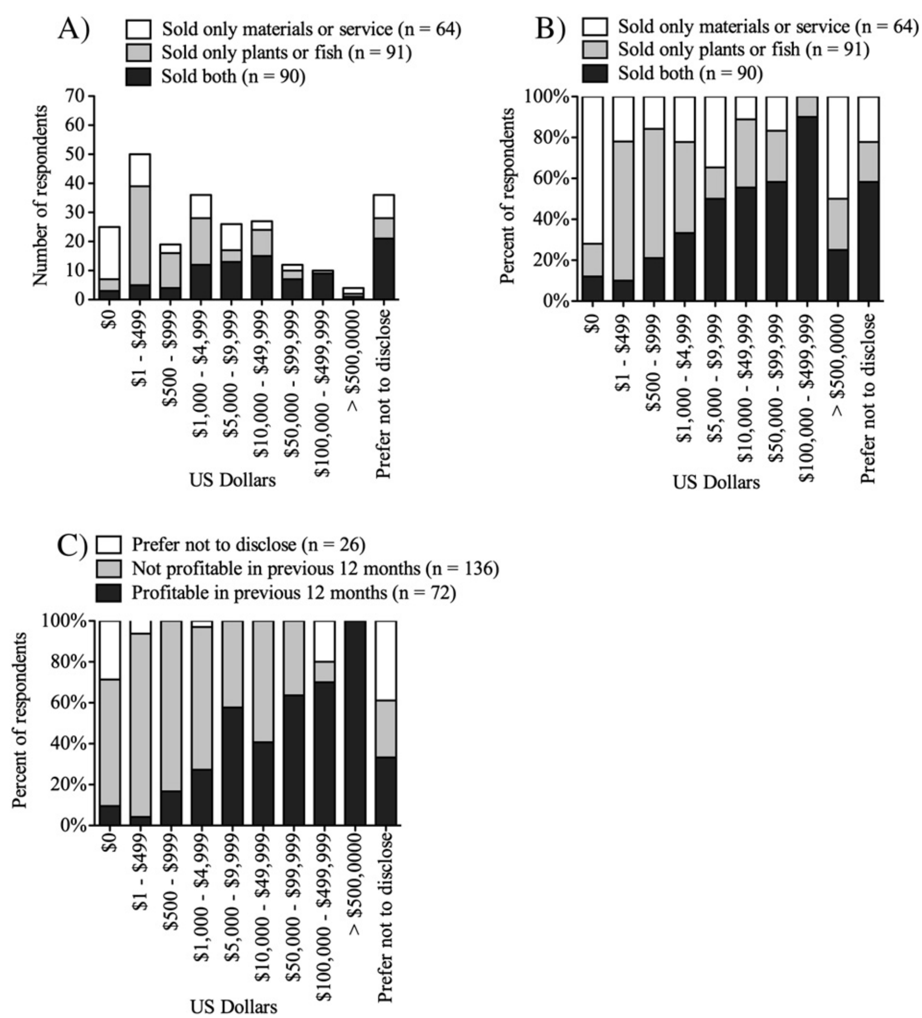

Fig. 3. Gross sales revenue in the previous 12 months by A) the number of respondents among three groups, and B) the relative response rates among three groups. Gross sales revenue was compared to C) respondent self-reported profitability in the previous 12 months.

Table 6
Sales outlets used by commercial aquaponic producers versus farms surveyed by USDA (% of farms/facilities).[a]

Sales	Commercial aquaponics producers	USDA farm survey[b, c]			
		Small	Medium	Large	All
Average number of sales outlets per farm/producer	3.0	1.4	1.7	2.1	1.5
Direct sales (%)	83.0	78	70.7	55.5	75.3
At their farm/facility	62.2	8.3	17.4	15.7	10.4
Farmers markets	52.1	34.6	25.9	14.7	31.8
Road-side stands	17.6	34.1	24.9	23	31.8
CSA[d]	22.3	1.1	2.5	1.4	1.3
Indirect sales outlets (%)	59.0	22	29.3	45	24.7
Grocery stores and restaurants	53.2	17.2	26	23.7	19.2

[a] Some overlap may be present as farms participating in the US Department of Agriculture (USDA) ARMS survey may also be aquaponic producers.
[b] Low and Vogel (2011).
[c] Small farms are defined as having sales of less than $50,000; medium farms with sales between $50,000 to $249,999, and large farms have sales of $250,000 or more.
[d] CSA = community supported agriculture.

Table 7
Logistic regression of profitability in previous 12 months, based on respondents' primary source of income, USDA climate zone, sales revenue, knowledge, and type of sales (n = 154).

Profitability in previous 12 months	Odds Ratio	p value	95% Confidence Interval
Primary income[a]	5.79	<0.01	3.8–9.0
USDA climate zone[b]	4.17	<0.01	3.2–5.5
Sale revenue[c]	3.58	<0.01	2.2–5.8
Knowledge[d]	2.37	<0.01	2.0–2.9
Sales type[e]			
Only sold materials/services	2.13	0.028	1.1–4.2
Sold plants/fish and materials/services	1.33	0.294	0.8–2.3

[a] A binary variable to compare respondents with or without an aquaponics-related job as their primary source of income in the previous 12 months.
[b] A binary variable to compare farms in USDA plant hardiness zones 1–6 compared to zones 7–13, adjusted for correlation within continents.
[c] A binary variable to compare respondent gross sales revenues ≥$5000 versus <$5000 US in the previous 12 months.
[d] A binary variable to compare a high knowledge score versus low knowledge score, based on seven aquaponics knowledge-related questions.
[e] The reference level for Sales type was "only sold plants and fish."

