

Energy and water use of a small-scale raft aquaponics system in Baltimore, Maryland, United States

David C. Love^{a,b,*}, Michael S. Uhl^c, Laura Genello^{a,b}^a Johns Hopkins Center for a Livable Future, Johns Hopkins University, Baltimore, MD, USA^b Department of Environmental Health Sciences, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD, USA^c Department of Geography and Environmental Engineering, Johns Hopkins University, Baltimore, MD, USA

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ABSTRACT

Aquaponics is a form of aquaculture that integrates hydroponics to raise edible plants and fish. There is growing interest in aquaponics because it can be practiced in non-traditional locations for agriculture such as inside warehouses and on marginal lands, and it can provide locally grown products without using synthetic pesticides, chemical fertilizers, or antibiotics. Yet questions remain about the ecological and economic sustainability of aquaponics. The objective of this study was to describe the operating conditions, inputs (energy, water, and fish feed) and outputs (edible crops and fish) and their relationship over two years for a small-scale raft aquaponics operation in Baltimore, Maryland, United States. The system had roughly 1% water loss per day and used an average of 35,950 L for replenishment per year. Predicted values suggest rainfall could completely replace the existing water needs. The average energy use was 19,526 kWh for propane and electricity per year at a cost of \$2055 US dollars. The largest uses of electricity were in-tank water heaters. Comparing inputs to outputs, 104 L of water, 0.5 kg feed, and 56 kWh energy (\$6 in energy costs) were needed to produce 1 kg of crops; and 292 L of water, 1.3 kg feed, and 159 kWh of energy (\$12 in energy costs) were needed to produce a 1 kg increase in tilapia. Raising tilapia was a net loss, while raising crops was a net gain when comparing market prices to energy costs. Understanding energy, water, and feed use in aquaponic systems is essential to inform farm business plans. These data can serve as a point of comparison to other small-scale aquaponic systems, and inform future work on life cycle assessments of aquaponics.

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1. Introduction

Aquaponics is a form of aquaculture that integrates soilless crop production (hydroponics) to raise edible plants and fish. The fish are fed and excrete waste, which is broken down by bacteria into nutrients. Plants utilize some of these nutrients, and in the process filter the water in the system. Most aquaponics systems are recirculating aquaculture systems where water is continuously recycled through an interconnected series of fish tanks and waste treatment systems (Timmons and Ebeling, 2002). Early attempts at recirculating aquaculture were challenged by the accumulation of ammonia, a potentially toxic by-product of fish waste (Bohl, 1977; Collins et al., 1975). In one approach to improve water quality, researchers incorporated plants as biofilters (Lewis et al., 1978; Naegel, 1977; Sneed et al., 1975; Sutton and Lewis, 1982), which was an early

application of aquaponics. A common application of aquaponics today is raft (deep water culture) aquaponics, in which water from the fish tanks flows into a series of solid filtration and biofilter tanks, which respectively serve to remove large solids and use bacteria to break down ammonia into nitrate. From these tanks water flows through the plant beds before returning to the fish tanks. To create a stable ecological system and maximize crop and fish production, aquaponics practitioners now control a variety of factors such as the water temperature, pH, micro- and macronutrients, dissolved oxygen, and sunlight/photo-period. Several studies have attempted to optimize various factors and report the commercial production associated with these optimized states (Rakocy, 1984, 2012; Rakocy et al., 2006; Savidov, 2005; Watten and Busch, 1984), and much of this literature has been reviewed by Tyson et al. (2011).

Aquaponics has been discussed as a part of sustainable intensive agriculture, however there are several limitations to aquaponic food production that may make aquaponics a better or worse fit at certain scales or in some climates or regions of the world. The weaknesses of aquaponics, as described in a United Nations Food and Agriculture report, include: it is knowledge intensive, expensive to

* Corresponding author at: 615 North Wolfe Street, Room W7009, Baltimore, MD 21211, USA.

E-mail address: dlove8@jhu.edu (D.C. Love).

start-up, energy/resource demanding, requires daily maintenance, has fewer management choices than agriculture or aquaculture, requires access to fish and plant seed, the fish in the system have narrow temperature ranges, and mistakes or accidents can result in catastrophic collapse of the system (Somerville et al., 2014). The benefits of aquaponics are the efficient use of water, limited waste, organic-like management, colocation for producing two agricultural products (i.e., edible fish and plants), increased density of crop production, and it addresses a growing interest in locally grown food (Somerville et al., 2014). These benefits must outweigh the limitations for aquaponics to be economically viable for the farmer, environmentally sustainable, and beneficial for the community.

The field of aquaponics has grown dramatically in the past few years (Love et al., 2014), however, data gaps exist on the resource use, cost–benefit analysis, and life cycle assessment (LCA) of aquaponics. The objective of this study was to describe the operating conditions, inputs (energy, water, and fish feed) and outputs (edible crops and fish) over two years for a small-scale, raft aquaponics operation in Baltimore, Maryland, United States (U.S.), and explain the relationships between inputs and outputs. These data can help fill gaps on energy use in aquaponics, serve as a point of comparison to other small-scale aquaponic systems in other regions with different climates, inform farm business plans, and serve as a starting point for future work on systems-level (i.e., LCA) studies of aquaponics.

We describe our operation as a “farm,” which fits within the U.S. Department of Agriculture (USDA) definition of a farm as a place where over \$1000 in agricultural products were produced and sold during a year (USDA, 2015). Over the two-year study period our operation had roughly \$10,000 in sales. Within the USDA Farm Classification system, our operation most closely fits with a “Residential/Lifestyle farm,” which is a small farm whose operators have a primary occupation that is not farming (in our case educators and researchers) and have gross sales less than \$250,000 per year (USDA, 2013).

