agriculture

Brief Report

Fish Effluent as a Source of Water and Nutrients for Sustainable Urban Agriculture

Brunno S. Cerozi [1,*], Caitlin G. Arlotta [2] and Matthew L. Richardson [2]

[1] Department of Animal Science, College of Agriculture, University of Sao Paulo, Sao Paulo 13418-900, Brazil
[2] Center for Urban Research, Engagement and Scholarship, University of the District of Columbia, Washington, DC 20008, USA
* Correspondence: brunno.cerozi@usp.br

Abstract: Integrating urban agriculture with aquaculture can reduce the use and cost of water, competition for water, chemical fertilizers, and environmental impact of discharging nutrient-rich agricultural water into fresh and saltwater bodies. In addition, aquaculture in cities can directly benefit human health by providing a local source of lean protein. Despite the potential advantages, few studies have demonstrated the feasibility and production advantages of using aquaculture wastewater to fertigate specialty crops in an urban environment. Therefore, we grew four spring crops (bok choy, tatsoi, radish, turnip) and two fall crops (pole beans, sugar snap peas) in nutrient-rich effluent from fish aquaculture versus well or municipal water to evaluate whether the effluent improved soil fertility and crop production. The fish effluent resulted in changes to the soil through an increase in pH and potassium and to crop production through a 9.1% increase in the number of pole beans (mass of beans also trended toward significance). The soils we used were relatively nutrient-rich prior to the application of the fish effluent, which may be responsible for the limited impact, and differences may be more apparent in acidic and nutrient-poor soils or when fertigation is used over a longer duration.

Keywords: aquaculture; fertigation; soil nutrient; pole beans; potassium; soil pH; irrigation; water quality

Citation: Cerozi, B.S.; Arlotta, C.G.; Richardson, M.L. Fish Effluent as a Source of Water and Nutrients for Sustainable Urban Agriculture. *Agriculture* **2022**, *12*, 1975. https://doi.org/10.3390/agriculture12121975

Academic Editor: Ronald K. Luz

Received: 6 October 2022
Accepted: 18 November 2022
Published: 22 November 2022

1. Introduction

Cities place immense pressure on resources at local, regional, and global scales. The continuous growth of urban populations with the concomitant exploitation of natural resources is a major challenge for achieving environmental sustainability [1]. The food system needed to support a growing population is a large contributor to environmental impacts worldwide [2]. The food system produces 19–29% of global greenhouse gas (GHG) emissions [3] at all stages of its life cycle, from preproduction activities (e.g., production of animal feeds, fertilizers, and pesticides), to production activities (e.g., agriculture), to postproduction activities (e.g., primary and secondary processing, storage, packaging, transport, refrigeration, retail activities, catering and domestic food preparation and consumption, and waste management) [3,4]. Recognizing the current and future dynamics in food systems are crucial to making cities inclusive, healthy, resilient, and sustainable [5].

Novel urban food systems have been designed and deployed in cities worldwide, driven by principles of sustainability and resource use efficiency [1,6]. Community gardens, green roofs, urban farms that span several city blocks, and intensive hydroponic or aquaculture facilities are all examples of urban agriculture that can produce nutritious specialty crops [7–9] and satisfy a substantial proportion of local food demand [10]. Most produce from urban agriculture is used for consumption by households and sold in local markets, which helps alleviate urban food deserts [11] while shortening transportation distances [12]. Urban agriculture also has the potential to benefit the nutritional health of a community [13–15], create business opportunities for urban farmers and neighborhoods [16], improve social cohesion and ecosystem awareness [11], and mitigate urban heat islands, in part, by reducing energy needed to cool buildings [17].

Urban agriculture in the United States mostly relies on city water for irrigation (MLR, unpublished data) but limiting the use of water will be of fundamental importance to achieve sustainability and reduce cost and competition with domestic and industrial demands for a potentially scarce resource [18]. Integrating urban agriculture with aquaculture (the farming of aquatic plants and animals) has several advantages, such as reducing: the use and cost of water; competition for water; chemical fertilizers; and environmental impact of discharging nutrient-rich agricultural water into fresh and saltwater [19]. Fish farming coupled with irrigation structures may also improve the cost–benefit ratio of agriculture and aquaculture simultaneously. The income from selling fish can offset costs of obtaining water. Raising fish in water used to irrigate crops has the potential to add substantial amounts of nutrients (metabolic by-products of fish production) to the water, thus reducing the need for commercial fertilizers for crops. A major portion of a crop's nutritional demand can be supplied from the effluent from fish production [20]. Despite the potential advantages of using aquaponics technology, few studies have demonstrated the feasibility and production advantages of using aquaculture wastewater to fertigate field crops in the urban environment. Therefore, we used four spring crops and two fall crops grown in nutrient-rich effluent from fish aquaculture versus well or municipal water to evaluate whether this affected soil fertility and crop production.

