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

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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.

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

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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 m^3 aquaponics system was sited in a 116 m^2 hoophouse 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 hoophouse, 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 hoophouse 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 hoophouse. The potential for rainwater use was calculated based on the local water data for monthly inches of rainfall, the square footage of the hoophouse, 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 = hoophouse length, h = hoophouse height, and times 2 because the hoophouse height is ½ the hoophouse width in this case.

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

$$\mathrm{RW} = P \times z \times l \times h \times 2 \tag{1}$$

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