2. Materials and methods

2.1. Aquaponics system design

The 10.3 m³ aquaponics system was sited in a 116 m² hoop-house on the grounds of the Cylburn Arboretum in Baltimore, Maryland, U.S. The system was operated with fish and plants for six months (starting in June 2012) prior to the beginning of the study period to allow the biofilter to ripen and nutrient levels to increase sufficiently to support consistent crop growth. The period under study was January 1, 2013 to December 31, 2014. The design and specifications of the system are presented in Fig. 1. Four fish tanks were part of the same system and should be considered one experimental unit. It is typical for aquaculture systems to have more than one tank so that fish at varying stages of development can be raised and harvested in a staggered fashion. The mechanical systems and their energy demands are reported in Table 1. Mechanical components drawing electricity were a water pump, an air blower, four in-tank electrical water heaters, a 4-ft wall-mounted greenhouse fan, an inflation blower to maintain a pillow of insulation between the layers of greenhouse film, several box fans to distribute air throughout the greenhouse, and fluorescent lights. In cold weather, thermostat-controlled, propane-fired space heaters maintained the air temperature at no less than 4–7 °C. If the water temperature dropped below 22 °C, the thermostat-controlled electric heaters operated. The system did not have an electric water-cooling mechanism and in summer months the water temperature would increase above 22 °C. To mitigate excessive temperature increases, in summer months a 50% shade cloth (Aluminet, Maryland Plants and

Supplies, Inc.) was installed above the hoop-house, a reflective plastic tarp was hung 1.5 m above the fish tanks, and a thermostat-controlled 4-ft greenhouse fan was used to pull air through two sets of louvered windows. Additional cooling was achieved by rolling up the sides of the hoop-house to 1 m in height. In the event of a power outage, backup power was supplied by a propane-driven generator.

2.2. Permit and fish stocking

Consistent with state regulations for commercial finfish aquaculture operations, a permit was obtained from the Maryland Department of Natural Resources (DNR). The permit requirements included a site inspection, a map of the location, fish health certification and species origin documents, a plan for the treatment of non-native species to prevent introduction into the wild, a waste management plan, and annual reporting of activities under the permit. The DNR permit also allows for the commercial sale of live unprocessed fish.

Fish tanks were stocked with 21 Nile tilapia (*Oreochromis niloticus*) to ripen the system, and 227 blue tilapia (*Oreochromis aureus*) were stocked for grow-out. For the first year of the study period the fish were fed two different plant based diets: for 9 months a slow sinking feed with 50% protein provided by Watson et al. (2013) and for 3-months an expensive and less palatable USDA Organic feed with 32% protein (AquaOrganic diet from The Aquaponics Source). For the second year of the study, a more consistent, commercially available feed was introduced, a slow sinking feed with 35% protein (Finfish Bronze, Ziegler Brothers Inc. Gardners, PA). Fish were fed by hand once or twice a day in quantities based on the number of fish in the system and their body weight and the water temperature, feeding to satiation.

2.3. Water use

Water was continuously cycled through the system at a rate of 93 Lpm throughout the study period. Water additions were made from a 625 L storage tank into the aquaponic system. The storage tank allows for a waiting period in which chlorine can dissipate from the municipal water supply, which can then be gravity-fed into the hydroponic tanks. Sources of water loss were evaporation, evapotranspiration, spillage, leakage, and water exchange (38 L of 10% fish solids per day). Originally, fish tanks were operated without covers. After experiencing significant condensation during winter months on the interior of the greenhouse film, additional measures were taken to cover the fish tanks in the winter using a radiant barrier (TekFoil) to reduce the heat and water loss due to evaporation out the top of the tanks and reduce the relative humidity in the hoop-house. The potential for rainwater use was calculated based on the local water data for monthly inches of rainfall, the square footage of the hoop-house, and an estimated collection efficiency of 70%. Rainfall collection potential is reported in Eq. (1) as Lpm. In the equation, RW = rainwater, P = collection efficiency (70%), z = amount of rainfall per month, l = hoop-house length, h = hoop-house height, and times 2 because the hoop-house height is ½ the hoop-house width in this case.

Eq. (1): Rainwater collection possible (United Nations Environment Programme, 1998)

$$RW = P \times z \times l \times h \times 2 \quad (1)$$

2.4. Water quality and chemical amendments

Water treatment was performed using four 190-L cone-bottom clarifiers (one per fish tank) followed by two 132-L biofilter tanks