(e.g., a binary variable): "more knowledgeable" and "less knowledgeable." Aquaponics, like many fields of aquaculture, is a knowledge intensive topic, and more knowledgeable respondents were over twice as likely to be profitable than respondents who rated themselves as less knowledgeable.

3.12.3. Primary source of income

A binary variable was constructed to differentiate between respondents with and without an aquaponics-related job as their primary source of income in the previous 12 months. Statistical results suggest

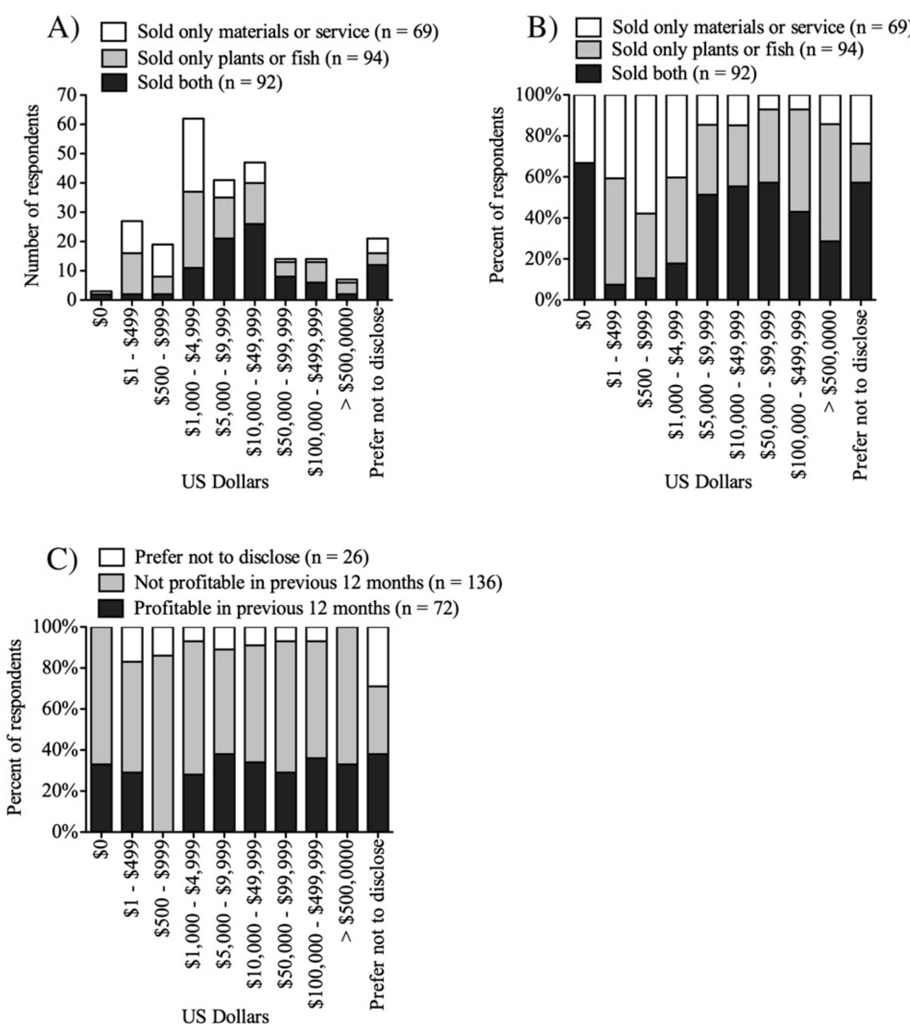

Fig. 4. Investments in the previous 12 months by A) the number of respondents among three groups, and B) the relative response rates among three groups. Investments were compared to C) respondent self-reported profitability in the previous 12 months.

that people whose aquaponics-related job was their primary source of income were over five times more likely to make a profit than people who indicated that aquaponics was not their primary source of personal income.

3.12.4. Sales revenue

We created a binary variable based on whether or not the gross sales revenue over the previous 12 months was equal to or larger than \$5000. This break point for sales revenue was chosen because the median gross sales revenue falls in the \$1000–\$4999 range. Respondents were over three times more likely to be profitable if their gross sales revenues were ≥\$5000 compared to gross sales revenues <\$5000.

3.12.5. USDA climate zone

This is a binary variable based on the US Department of Agriculture plant hardiness zones, a measure based on the average annual minimum winter temperature. US Department of Agriculture (USDA) plant hardiness zones were used to dichotomize climate zones. USDA plant hardiness zones 1–6 with an average annual extreme minimum winter temperature below 0 °F were compared to zones 7–13 with average annual extreme minimum temperatures equal to or above 0 °F. Plant hardiness zones in other countries were converted into the USDA plant hardiness zone scale. Based on the logistic regression analysis, respondents farming in areas with mild winter temperatures (USDA zones 7–13) were approximately four times as likely to be profitable in the past 12 months. Heating costs and a shorter growing season may be reasons that respondents in colder climates were less likely to be profitable than respondents in warmer climates.

4. Conclusion

There is growing interest in locally produced food that is sold directly to consumers, and aquaponics is a growing form of aquaculture that easily fits into a local and regional food system model in part because it can be practiced in or near large population centers. Many operations in the survey resembled small farms in their size and gross sales revenue, and they utilized more direct sales outlets to sell their products than a typical small farm. We found that gross sales revenue and profitability were higher for operations that diversify their revenue stream by selling non-food products, services, or educational trainings. In addition, less than one-third of respondents were profitable in the previous year, and while many of these are new businesses that expect to be profitable in the short term, future studies are needed to track their outcomes. Our findings indicate that more research and development are needed to determine if aquaponics will evolve into a profitable food production method.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.aquaculture.2014.09.023.

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