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Fate of nitrogen in floating-raft aquaponic systems using natural abundance nitrogen isotopic compositions

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ABSTRACT

Nitrogen is a key nutrient for fish and vegetable productions in aquaponic systems. However, the fate of nitrogen in aquaponic systems has not been fully understood, leading to difficulty in optimizing nitrogen use efficiency (NUE) and plant production. In this study, the fate of nitrogen in floating-raft aquaponic systems with two plant species, pak choi (*Brassica rapa* L. *chinensis*) and lettuce (*Lactuca sativa longifolia* cv. *Jericho*), and tilapia (*Oreochromis* sp.) was evaluated using mass balance and natural abundance nitrogen isotopic compositions. Dissolved oxygen (DO) levels associated with hydraulic loading rate (HLR) were found to positively affect nitrite oxidation rate. Increase in nitrite concentration was observed in recirculating water under low DO levels. Nitrite is an intermediate in the dissimilatory reduction of nitrate to N_2 gas. Based on progressive enrichment of ^{15}N of nitrate with time in the recirculating water, we estimated total nitrogen loss of up to 46.3% via denitrification. Nitrogen loss via denitrification was reduced by 44–56% when the feed-to-plant ratio was decreased by 30%. Results of this study provide better understanding of nitrogen transformations, which could help in designing and operating efficient aquaponic systems.

1. Introduction

Rapid growth in global food demand due to increasing population coupled with rising affluence will have significant impact on food security. The consumption rates of food and fertilizer use are projected to outpace their availability by 2050 and 2018, respectively (Conforti, 2009; FAO, 2015). Aquaponics, a soilless crop production system that integrates both aquaculture for fish production and hydroponics for edible plant production could play an important role in sustainable food production (Hu et al., 2012). Aquaponics has several inherent merits, such as efficient use of water, nutrient recycling, and the increased potential of higher plant productivity (Love et al., 2015; Wongkiew et al., 2017).

Nitrogen is a key nutrient in aquaponic systems and has been used as an indicator to evaluate the efficiency of aquaponic systems. In an aquaponic system, the ammonia nitrogen-rich aquaculture effluent is converted to nitrate (NO_3^-) via nitrification, and the NO_3^- is recycled as a fertilizer for plant growth in the hydroponic grow bed (Lam et al., 2015; Wongkiew et al., 2017). The oxidation of excreted NH_4^+ to NO_2^- and then to NO_3^- occurs through microbial nitrification under aerobic conditions. Vegetables primarily utilize NO_3^-, which is converted to plant biomass (Lam et al., 2015; Wongkiew et al., 2017). Ammonia (NH_3) and NO_2^- must be kept at low concentrations to avoid fish toxicity (Popma and Masser, 1999). In addition, nitrous oxide (N_2O) in aquaponic systems can be produced by nitrification and denitrification, and N_2O emission rate was proportional to N_2 emission and feeding rates (Buzby and Lin, 2014; Hu et al., 2015). N_2O is an atmospheric greenhouse gas that on a molecule per molecule basis has the potential to contribute more to the atmospheric greenhouse effect than CO_2 (Forster et al., 2007). Atmospheric N_2O also plays a primary role in ozone depletion in the stratosphere (Ravishankara et al., 2009). Nitrogen recycling improves nitrogen use efficiency (NUE) in an aquaponic system.

However, due to the simultaneous operation of aquaculture and hydroponic systems, it is often challenging to balance nitrogen generation by fish and uptake by hydroponically grown plants in large-scale aquaponics. There have been several attempts to optimize the performances of aquaponic systems, such as balancing

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plant uptake and fish output, recovering energy and nutrient, and reducing nitrous oxide (N_2O) gas emissions (Buzby and Lin, 2014; Hu et al., 2015; Lam et al., 2015). However, these optimization studies were very specific to a particular design and operating conditions. For example, Endut et al. (2010) varied hydraulic loading rates (HLRs) to increase the nitrogen uptake and plant growth rates. HLR is defined as water recirculation rate per unit area of a grow bed (m^3/m^2-day), and HLR is used to control water retention time for biochemical reactions in aquaponic systems (e.g., fish tanks, biofilters, and grow beds) (Wongkiew et al., 2017). In addition, Zou et al. (2016) focused on the optimum pH for maximizing NUE and reducing N_2O emission in media-based aquaponics. However, few studies have integrated optimizing NUE, water quality, and operations, simultaneously. Since nitrogen is a key nutrient in aquaponic systems, there is need to examine the fate of nitrogen for their design and efficient operation.

Nitrogen mass balance techniques were employed to determine NUE and nitrogen budgets in aquaponic systems (Hu et al., 2015). The mass balance approach provides information on the yield of products relative to the input (fish feed). However, it does not provide insight into the microbial processes involved in nitrogen transformations. Natural abundance stable nitrogen isotopic compositions of nitrogen species have been widely employed to identify the microbial processes involved in nitrogen transformations in ecological and biogeochemical studies (e.g., Robinson, 2001; Onodera et al., 2014; Ryabenko, 2013). The $^{15}N/^{14}N$ ratios ($\delta^{15}N$ values) in different compounds are not identical due to the isotopic fractionation caused by physical, chemical, and biochemical reactions. For example, nitrogen metabolism in fish results in waste produced depleted in ^{15}N relative to fish feed, and by mass balance, other metabolic products such as fish muscle tissue and feces become enriched in ^{15}N. Moreover, the total nitrogen isotopic ratio in a system is largely conserved, such that if one product is enriched in ^{15}N (increase in $\delta^{15}N$ value), another product must become depleted in ^{15}N, and vice versa. This approach does not require the addition of an enriched ^{15}N source, which can permanently alter the $\delta^{15}N$ values of the system. Natural abundance nitrogen isotopic fractionation associated with nitrogen transformations is typically large enough to easily identify the mechanisms of nitrogen transformations, despite the slow metabolisms of fish, plants, and microorganisms. Thus, studying fate of nitrogen with natural abundance stable isotope can be critically important to optimize aquaponic performances and identify biological interactions with a better understanding of nitrogen transformations in aquaponic systems.