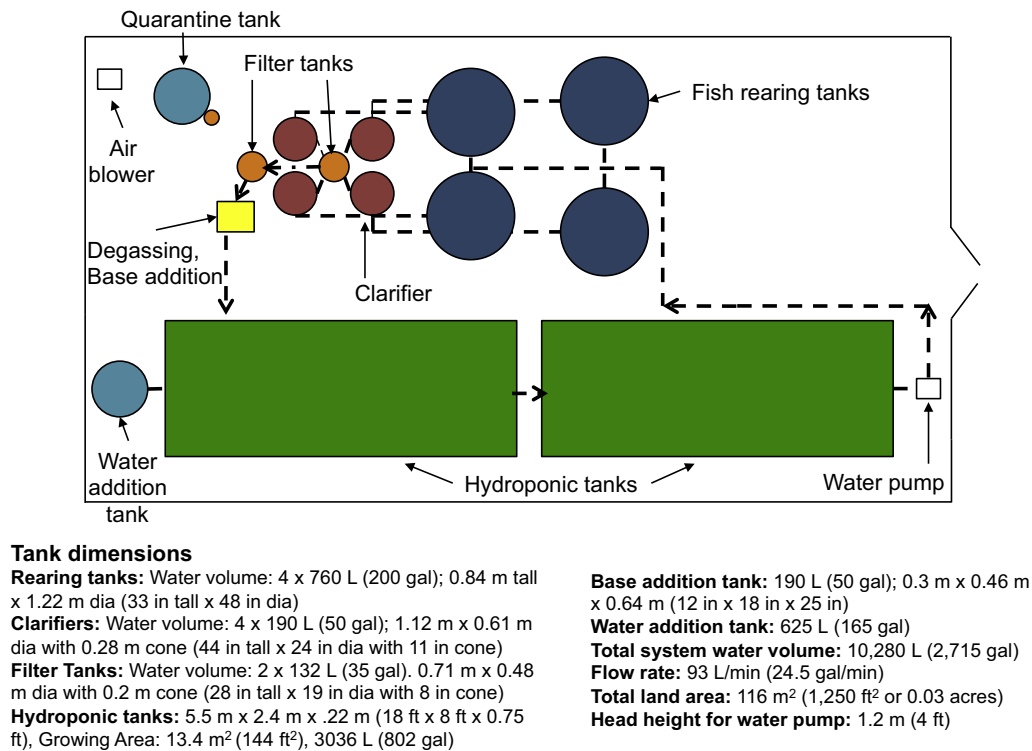


Fig. 1. Small-scale raft aquaponics system layout. The system designers were Nelson and Pade, Inc. (Montello, WI).

in series (the first one filled with orchard netting, the second filled with aerated Kaldnes K1 media). Data on water quality monitoring and the addition of chemical amendments are presented in Fig. 2. Alkalinity and pH were maintained using a combination of hydrated lime (Good Earth Organics, Cave Junction, OR) and potassium bicarbonate (Nuts.com, Cranford, NJ), typically on a daily basis in 50–150 g amounts. The water pH was measured daily using a colorimeter (model DR850, Hach, Loveland, CO) and a phenol red indicator (Hach). The alkalinity of the system water was measured weekly (Lamotte, Chestertown, MD). Ammonia and nitrite were measured routinely using a colorimeter (Hach) to confirm that levels were below known tolerances for tilapia. Powdered iron chelate (Grow More, Gardena, CA) was added in roughly 20–80 g amounts on a semi-weekly basis to the base addition tank whenever yellowing was observed in plant leaves. Greenhouse temperature and water temperature were measured daily using a greenhouse thermometer and an in-tank digital thermometer. Dissolved oxygen was not measured routinely.

2.5. Energy use

There were five main contributors to electrical energy usage in the system: water heaters, air blowers, box fans, a pump, and lights in the winter for seedling germination. Propane was used to power a backup generator in case of power outage and heaters to ensure that night-time temperatures in the hoop house remained above 7 °C. Data for electrical and propane usage were collected from the site. Energy calculations for the radiant solar heat gain (RSHG) and solar heat gain factor (SHGF) (American Society of Heating, 2013) were estimated based on the orientation of the site (Google Maps, Mountain View, CA), the specific latitude, the cloudiness for the zip code, and estimates of infiltration and exfiltration of outside air due to the prior construction effectiveness of the hoop house (Eq. (2)). In the equation, $RSHG_N$ = radiant solar heat gain in the X-direction (i.e., north, south, east, west), $SHGF_N$ = solar heat gain factor in the X-direction, A_N = area of the hoop house in the X-direction, $Cloud\%$ = percent of cloud cover, ε = material emissivity.

Table 1
Mechanical equipment and energy use in a small-scale raft aquaponics systems.

Item	Use	Number	Energy source	Make and model
Water pump	Continuous	1	Electricity	1/8 hp (0.95 A @230 V AC) System Pump, RK2 System
Air blower	Continuous	1	Electricity	0.5 hp Lafert
Inflation blower	Continuous	1	Electricity	1/25 hp (0.42 A @115 V AC) FarmTek
20 inch box fan	Continuous	3	Electricity	Lasko
4-ft greenhouse fan	On demand thermostat	1	Electricity	1/2 hp, generic belt driven exhaust fan
Electrical water heaters	On-demand thermostat	4	Electricity	2500 W (10.4 A @230 V AC) "L" shaped immersion heater Process Technology
4-ft fluorescent light fixtures	Plant propagation	4	Electricity	2 bulbs per fixture, 40W bulbs, 10 h timer switch
Wall-mounted heater	On demand thermostat	2	Propane	Vertical power vented unit heater, Modine
Generator	On demand solenoid	1	Propane	17 kW Guardian Series, Generac

