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Fishpond Water Potential on Vineyard Soil Health: An Exploratory Study of a Circular System

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Abstract: Climate variabilities continue to hinder sustainable food production with an increasing need to use resources such as water and soil efficiently. The quest for these efficiencies in agriculture systems drives innovations among farmers. However, limited data on farm practices, such as irrigating with fishpond water and their effects on soil health, hinder their adoption as climate-smart innovations. In a nearly twenty-year-old vineyard with two distinct irrigation practices (irrigation with recycled fishpond water and irrigation with ditch water), this study was carried out as an exploratory study to investigate the influence of recycling fishpond water on soil health parameters and yield. Soil samples were taken from two different irrigation fields in summer and winter for lab analysis on soil health parameters (organic matter and carbon, nitrogen, phosphorus, microbial biomass, and microbial respiration). Averages over the two seasons of field measurements indicate that long-term irrigation using recycling fishpond water increased the measured soil health parameters (organic matter (13%), organic carbon (30%), nitrogen (17%), phosphorus (46%), microbial biomass (18%), and microbial respiration (56%)) in both summer and winter months when compared to fields receiving just ditchwater irrigation. Using water in a way that can improve soil health increases biodiversity and improves the efficiency of our limited water resources in semi-arid agricultural lands, and this strategy is a climate-smart tool that can help reduce water risks in dry agricultural regions such as Arizona.

Keywords: circular agriculture; fishpond water; irrigation; soil health; regenerative agriculture

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1. Introduction

Water, soil health, and biodiversity are major issues in semi-arid agriculture systems, especially as climate variabilities continue to increase and hinder sustainable food production. Nitrogen and phosphorus play key roles in plant development, and they have been harnessed in agricultural systems to improve crop yield and profitability [1,2] through synthetic and/or organic fertilizer source applications. In most agricultural systems, synthetic fertilizers are used to meet crop nutrient requirements. The efficient use of both organic and synthetic fertilizer sources is important to avoid excessive use in agriculture [3], environmental risks such as eutrophication, the leaching of nutrients into our aquifers, and more [4–8]. The need for these efficiencies in agriculture is shifting many practitioners' approaches toward circular agriculture systems.

Circular agriculture is a re-emerging ancient practice that was prominent among preindustrial societies but was pushed aside by modern large-scale farming based on monoculture [9] and highly intensive practices that prioritized farm-level profits over environmental concerns. The focus of circular agriculture is on the minimal use of external inputs, closing nutrient loops, and regenerating soils with practices that have lesser negative impacts on human health and the environment. Circular agriculture emphasizes promoting farming practices such as mixed cropping, crop rotations, waste reuse, and agroforestry practices [9] that are regenerative in nature for both plant and soil health improvement. In practice, a wider-scale acceptance and use of these regenerative and circular agricultural practices is common among smallholder farms, and circular practices can use resources more efficiently and reduce our agricultural ecological footprint [10], especially in resource-constraint areas such as arid and semi-arid regions.

In semi-arid regions, irrigation water, soil organic matter, and carbon are key drivers for improving soil health and providing sustainable crop production regimes. Soil organic matter and carbon are linear to soil nitrogen and phosphorus available to plants [11] and are good soil health indicators. Soil health is a concept that refers to the functionality of soil and its ability to maintain a balanced ecosystem with high biodiversity and productivity that is responsive to management practices [12,13]. Also, soil health includes the role of soil on water quality, climate change, and human health [14]. Techniques such as intercropping, cover crops, reduced tillage, no-till, nutrient management, and manure applications are high-ranking sustainable approaches that have been recommended for soil health improvement in the context of circular agriculture [15,16].

Animal waste products can also be incorporated into crop production systems as farm inputs, providing a nitrogen source with additional benefits such as improved soil structure, water holding capacity, and soil carbon, as well as the activity of beneficial microorganisms in the soil [17]. The proper management of all nitrogen sources is key to minimizing leaching into drinking water aquifers, whereas organic sources of fertilizers such as manure, plant waste material, and compost are challenging to manage well due to their slow and unpredicted release [18,19]. Also, the processing, handling, and transportation of manures has been a major limitation, but the concept of the "manure shed" (which has been identified as a major solution to the logistic problem of transporting manure) can be advantageous if maximized [20].