2. Materials and Methods

2.1. Aquaculture System and Fish Culture Conditions

The recirculating fish culture system was maintained in a climate-controlled greenhouse equipped with fans and thermostats (Beltsville, MD, USA). The water recirculated at a flow rate of 1 m^3 h^{-1} from two fish tanks (4000 L) to a drum filter, two biofilters (400 L total), a sump collector tank (200 L), and a back to the fish tanks. Approximately 150 L of water was transferred from the sump container to a storage tote weekly for irrigating crops and replaced with municipal water. The tanks contained 648 blue tilapia with an approximate total weight of 125 kg. Fish were fed daily with 400 g of a commercial feed (Purina® AquaMax® Pond Fish 2000, Purina Mills, St. Louis, MO, USA). We measured water quality parameters (ammonia, nitrite, and nitrate) weekly with an API Master Kit (Aquarium Pharmaceuticals, Inc., Chalfont, PA, USA). The system received equal amounts of calcium carbonate and potassium hydroxide as needed to maintain a water pH of 6.8.

2.2. Plant Growing Conditions and Experimental Design for Spring Crops

A high tunnel (30.48 m long × 9.1 m wide × 4.6 m high) was covered with a 6-mil thick double-layered polyethylene film (Sun Master®, Farmtek, Dyersville, IA, USA). There were five rows of approximately 15.2 m in length each and within each row there were four blocks (20 total blocks, numbered from 1–20) with each block containing four crops: tatsoi, bok choy, radish, and turnip. We randomly assigned the layout of the crops within each block. Half the blocks within each row received aquaponics effluent and half received municipal water. Therefore, there were a total of 10 replicated blocks for each crop receiving effluent and 10 receiving water. We randomly selected which treatment would be applied to the blocks numbered 1 and 2 and then alternated the treatments for each subsequent pair of blocks. We used drip tape (Model 510-12-450, Rivulis Irrigation Inc., San Diego, CA, USA) with a dripper spacing of 30 cm in each row to apply the irrigation treatments. Plants were watered from 45 to 120 min as needed every other day.

Tatsoi (variety "Tatsoi") and bok choy (variety "Black Summer") were planted on 2 February 2019 in plastic trays and maintained in a greenhouse until seedlings were transplanted into the loam soil in the high tunnel on 19 March at 30 cm spacing. The radish (variety "Cherrette") and turnip (variety "Hakurei") were direct seeded in the high tunnel on 20 March, and seedlings were later thinned on 3 April to approximately 5–8 cm of spacing. We harvested tatsoi and bok choy between 23–26 April 2019, with equal numbers of plants harvested from each block on each day. The entire edible portion was separated from the roots and weighed. We harvested radishes and turnips 26–29 April and 6 May 2019, respectively, and weighed the entire plant.

2.3. Plant Growing Conditions and Experimental Design for Fall Crops

In the summer, a field row was prepared (30 m long × 0.9 m wide) in an open field (Beltsville, MD, USA). This row was divided into ten consecutive blocks, with each block containing both tested crops: pole beans and peas. We randomly assigned the layout of the crops within each block. We randomly selected the irrigation treatment applied to the first block and then alternated treatments for each subsequent block such that half the blocks received aquaponics effluent and half received well water.

We direct-seeded pole beans (variety "Monte Gusto") and peas (variety "Super Sugar Snap") 30 July 2020 and 11 August 2020, respectively. We then thinned the beans and peas to 8 cm spacing and ten plants per block each on 21 August and 31 August, respectively. We applied the irrigation treatments using drip tape (Model 508-12-450, RainFlo Irrigation, East Earl, PA, USA) with a dripper spacing of 30 cm. Plants were watered for 30 to 60 min as needed three times per week. Neither treatment was watered if rainfall was sufficient to irrigate. Crops were harvested three times per week from 24 September to 28 October 2020 (beans) and from 19 October to 16 November 2020 (peas). The number of bean and pea pods from each block was counted, and the total mass per crop per block was weighed at each harvest. The total number of plants per crop per block was adjusted if plants died.