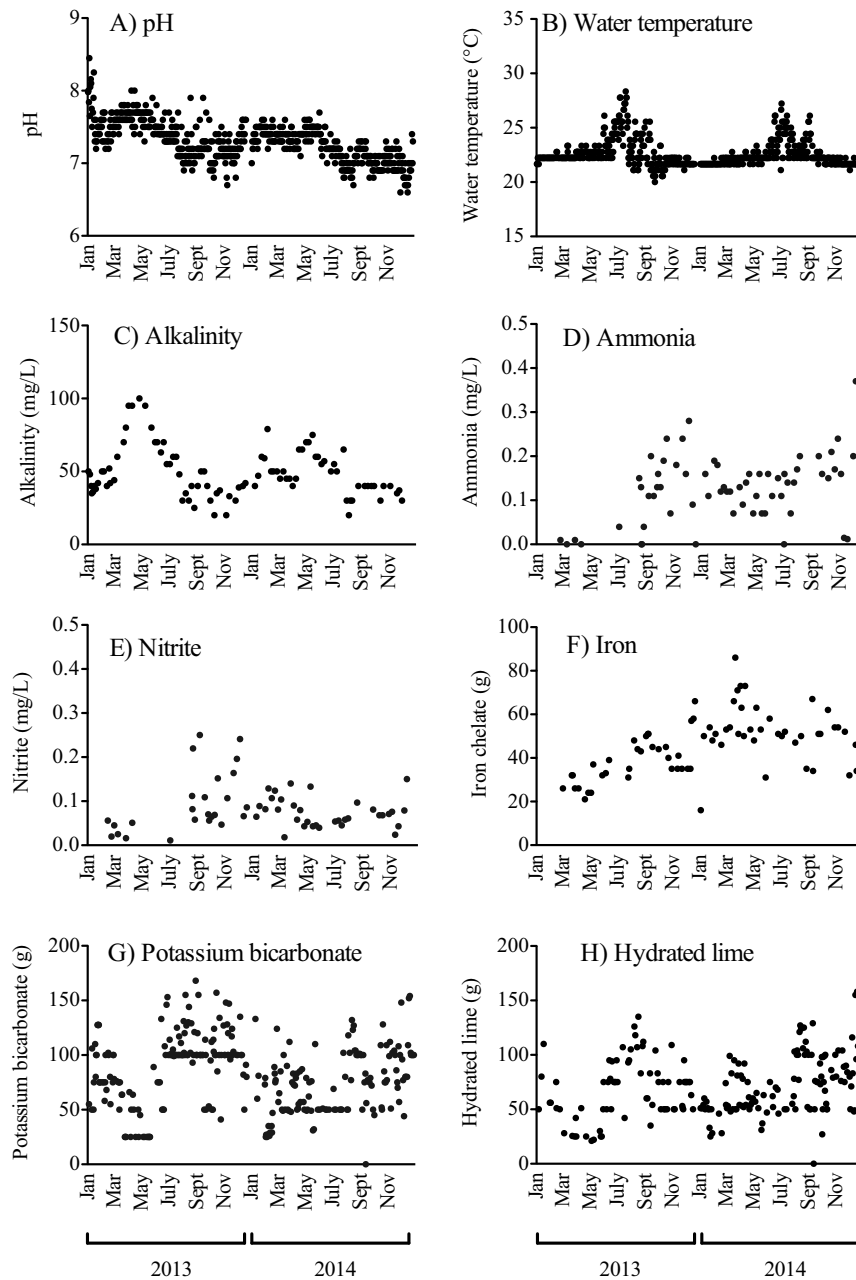


Fig. 2. Water quality monitoring (A) pH, (B) water temperature, (C) alkalinity, (D) ammonia, (E) nitrite, and chemical amendments (F) chelated iron, (G) potassium bicarbonate, and (H) hydrated lime over two years in a small-scale raft aquaponics system.

Eq. (2): RSHG of the hoophouse, based on cardinal direction, cloudiness, and material emissivity

$$\text{RSHG}_N = \text{SHGF}_N \times A_N \times \text{Cloud}\% \times \varepsilon \quad (2)$$

Prior to the study period, sprayfoam insulation and foam-board insulation were installed to reduce thermal losses through doors, leakage through vents and along cracks, and repair holes. The electricity consumption during the study was recorded over time from an electric meter. Propane use was recorded from the propane tank dial and converted to kWh based on the energy content at sea level. Energy costs were estimated based on local energy rates: \$0.10/kWh for electricity and \$0.11/kWh for propane (or \$3.00 per gallon).

2.6. Fish and plant production

A sample of five to ten fish from each tank were weighed on a semi-monthly basis (13 times over the course of the study), and these weights were multiplied by the estimated number of fish in a tank to calculate a tank weight. Samples were obtained by dipping the net into each tank five times and weighing the fish caught. Fish were not crowded prior to sampling because the small tank size and a center stand pipe made this impractical. The feed conversion ratio (FCR) was calculated by dividing the total feed administered over the time between fish weightings by the change in tank weight over that time.

A variety of crops were grown in the aquaponics system and harvested on weekly basis starting in January 2013 and sold at market rate at a local farmers market. Weights of the harvested portion of each crop were recorded. Seasonal plantings included herbs (basil,

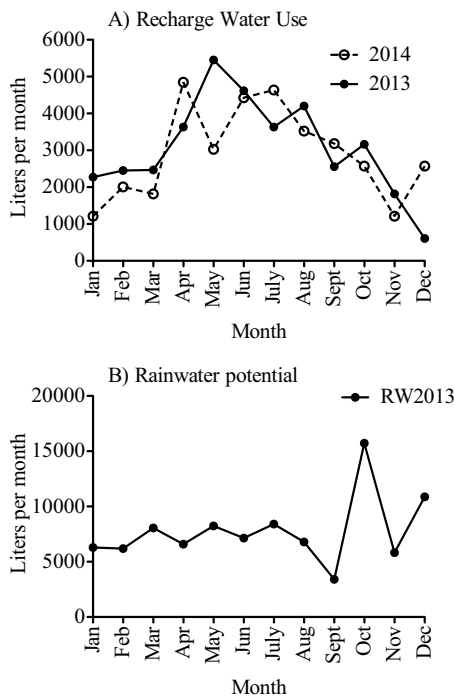


Fig. 3. (A) Recharge water use over two years in a small-scale raft aquaponics system and (B) rainwater collection potential from the hoophouse roof in Baltimore, Maryland in 2013.

chives, dill, etc.), loose-leaf greens (salad mix, mustard mix, etc.), greens harvested by the head (lettuces, bok choy, tat soi, etc.), fruiting crops (cucumbers, peppers), and bunched greens (kale, chard, mustard).