Exploring the interplays between an agroecosystem is also crucial, as nutrient pools that have been considered waste in some agricultural systems can be easily reutilized in other systems, thereby improving N use efficiencies within and between agroecosystems. Elsewhere, the irrigation of crop plants with water from fishponds has been demonstrated to improve crop yields [21,22]. They can also be used directly in hydroponic and/or aeroponic farming systems as nutritional sources for plants. Alternatively, fishpond effluent could be a good irrigation water source for pasture and crop fields as water scarcity continues to increase around the globe due to warmer temperatures, growing populations, and climate variability. For instance, in the United States and across the globe, the use of irrigation water has increased significantly in recent decades due to multiple extended drought conditions with a need for the sustainable use of irrigation water in agriculture. Urgency persists in semi-arid regions that have record low water levels such as the Southwest United States. The use of integrated approaches that combine technology with best management practices is needed to develop sustainable approaches to tackle our water crises [23,24] with additional benefits such as soil health. To contribute to the concept of sustainable water use in a circular agroecosystem that improves soil health and biodiversity for a resilient food system in Northern Arizona, this study was conceived. Here, we investigate the effect of irrigating with fishpond vs. ditchwater (control) on soil (organic matter, carbon, nitrogen, and phosphorus), microbial activities (respiration and biomass), and grape crop yields after two decades.

This exploratory study aims to understand how long-term furrow irrigation with recycling fishpond water may influence soil health (organic matter and carbon, nitrogen, phosphorus, and soil microbial biomass and respiration) in a semi-arid vineyard soil compared to furrow irrigation with just ditchwater from a mountain-fed creek.

2. Materials and Methods

2.1. Study Location, Field Layout, and Soil Sampling

Location: This exploratory study was carried out at Clear Creek Vineyard, Camp Verde, AZ, USA, where the irrigation system currently practiced was installed over two decades ago (Figure 1).