2.4. Soil Samples

We collected soil samples before and after field experiments, one sample per block, using a soil auger in the center of each block to a depth of 15–25 cm. We mailed samples to a third-party, ISO 17025 accredited laboratory (Waters Agricultural Laboratories, Inc., Camilla, GA, USA), for analysis.

2.5. Statistical Analysis

Comparison between the two treatments (aquaculture effluent versus water) was performed using the Student's *t*-Test with TIBCO Statistica® (version 13.3.0, TIBCO Ltd., Palo Alto, CA, USA). Differences were considered significant when $p < 0.05$. Experimental data are expressed as means and standard deviation.

3. Results and Discussion

3.1. Soil Fertility

Soil pH was higher in blocks treated with aquaculture effluent, whereas all other soil fertility parameters were similar between treatments for the spring crop trial (Table 1). Soil pH was also higher in blocks treated with aquaculture effluent during the fall crops trial, along with potassium.

The higher soil pH and potassium concentration in plots receiving aquaculture effluent was possibly due to the potassium hydroxide and dolomitic lime added to control the pH in the aquaculture system. Several studies have reported variations in soil pH resulting from irrigation with effluents [21,22]. In general, the soil pH reflects the pH of the effluent used for fertigation [21]. Although the pH change was not dramatic, this effect shows that irrigation with aquaculture effluent might be more suitable for acidic soils than basic soils. In basic soils, one must routinely monitor the pH so it does not increase to undesired levels.

No major differences in soil fertility parameters between the two treatments were detected except for potassium, which may suggest that a single season is not sufficient for a high accumulation of nutrients in the soil. Other studies have also reported slight changes in soil fertility after fertigation with wastewater. For instance, Fonseca et al. [23] reported no variation in total carbon and phosphorous, but total nitrogen increased in soils irrigated with treated sewage effluent. It is worth noting that the high tunnel and field used for our research had been extensively used for agriculture for many years, thus background residual nutrients were expected to be present, which was demonstrated by the soil samples analyzed prior to the irrigation treatments (unpublished data).

Table 1. End-of-trial means ± standard deviation of soil fertility parameters in blocks irrigated with aquaculture effluent or water.

Soil Fertility	Treatments		*p*-Value
	Effluent	Water	
Spring crops			
pH	7.70 ± 0.12	7.46 ± 0.15	0.02
NO_3-N (ppm)	18.0 ± 6.6	15.4 ± 3.4	0.46
Phosphorus (kg/ha)	39.2 ± 5.1	38.6 ± 10.9	0.90
Potassium (kg/ha)	39.0 ± 6.6	36.3 ± 6.8	0.54
Organic matter (%)	8.82 ± 1.14	7.74 ± 1.09	0.34
Fall crops			
pH	7.28 ± 0.19	7.00 ± 0.24	0.01
NO_3-N (ppm)	7.19 ± 4.77	7.07 ± 3.78	0.95
Phosphorus (kg/ha)	70.9 ± 9.7	77.9 ± 18.4	0.30
Potassium (kg/ha)	330.4 ± 130.3	210.7 ± 39.7	0.01
Organic matter (%)	2.71 ± 0.27	2.65 ± 0.33	0.68

3.2. Plant Growth

The type of irrigation water had no effect on biomass of spring crops (Table 2). Irrigating fall crops with aquaculture effluent increased the number of beans by 9.1% ($p < 0.01$), and the total mass of beans was marginally non-significant. The number and mass of pea pods did not differ between irrigation treatments (Table 2).

Table 2. Mass (g) of four spring crops and number and mass (g) of two fall crops irrigated with either aquaculture effluent or water.

Crop	Treatments		*p*-Value
	Effluent	Water	
Bok choi (g)	397 ± 93	330 ± 74	0.10
Tatsoi (g)	305 ± 66	266 ± 64	0.19
Radish (g)	30 ± 10	27 ± 7	0.42
Turnip (g)	67 ± 28	55 ± 18	0.31
Pole beans (no.)	1056 ± 28	968 ± 56	0.01
Pole beans (g)	5189 ± 226	4826 ± 324	0.07
Snap pea pods (no.)	141 ± 61	141 ± 40	0.99
Snap pea pods (g)	656 ± 292	682 ± 208	0.90