3. Results and discussion

3.1. Water

Initially, there was a large water demand to fill the system, and thereafter there was a daily or weekly need to “top-off” the system to replace water lost due to evaporation, evapotranspiration, spillage, leaks, and water exchanges (Fig. 3a). The daily water loss of about 1% was near the expected range of 0.5–10% reported previously (Rakocy et al., 2006). The total annual water demand to maintain the system was 36.9 m³ in 2013 and 35.0 m³ in 2014. Comparing between years, there were natural variations in the amount of monthly water use, for example May 2013 had less water use than May 2014. The need for water addition was greater in warmer months than cooler months, and relatively similar between the two years in the study period (Fig. 3a).

At the scale of the operation, however, natural rainwater collection could supplement or replace any water losses. Fig. 3b provides the monthly amount of rainwater in Baltimore, MD in 2013 that could be collected and used in the aquaponics system (93.5 m³ in total), which was greater than the amount needed due to water loss.

Agriculture is one of the major users of fresh water globally. While aquaponics offers a water-efficient method for both aquaculture and hydroponics, in a previous survey of 809 aquaponics operations, 90% of respondents used drinking water (community piped water or well water) as their water source for aquaponics (Love et al., 2014). In the survey, however, some respondents (39%) used rainwater to supplement potable water use (Love et al., 2014) indicating that they may be willing to use other biosecure water sources. For aquaponics to become more ecologically sustainable,

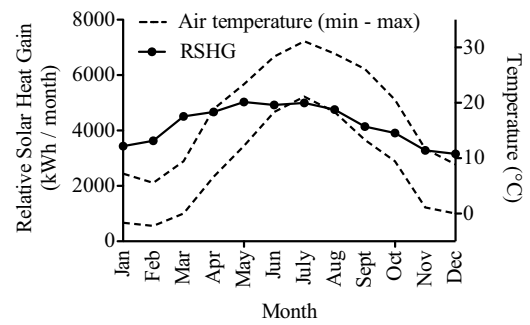


Fig. 4. The relative solar heat gain (RSHG) in the hoophouse accounting for thermal losses, and average monthly max and min air temperature in Baltimore, Maryland in 2013.

aquaponic system operators and designers should be encouraged to make full utilization of available rainwater.

3.2. Energy

To assess the net energy demand in the study system, the RSHG in the hoophouse was calculated for 2013 (Fig. 4) and monthly energy usage was monitored in 2013 and 2014 (Fig. 5). Hoophouses are designed for passive solar heating, and the total annual RSHG for the orientation of the hoophouse and its latitude was predicted to be 71,924 kWh, which does not account for shading from nearby trees. When accounting for losses due to the hoophouse building envelope, the total effective RSHG annually was determined to be 50,443 kWh, and reported by month in Fig. 4. During some periods in the summer, solar energy can completely replace both propane and electric water heating, barring extreme conditions. Excess solar energy was deflected in the summer using a 50% shade cloth and heat in the hoophouse was exhausted using fans and roll-up sides.

The total electricity use in 2013 and 2014 was 10,903 kWh and 10,844 kWh, respectively and varied by month due to seasonal changes in temperature (Fig. 5a). Water heating consumed the largest amount of electricity in the aquaponic system in all months except June, July, August and September, when the water temperature was maintained almost exclusively by RSHG. Propane use (to maintain air temperature > 7 °C in cold months) totaled 8451 kWh and 8553 kWh in 2013 and 2014, respectively (Fig. 5b). These values equate to approximately 315–330 gallons of propane each year. The propane volume dial was less precise than the electrical digital readout, and propane readings were taken less frequently than electrical readings, which resulted in variability in reported propane use. Due to the use of propane to maintain hoophouse air temperatures, the energy loss from tank conduction decreases. Therefore, both the propane and electricity were indirectly and directly heating the water, respectively, and need to be considered as the total resources required for heating water. The total combined propane and electricity use was 19,354 kWh and 19,698 kWh in 2013 and 2014, respectively (Fig. 5c). January was the month with the highest energy demand, using roughly a third of total yearly energy use.

The total energy costs in 2013 and 2014 were \$2035 and \$2074 (Table 2). Energy costs in January represent one third of total annual energy costs. Total electricity and propane costs were roughly equal, however, the electricity costs had a narrower range (\$12–\$203 per month) than propane costs (\$0–\$600 per month), which was due to high propane use in cold weather months. These data indicate it is more cost effective to heat water than air during cold weather months.