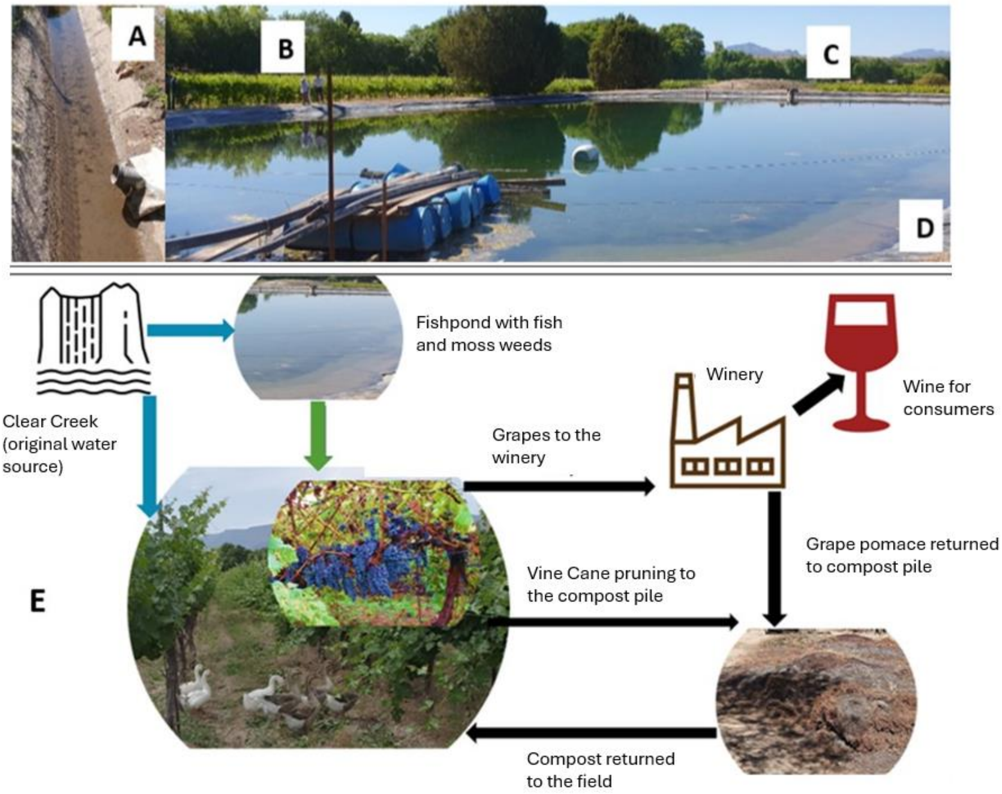

Figure 1. Clear Creek Vineyard, Camp Verde, Arizona, United States. The vineyard (**B**) is irrigated with either direct ditchwater (**A**) from Clear Creek near Camp Verde or stored in a fishpond (**D**) for 3–4 weeks before using it for the vineyard (**C**) in a circular agricultural setup (**E**).

History of vineyard: Clear Creek Vineyard and Winery was originally a horse and cattle pasture dating back to 1875, which changed after the current owner bought the property in 1999 and started a vineyard and winery. The vineyard is set up as a circular farm as all waste is composted and reused on the farm and only the wine processed from the grapes leaves the farm (Figure 1E).

The fishpond and creek: The fishpond (Figure 1D) was constructed and stocked with fish in 2005 (Figure 1A). The pond has fish species such as smallmouth bass, largemouth bass, bluegill, catfish, and trout in the winter. The pond also has moss weed, which serves as feedstock for the fish. The moss weed population is controlled every two years by manually pulling some out into the field. The chemical properties of both creek and pond water are presented in Table 1.

Planting distance of vines: The planting distance of the vines is 2 m between vines in the row and 3 m between the vine rows with a metal trellis system for training the vines.

Irrigation: The farm applies furrow irrigation from either the ditch or fishpond water at 100 cubic meters per hectare every three weeks depending on the weather.

Soil amendment and weed control: The compost made on the farm with waste from the winery and poultry manure sourced from Hickman Farm (Phoenix, AZ, USA) is applied to both fields at the same rate of two tons per hectare in spring. Weed Wacker, hand pulling, and geese are used alternatively as needed to control weeds and pests in the vineyard on both sides of the fields.

Pruning: Vine canes are pruned from February to March before bud break, and the management of excessive growth and fruit set is carried out in June after fruits are set. The June pruning is performed to have adequate airflow in the vineyard to prevent fungal infections and have quality fruit clusters with high sugar content.

Table 1. Chemical properties of the ditch/creek and pond water at Clear Creek Vineyard, Arizona.

	Ditchwater	Fishpond Water
pH	8.5	8.1
Sodium absorption ratio	0.2	0.3
Electrical conductivity (mmho/cm)	0.4	0.3
Cations (me/L)	4.0	4.1
Anions (me/L)	4.1	3.4
Sodium (mg/L)	7.0	8.0
Calcium (mg/L)	36.1	30.8
Magnesium (mg/L)	22.0	26.0
Potassium (mg/L)	3.0	4.0
Total hardness (mg/L)	182.0	186.0
Nitrate (mg/L)	0.1	0.1
Sulfur (mg/L)	2.0	1.0
CO_3 (mg/L)	3.7	<1.0
HCO_3 (mg/L)	227.0	185.0
Chloride (mg/L)	4.0	10.0
Total alkalinity (mg/L)	192.0	154.0

Field layout and Experimental design: The vineyard has historically been irrigated in two fields (side-by-side along a slight slope gradient) based on the type of water (ditch or fishpond) used for irrigation. The field irrigated with ditchwater has received water only from the ditch since 1999, while the field irrigated from the fishpond has received irrigation water only from the fishpond since 2005. To replicate our collection of samples, each field was subdivided into three sections along the slope gradient.

Soil sampling: Soil samples were collected one foot from vine trunks at 0–15 cm depth in the summer (June) and winter (December) of 2021. On each replicate, ten composite samples were collected within the grape plants using a soil probe. The soil samples were collected on ice in a chest and frozen immediately after sampling at −20 °C for one week before shipping with ice packs to the laboratory (Ward Laboratories, Inc., Kearney, NE, USA) for soil health indicator measurements.