In this study, fate of nitrogen in floating-raft aquaponic systems with pak choi and lettuce were evaluated under different DOs and HLRs using nitrogen isotope mass balance. This study provides better insight into the nitrogen transformations in aquaponic system, which could be helpful in designing and operating an efficient aquaponic system. Moreover, this paper evaluated the strategies to achieve an effective nitrification for improving NUE in aquaponic systems by optimizing DO level, HLR, and feeding rate.

2. Materials and methods

2.1. Experimental setup and operation

Two floating raft aquaponic systems were operated in parallel in triplicate in a greenhouse at the University of Hawaii's Magoon Research Facility. Each aquaponic system (Fig. 1) included a fish tank (volume = 335 L), 2-stage biofilter (up-flow and down-flow with partial aeration, volume = 15 L), and a hydroponic bed (300 L) containing a single raft (24 plants per raft, area = 1.5 m^2). Water at the mid-depth of the fish tank was pumped to the 2-stage biofilter (fixed-bed upflow biofilter followed by trickling biofilter). The aquaculture effluent from the tricking biofilter entered the hydroponic bed and was recirculated to the fish tank. The fish tank was constantly aerated with an aquarium pump, and fish were fed daily with fish feed. The biofilter was the only component where accumulation of solids (sediment) took place during the operation. Kaldnes filter media (surface area ≥800 m^2/m^3) were used in both biofilters to promote nitrification. The surface area of the filter media was designed to achieve ammonia removal rate for a maximum constant feeding rate of 50 g feed/day. In this design, the production rate of total ammonia nitrogen (TAN) was approximated based on protein content in feed (40%) and feeding rate (50 g feed/day) (Hu et al., 2012; Wongkiew et al., 2017). The required total surface area of the filter media was calculated based on TAN conversion rate of 1.0 g/m^2-day (Timmons et al., 2002). The volume of recirculating water in the aquaponic systems was held constant by adding tap water to each fish tank daily to compensate the water loss by evapotranspiration. Organic nitrogen, TAN, NO_2^- and NO_3^- concentrations in the tap water were below detectable levels, and no additional nutrients were added to the system.

Tilapia (*Oreochromis* sp.) was used as the growing fish. Tilapia is a warm-water species that grow well in recirculating tanks and is tolerant to fluctuating water conditions such as pH, temperature, DO, and TAN concentration. No fish mortality occurred during the experimental period. Tilapia in each tank at average stocking density of 17.8 ± 8.0 kg/m^3 were fed daily with commercial fish feed, classic trout, 3.5 mm diameter (Skretting, Utah, USA). Feeding rates were kept constant at a harvesting cycle. Pak choi (*Brassica rapa* L. *chinensis*) and lettuce (*Lactuca sativa longifolia* cv. *Jericho*) were selected for this study due to their popularity as leafy vegetables and better growth in soilless systems (Kratky, 2010). Water in the fish tanks was continuously mixed by aeration using fine diffusers, and the HLR was kept constant in each experiment. The aquaponic systems were operated at varying HLRs (e.g., 0.5, 1.0, 1.5, 2.0, and 2.5 m^3/m^2-day) and two DO concentrations (low DO and high DO, see values in Table 1) for both pak choi and lettuce. At a harvesting cycle (run no., see Tables 1 and 2), two conditions were compared. Low DO conditions are defined as the minimum DO level in which fish consumed feed without stress (Popma and Masser, 1999), and high DO conditions are defined as the DO levels (5.88–7.44 mg/L) in which a fish tank was supplied with a maximum aeration rate of an air pump used in this study (16 L/minute). The DO in the fish tanks were maintained by constant aeration. The pH in the tanks was maintained between 6.7 and 7.2 by using a 1:2 mixture of KOH:$Ca(OH)_2$ (Rakocy, 2007). The water temperature was not controlled, but it remained between 25 and 30 °C throughout the operation of the system, which is considered within the comfort range for the growth of tilapia (Popma and Masser, 1999). The vegetable seeds were germinated for 14 days before being transplanted into the hydroponic beds. The pak choi and lettuce were harvested at the end of 37 and 32 days of transplantation, respectively.

To eliminate nitrogen transformation associated with plants (sections 3.3 and 3.5), aquaponic systems without plants at high DO (DO: 6.9 ± 0.4 mg/L) and low DO (DO: 3.0 ± 0.4 mg/L) concentrations in the fish tank (inlet of biofilters) were run simultaneously and compared over 12 days. The systems were operated at HLR of 1.5 m^3/m^2-day, and fish were fed at a constant feeding rate of 35 g/day. The recirculating waters of aquaponic systems were mixed thoroughly to obtain the same initial concentration of NO_3^- and $\delta^{15}N$ of NO_3^- prior to the start of the plant-less experiment. To study the effect of feeding rate on denitrification, lettuce-based aquaponic systems (HLR of 1.5 m^3/m^2-day) operated at two constant feeding rates (35 and 50 g/day) were compared in section 3.6.