The driving factors in heat losses in the study system was water loss through evaporation and evapotranspiration, reheating influent water when “topping up” the system, conduction through

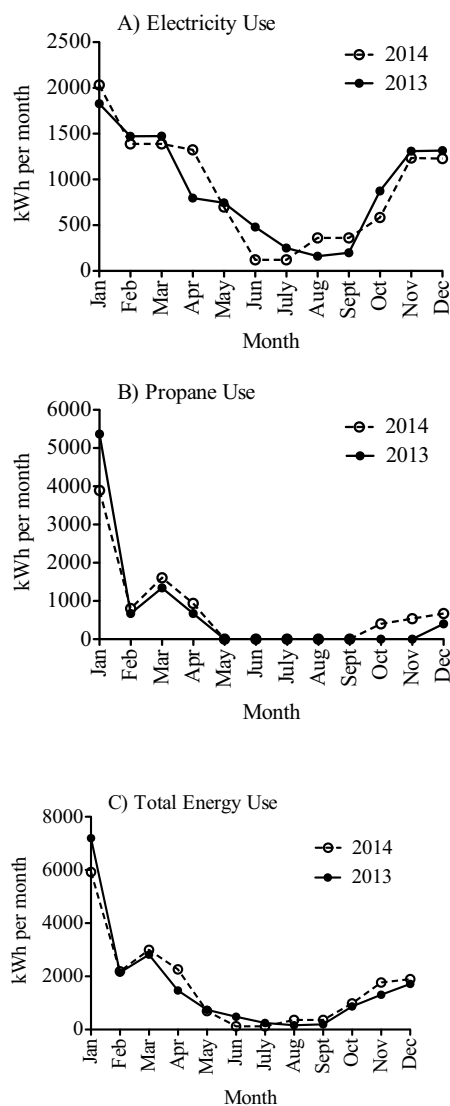


Fig. 5. Energy use (kWh per month) for (A) electricity, (B) propane and (C) total energy use over two years in a small-scale raft aquaponics system. Note: different y-axis scale in (A).

Table 2
Energy use by month in a small-scale raft aquaponics system.

Energy source	Total	Month											
		Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Electricity^a													
2013	\$1090	\$183	\$147	\$147	\$80	\$74	\$48	\$25	\$16	\$20	\$87	\$131	\$132
2014	\$1084	\$203	\$139	\$139	\$132	\$70	\$12	\$12	\$36	\$36	\$58	\$124	\$123
Avg	\$1087	\$193	\$143	\$143	\$106	\$72	\$30	\$19	\$26	\$28	\$73	\$127	\$127
Propane^b													
2013	\$945	\$600	\$75	\$150	\$75	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$45
2014	\$990	\$435	\$90	\$180	\$105	\$0	\$0	\$0	\$0	\$0	\$45	\$60	\$75
Avg	\$968	\$518	\$83	\$165	\$90	\$0	\$0	\$0	\$0	\$0	\$23	\$30	\$60
Total energy													
2013	\$2035	\$783	\$222	\$297	\$155	\$74	\$48	\$25	\$16	\$20	\$87	\$131	\$177
2014	\$2074	\$638	\$229	\$319	\$237	\$70	\$12	\$12	\$36	\$36	\$103	\$184	\$198
Avg	\$2055	\$711	\$226	\$308	\$196	\$72	\$30	\$19	\$26	\$28	\$95	\$157	\$187

^a Assuming \$0.10/kWh; used to power a water heater, fans, blower, water pump, air barrier, and lights.

^b Assuming \$0.11/kWh (\$3 per gallon); used to power propane-fired air heaters and a generator.

the tank walls, and leaks in the hoop house. These sources of heat loss can be minimized through structural improvements to the hoop house building envelope, more effective insulation of tanks, and more effective lid enclosures. Hoop houses have very little insulation and drop to ambient temperatures at night, therefore strategies to capture RSHG during the day using solar thermal water heaters would help reduce energy demands. Removing nearby coniferous trees that shaded the hoop house in the winter and changing the hoop house orientation so that the broad side faced south, are strategies that would likely have reduced the need for heating in our study. There are also opportunities to use heat recovery hot water heaters in line with the aquaponics piping, for example from ice makers and refrigeration. Heat recovery provides thermal heat at a cheaper rate than electric resistance heaters, in a more direct and effective delivery method than propane, and improves the cooling performance of the refrigeration equipment. Additionally, row covers could be used to protect plants at night from frost to reduce winter air heating needs. Warm air rising from the heated water would likely be trapped under the row cover, potentially reducing the need for heating of the air. The fish in aquaponics have much higher temperature requirements than the plants, and hardy winter greens are commonly raised in hoop houses throughout the winter in the mid-Atlantic, U.S. often without supplemental heating. While taking the winter off may be one possible strategy to lower energy costs, this may be impractical because of the length of time needed for biofilter ripening upon start-up and the need to maintain a fish population to support hydroponics.

Energy demand and access to electricity are notable limitations of small-scale aquaponics (Somerville et al., 2014). In a survey of commercial aquaponics operators, those in temperate to warm climates were four times as likely to be profitable as those in colder climates (Love et al., 2015), suggesting that heating costs could be a constraint. Over 70% of commercial systems are sited in a greenhouse or use a greenhouse in combination with other growing locations such as indoors or outside (Love et al., 2015). In colder climates there may be a benefit to siting aquaponics operation indoors instead of greenhouse because buildings can be insulated to minimize heat loss. Among the drawbacks of such siting, however, is the loss of RSHG and the need to use artificial light for plant production. Future studies are needed to compare the benefits and drawbacks of farming in greenhouse versus inside building in cold climates, or whether it is more efficient to use other means such as shipping in food from other regions.