Crops can produce high yields when supplied with aquaculture wastewater [24–26]. However, in our study most crops irrigated with aquaculture wastewater produced similar yield to those irrigated with plain water, possibly due to the history of previous agricultural practices and high soil nutrients where this study was carried out. Urban agricultural systems with nutrient-poor soil or no history of conventional agricultural practices may receive a prominent benefit from fertigating their crops with aquaculture effluent as opposed to plain water. The long-term use of fertigation may yield different results as well. Additionally, even in nutrient-rich soils, there could be benefits to using aquaponic wastewater on crops instead of commercial fertilizers, including being a more sustainable practice because waste is repurposed as fertilizer, economic savings are realized by eliminating the purchase of commercial fertilizers, and the carbon footprint of food production may be reduced by eliminating commercial fertilizers. Aquaculture also has distinct value in urban agriculture because it creates local production and access to a source of high-quality lean protein in the fish. Blue tilapia, the fish species selected for this experiment, is prevalent in aquaculture and hardy in a wide range of rearing conditions. Tilapia can gain weight with high feed efficiency at low-cost inputs, so it could be incorporated into urban agriculture without major impediments. Aquaculture can be an asset to the local community and its integration with urban specialty crops in an urban environment should be further explored.

In conclusion, aquaculture wastewater increased soil pH and potassium (in one of two instances) and increased the number of beans, whereas it had no effect on other soil fertility and measures of plant productivity. We attribute the lack of observable effects to the high fertility of the soil where this work was done and the short duration of the study. As next steps, we recommend trials in nutrient poor soils with crops that need high nutrient inputs and for multiple growing seasons. Additionally, a life cycle sustainability assessment of using aquaculture wastewater to fertilize crops versus conventional fertilizers would show the economic, environmental, and social costs and benefits of each practice.

Author Contributions: Conceptualization, B.S.C. and M.L.R.; methodology, B.S.C., C.G.A. and M.L.R.; formal analysis, B.S.C.; investigation, C.G.A. and M.L.R.; writing—original draft preparation, B.S.C.; writing—review and editing, C.G.A. and M.L.R.; supervision, M.L.R.; funding acquisition, M.L.R. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by a USDA-AMS Specialty Crop Block Grant (to MLR), agreement number AM170100XXXXG055.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We thank Brian Barnes and Christina Ashe for their help and two anonymous reviewers for their constructive feedback.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Al-Chalabi, M. Vertical farming: Skyscraper sustainability? *Sustain. Cities Soc.* **2015**, *18*, 74–77. [CrossRef]
2. Gren, Å.; Andersson, E. Being efficient and green by rethinking the urban-rural divide—Combining urban expansion and food production by integrating an ecosystem service perspective into urban planning. *Sustain. Cities Soc.* **2018**, *40*, 75–82. [CrossRef]
3. Vermeulen, S.J.; Campbell, B.M.; Ingram, J.S.I. Climate change and food systems. *Annu. Rev. Environ. Resour.* **2012**, *37*, 195–222. [CrossRef]
4. Camanzi, L.; Alikadic, A.; Compagnoni, L.; Merloni, E. The impact of greenhouse gas emissions in the EU food chain: A quantitative and economic assessment using an environmentally extended input-output approach. *J. Clean. Prod.* **2017**, *157*, 168–176. [CrossRef]
5. United Nations Department of Economic and Social Affairs, Population Division. *World Urbanization Prospects: The 2018 Revision*; ST/ESA/SER.A/420; United Nations: New York, NY, USA, 2019. [CrossRef]
6. Rufí-Salís, M.; Calvo, M.J.; Petit-Boix, A.; Villalba, G.; Gabarrell, X. Exploring nutrient recovery from hydroponics in urban agriculture: An environmental assessment. *Resour. Conserv. Recycl.* **2020**, *155*, 104683. [CrossRef]
7. Richardson, M.L.; Arlotta, C.G. Differential yield and nutrients of *Hibiscus sabdariffa* L. genotypes when grown in urban production systems. *Sci. Hortic.* **2021**, *288*, 110349. [CrossRef]
8. Richardson, M.L.; Arlotta, C.G. Producing cherry tomatoes in urban agriculture. *Horticulturae* **2022**, *8*, 274. [CrossRef]
9. Richardson, M.L.; Arlotta, C.G.; Lewers, K.S. Yield and nutrients of six cultivars of strawberries grown in five urban cropping systems. *Sci. Hortic.* **2021**, *294*, 110775. [CrossRef]
10. United States Department of Agriculture. Urban Agriculture Toolkit. United States Department of Agriculture. 2016. Available online: https://www.usda.gov/sites/default/files/documents/urban-agriculture-toolkit.pdf (accessed on 17 November 2022).
11. Attanayake, C.P.; Hettiarachchi, G.M.; Harms, A.; Presley, D.; Martin, S.; Pierzynski, G.M. Field evaluations on soil plant transfer of lead from an urban garden soil. *J. Environ. Qual.* **2014**, *43*, 475–487. [CrossRef] [PubMed]
12. Jones, A. An environmental assessment of food supply chains: A case study on dessert apples. *Environ. Manag.* **2002**, *30*, 560–576. [CrossRef] [PubMed]
13. Brown, K.H.; Jameton, A.L. Public health implications of urban agriculture. *J. Public Health Policy* **2000**, *21*, 20. [CrossRef] [PubMed]
14. Luthria, D.L.; Tareq, F.S.; Kotha, R.R.; Marupaka, R.; Harnly, J.M.; Arlotta, C.G.; Richardson, M.L. Variation of phytochemicals in leaves of seven accessions of *Hibiscus sabdariffa* grown under field, green roof, and high tunnel conditions. *ACS Food Sci. Technol.* **2021**, *1*, 1702–1710. [CrossRef]
15. Taylor, J.; Hanumappa, M.; Miller, L.; Shane, B.; Richardson, M. Facilitating multifunctional green infrastructure planning in Washington, DC through a Tableau interface. *Sustainability* **2021**, *13*, 8390. [CrossRef]