2.2. Soil Analysis

The Haney test was used to analyze N, P, organic carbon, organic matter, and soil respiration at Ward Laboratories (website at www.wardlab.com), as described below.

Soil preparation: Each soil sample received at Ward Laboratories was dried at 50 °C, ground to pass a 2 mm sieve, and weighed into two 50 mL Erlenmeyer flasks (4 g each) and one 50 mL plastic beaker (40 g) that is perforated to allow water infiltration.

Soil NH_4-N and PO_4-P: Two 4 g samples were extracted with 40 mL of DI water and 40 mL of N-(3-chlorophenyl)-2-(3-methoxyphenyl) acetamide (H3A) (Sigma-Aldrich, Inc., St. Louis, MO, USA), respectively. The soil extractant mixtures were shaken for 10 min, centrifuged for 5 min, and filtered through Whatman 2V filter paper. The water and H3A extracts were analyzed on a Lachat 8000 flow injection analyzer (Hach Company, Loveland, CO, USA) for NO_3-N, NH_4-N, and PO_4-P [25].

Organic carbon and matter: The water extract from the 4 g soil samples was analyzed with Teledyne Tekmar Torch C: N analyzer (LabX Media Group, Midland, ON, Canada) for water-extractable organic C and N, which represent water-extractable organic C (WEOC) or the amount of organic C in the soil, which is roughly 80 times smaller than the total soil organic C pool (% organic matter) and reflects the energy source feeding soil microbes [25].

Total soil microbial biomass: The phospholipid fatty acid (PLFA) analytical method was used to determine soil microbial biomass. Frozen soil samples were shipped on dry ice to Ward Laboratories (WARD Laboratories, Inc., Kearney, NE, USA) for processing and analysis. The PLFA analyses in Ward Laboratories were based on the method described in [26], where total soil lipid fractions were extracted by shaking a mixture of 2 g frozen soil in 9.5 mL of a liquid buffer of dichloromethane, methanol, and citrate buffer (1:2:0.8 v/v) consistently for 1 h at 240 rpm. After lipid-class separation and creating fatty acid methyl esters, samples were then analyzed using an Agilent 7890A GC (OGMI, Ramsey, NJ, USA) equipped with a 7693 autosampler instrument and a flame ionization detector, which quantified the total microbial biomass.

Soil microbial respiration: The 40 g soil sample was analyzed in a 24 h incubation test at 24 °C. The soil was wetted through capillary action with 20 mL of deionized (DI) water in a 236.6 mL glass jar, capped, and incubated for 24 h. After 24 h, the gas inside the jar was analyzed using an infrared gas analyzer (IRGA) Li-Cor 840A (LI-COR Biosciences, Lincoln, NE, USA) for CO^2-C [25].

Statistical analysis: Data were first checked for normality using Proc GLM with plot = diagnostics followed by a t-test at p equal or less than 0.05 using two-tailed distributions and homogeneity of variances (homoscedasticity).

3. Exploratory Results

3.1. Grape Yields

Irrigation with fishpond water increased *Cabernet sauvignon* grape fruit cluster numbers, length (Figure 2a,b), and weight per plant and hectare when compared to the control treatment of just ditchwater (Figure 2c,d).

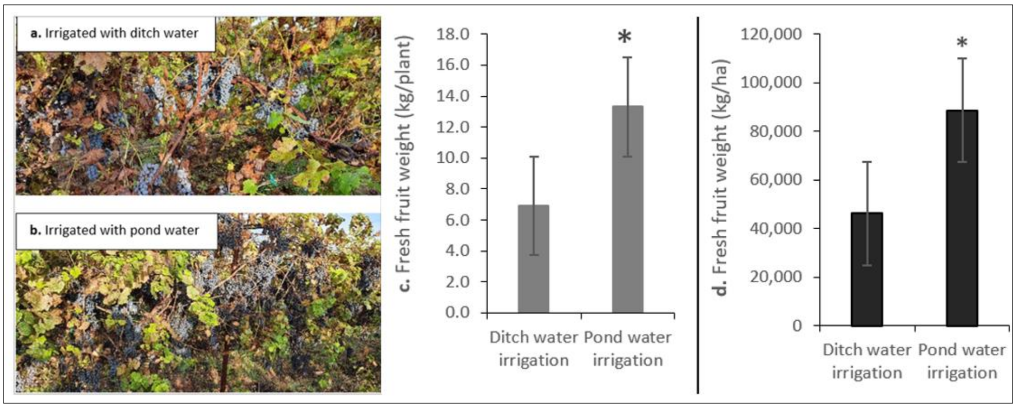

Figure 2. Average grape (Cabernet sauvignon variety) yields based on the two fields (ditchwater and fishpond irrigation water) (* = different at p = 0.05).