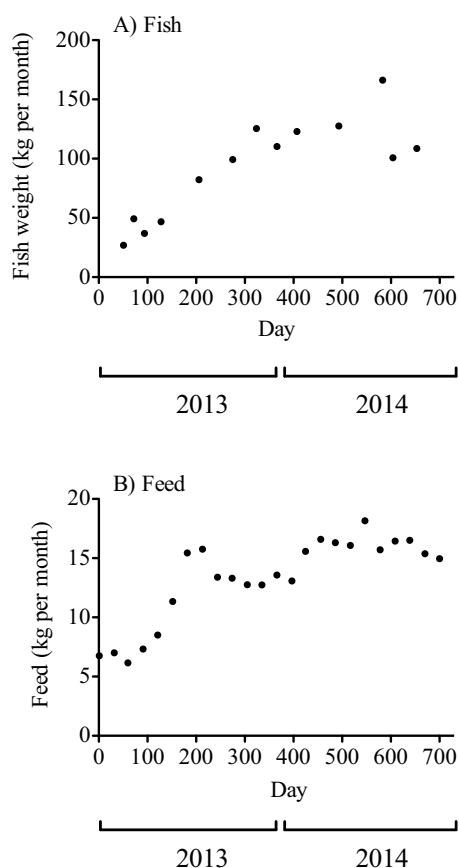


Fig. 6. Weight of (A) all fish (i.e., tank weight) by month and (B) feed by month over two years in a small-scale raft aquaponics system.

3.3. Biomass

Fish weight and crop harvests were tracked over the two-year study period. Tilapia gained a total of 129 kg in 2013 and 117 kg in 2014 including the weight of harvested and unharvested fish (Fig. 6a). The feed conversion ratio (FCR) was 1.29 over 2 years, which was based on a fish community of predominantly blue tilapia (94% blue tilapia, 6% Nile tilapia). These findings are similar to previous reported values for single populations of tilapia (Al Hafedh, 1999; Rakocy et al., 2006; Shnel et al., 2002). The tilapia grow-out period in this study was longer than a typical grow-out period (Rakocy, 1989), which led to growth rates suppressed relative to feeding rates in 2014. Additionally, the system was maintained with colder water temperatures (min. 22 °C) than what is typical for tilapia in aquaculture. There was a concern that warmer water temperatures (>27 °C) could cause plants to bolt prematurely. Admittedly, tilapia were not the main profit center of the operation, and balancing the needs of the plants and fish requires some compromises that may affect the productivity of each crop, which is a common limitation facing aquaponic managers.

Crops were harvested weekly for sale at a local farmers market, with 294 kg harvested in 2013 and 422 kg harvested in 2014. These crops were raised from the nutrients from fish with occasional supplemental nutrient additions of potassium, calcium and chelated iron (as described in Section 2). The 43% increase in harvests in 2014 can be attributed to improved farm management, and more gains in production efficiency could be possible over time. Crop plantings and productivity varied by season, and harvests in March through July were greater than other months due to favorable growing conditions (Fig. 7). Low production in December, January, February and the peak of the summer (August) was consistent

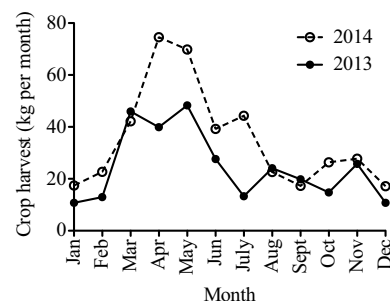


Fig. 7. Crop harvests over two years in a small-scale raft aquaponics system.

with others' experiences growing in greenhouses in the region (personal communication Scott Ritchie, Baltimore City Recreation and Parks, Horticulture Division). Winter plant harvests decreased due to ambient air temperature and fewer hours of direct sunlight reaching the hoophouse. Summer plant harvests decreased due to heat stress and pest outbreaks of aphids, spider mites, and harlequin beetles that suppressed plant yields. Integrated pest management strategies were employed, including the addition of beneficial insects and removing diseased plants, which helped control pest pressure. Seasonal variations in production are typical in agriculture. Others have also reported seasonal a drop in aquaponics production; in one case cucumber yield dropped in the winter due to root rot caused by *Pythium* (Savidov, 2005).

The system promotes nutrient cycling, however not all biomass was utilized. A small amount of fish waste solids were discarded. Roughly 38 L of 10% fish waste solids were removed daily from the system daily to prevent the buildup of anoxic conditions and were used to fertilize outdoor plants near the facility. On a larger scale, others have used geotextile bags to collect, dewater, and compost aquaponic fish waste solids (Danaher, 2009). Additional unused biomass included fish mortalities, inedible plant parts (roots, stalks, etc.) and damaged or blemished crops that were not sold.

3.4. Biomass relative to water and energy

Table 3 presents the monthly inputs of water, feed and energy required to produce 1 kg of crops in a small-scale raft aquaponics system. An average of 104 L of water, 0.5 kg feed, and 56 kWh energy was needed to produce 1 kg of crops. The most efficient season for converting feed to plant biomass was the spring where 1 kg of fish feed was converted into 5 kg of plants, which were mainly leafy green crops such as chard, lettuce, and kale. Others have reported as much as 9 kg of lettuce grown using 1 kg of fish feed (Love et al., 2015). The average monthly energy cost to grow 1 kg of crops was \$6, and varied by month with a maximum of \$55 in January to a minimum of \$1 in May through August. In a study of the economics of small-scale aquaponics in Hawaii, average energy costs were \$0.73/kg of lettuce, which were similar to the costs we observed during summer months (Tokunaga et al., 2015). At the farmers market where our crops were sold, loose-leaf salad greens sold for \$26.52/kg and bunched greens (such as kale and chard) sold for \$8.82/kg, which shows that for most months, sales were greater than energy costs when selling at farmers markets. Farmers receive higher farm gate prices when selling direct-to-consumers compared to lower farm gate prices for indirect outlets (distributors, retailers, and institutional buyers). Moreover, certain growing practices can allow farmers to receive a premium for their product. For example, hydroponic and USDA organic greens often fetch a higher price than conventional products.