16. Pearson, L.J.; Pearson, L.; Pearson, C.J. Sustainable urban agriculture: Stocktake and opportunities. *Int. J. Agric. Sustain.* **2010**, *8*, 7–19. [CrossRef]
17. Tsilini, V.; Papantoniou, S.; Kolokotsa, D.-D.; Maria, E.-A. Urban gardens as a solution to energy poverty and urban heat island. *Sustain. Cities Soc.* **2015**, *14*, 323–333. [CrossRef]
18. Zhang, J.; Chen, Y.; Li, Z.; Song, J.; Fang, G.; Li, Y.; Zhang, Q. Study on the utilization efficiency of land and water resources in the Aral Sea Basin, Central Asia. *Sustain. Cities Soc.* **2019**, *51*, 101693. [CrossRef]
19. Castro, R.S.; Azevedo, C.M.B.; Bezerra-Neto, F. Increasing cherry tomato yield using fish effluent as irrigation water in Northeast Brazil. *Sci. Hortic.* **2006**, *110*, 44–50. [CrossRef]
20. Robaina, L.; Pirhonen, J.; Mente, E.; Sánchez, J.; Goosen, N. Fish Diets in Aquaponics. In *Aquaponics Food Production Systems*; Goddek, G.B.S., Joyce, A., Kotzen, B., Eds.; Springer: Cham, Switzerland, 2019; pp. 333–352.
21. Xu, J.; Wu, L.; Chang, A.C.; Zhang, Y. Impact of long-term reclaimed wastewater irrigation on agricultural soils: A preliminary assessment. *J. Hazard. Mater.* **2010**, *183*, 780–786. [CrossRef] [PubMed]
22. Jaramillo, M.F.; Restrepo, I. Wastewater reuse in agriculture: A review about its limitations and benefits. *Sustainability* **2017**, *9*, 1734. [CrossRef]
23. Da Fonseca, A.F.; Melfi, A.J.; Montes, C.R. Maize growth and changes in soil fertility after irrigation with treated sewage effluent. I. Plant dry matter yield and soil nitrogen and phosphorus availability. *Commun. Soil Sci. Plant Anal.* **2005**, *36*, 1965–1981. [CrossRef]
24. Hussain, G.; Al-Jaloud, A.A. Effect of irrigation and nitrogen on water use efficiency of wheat in Saudi Arabia. *Agric. Water Manag.* **1995**, *27*, 143–153. [CrossRef]
25. Al-Jaloud, A.A.; Hussian, G.; Karimulla, S.; Al-Hamidi, A.H. Effect of irrigation and nitrogen on yield and yield components of two rapeseed cultivars. *Agric. Water Manag.* **1996**, *30*, 57–68. [CrossRef]
26. Buhmann, A.; Papenbrock, J. Biofiltering of aquaculture effluents by halophytic plants: Basic principles, current uses and future perspectives. *Environ. Exp. Bot.* **2013**, *92*, 122–133. [CrossRef]