Tilapia production was compared to water, feed and energy inputs in Table 4. Comparing inputs to outputs, 292 L of water, 1.3 kg feed, and 159 kWh of energy were needed to produce 1 kg

Table 3
Monthly water, feed, and energy use required to produce 1 kg of crops in a small-scale raft aquaponics system.

Metric	Average	Month											
		Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Water (L) per 1 kg crops													
2013	125	211	189	54	91	113	167	273	175	129	214	70	56
2014	83	70	88	43	65	43	113	105	155	184	98	44	150
Average	104	140	139	48	78	78	140	189	165	156	156	57	103
Fish feed (kg) per 1 kg crops													
2013	0.4	0.6	0.5	0.1	0.2	0.2	0.4	1.2	0.7	0.7	0.9	0.5	1.2
2014	0.5	0.8	0.6	0.4	0.2	0.2	0.4	0.4	0.7	1.0	0.6	0.6	0.9
Average	0.5	0.7	0.6	0.3	0.2	0.2	0.4	0.8	0.7	0.8	0.8	0.5	1.0
Energy (kWh) per 1 kg crops													
2013	66	668	165	61	37	15	17	19	7	10	59	51	159
2014	47	340	96	71	30	10	3	3	16	21	37	64	110
Average	56	504	131	66	34	13	10	11	11	15	48	57	135
Energy cost (\$) per 1 kg crops													
2013	\$7	\$73	\$17	\$6	\$4	\$2	\$2	\$2	\$1	\$1	\$6	\$5	\$16
2014	\$5	\$37	\$10	\$8	\$3	\$1	\$0	\$0	\$2	\$2	\$4	\$7	\$12
Average	\$6	\$55	\$14	\$7	\$4	\$1	\$1	\$1	\$1	\$2	\$5	\$6	\$14

Table 4
Average water, feed, and energy use required to produce 1 kg of tilapia and 1 kg crops in a small-scale raft aquaponics system.

Metric	Tilapia			Crops		
	2013	2014	Average	2013	2014	Average
Water (L) per 1 kg tilapia or crops	286	298	292	125	83	104
Fish feed (kg) per 1 kg tilapia or crops	1.0	1.6	1.3	0.4	0.5	0.5
Energy (kWh) per 1 kg tilapia or crops	150	168	159	66	47	56
Energy cost (\$) per 1 kg tilapia or crops	\$10	\$13	\$12	\$7	\$5	\$6

increase in tilapia weight. Relative to crops, fish require roughly 3-fold more water, feed, and energy per month to produce 1 kg of product. The energy costs to produce 1 kg of tilapia was on average \$12. The market price for whole tilapia sold to restaurants in Baltimore, MD was \$8.82/kg, which was less than the energy costs for raising the fish. A recent case study of small scale aquaponics in Hawaii had lower input costs for producing fish than in Baltimore, with a total costs \$4.80/kg and \$1.70/kg from energy costs (Tokunaga et al., 2015), which can be attributed to the warmer climate in Hawaii. The sales price for tilapia in the Hawaii case study was \$11.02/kg, and assuming that all other factors were equal, the authors speculate that aquaponics would be more profitable than hydroponics given the additional profit from fish (Tokunaga et al., 2015). We found the opposite situation in Baltimore, Maryland where fish sales prices were lower than input costs due to higher winter energy costs. Approaches to minimizing heating for fish would be raising species that can survive at lower water temperatures and require less heating, implementing renewable sources of energy such as photovoltaic (although there are higher start-up costs), raising higher value species to enhance the market price, or move location to sites with warmer winters or a better insulated space. Many factors such as markets, production scale, and start-up and recurring input costs need to be carefully considered when planning aquaponics businesses to avoid pitfalls.

3.5. Limitations and future work

A limitation of this study was the focus on a single operation as a case study, which can limit generalizability to other sizes and types of aquaponics systems. Other limitations were the lack of information on labor costs, which can contribute to half of the input costs (Tokunaga et al., 2015), and capital costs which is another hurdle for starting small-scale operations. The operation studied was subject to many of the same challenges and constraints typical of small-scale agriculture: labor shortages, learning curve of

management, budget constraints, pest control, etc. As such, these data can be useful to aspiring aquaponic growers by providing a real-world example to inform business plans.

The strength in the present study is in reporting values related to the inputs (water, energy, and feed) and outputs (fish and crops) for a facility located in the Mid-Atlantic and describing relationship between inputs and outputs. These data could support future work on cost benefit analyses or life cycle assessments to better flesh out the strengths and weaknesses of small-scale aquaponics. Additional case studies are needed to confirm our findings in small-scale raft aquaponics systems. One recent case study in Hawaii found small-aquaponics was economically feasible, however the authors were not as optimistic as previous reports and found economic outcomes were sensitive to market prices (Tokunaga et al., 2015). Further comparisons are needed across medium and large facilities in operation, in a range of climates, and under different management regimes to see if our findings are relevant for slightly larger or much larger operations.

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