3.2. Soil pH, Organic Matter, and Carbon

Interestingly, ditchwater stored in the fishpond with aquatic life before using it to irrigate the vineyards seems to have increased organic matter by 17% in the summer and 8% in the winter soil samples. Also, in fishpond irrigation, the total organic carbon was higher in both summer and winter soil samples at 40% and 18%, respectively, when compared to irrigating the ditchwater coming directly from Clear Creek (Table 2). Generally, summer month soil samples had higher organic matter and carbon, and rather minimal differences were observed in organic matter and carbon in the winter soil samples (Table 2). Also, no differences were observed in the soil pH between sampling seasons (Table 2).

3.3. Soil Nitrate and Ammonium

The use of fishpond water increased organic total N in both summer and winter soil samples by 36% and 10%, respectively, when compared to ditchwater irrigation. Inorganic N was also slightly higher in the fishpond-irrigated section with a 13% increase in both seasons. Nitrate analysis showed that fishpond irrigation had a minimal advantage over ditchwater irrigation in both summer and winter at 9%, with lower values in the winter samples. Ammonium forms between the treatments in the two sampling periods showed relatively high values in the fishpond-irrigated field for the summer (Table 3).

Table 2. Effects of fishpond irrigation water on semi-arid vineyard soil pH and organic matter.

	Soil pH	Organic Matter (%)	Total Organic C (mg C/kg Soil)
		Summer soil samples	
Ditchwater-irrigated field	8.1 [a]	3.9 [b]	138.7 [b]
Fishpond-water-irrigated field	8.1 [a]	4.6 [a]	193.7 [a]
t-test (p = 0.05)	na	0.0	0.0
		Winter soil samples	
Ditchwater-irrigated field	8.1 [a]	3.7 [a]	123.3 [a]
Fishpond-water-irrigated field	8.0 [a]	4.0 [a]	145.7 [a]
t-test (p = 0.05)	na	0.6	0.8

Same letter = no difference at p = 0.05. na = not applicable.

Table 3. Effects of recycling fishpond and direct ditch irrigation water on semi-arid vineyard soil nitrogen.

	Organic Nitrogen (mg N/k Soil)	Inorganic Nitrogen (mg N/kg Soil)	Nitrate (mg N/kg Soil)	Ammonium (mg N/kg Soil)
		Summer soil samples		
Ditchwater-irrigated field	24.0 [a]	47.6 [a]	46.5 [a]	1.1 [a]
Fishpond-water-irrigated field	32.7 [a]	53.7 [a]	50.7 [a]	3.0 [a]
t-test (p = 0.05)	0.1	0.1	0.1	0.1
		Winter soil samples		
Ditchwater-irrigated field	19.2 [a]	30.9 [a]	30.2 [a]	1.3 [a]
Fishpond-water-irrigated field	21.2 [a]	34.9 [a]	33.0 [a]	1.9 [a]
t-test (p = 0.05)	0.3	0.1	0.1	0.4

Same letter = no difference at p = 0.05.

3.4. Soil Phosphorus

The fishpond irrigation water had higher effects on inorganic phosphorus at 47%; however, a 4% increase for organic phosphorus was observed in favor of irrigation with just ditchwater in the summer soil samples. Considering the winter soil samples, when compared to irrigating with only ditchwater, fishpond irrigation seems to have the advantage of increasing both organic P (17%) and inorganic P (19%) (Table 4).

Table 4. Effects of recycling fishpond and direct ditch irrigation water on semi-arid vineyard soil phosphorus.

	Inorganic Phosphorus (mg P/kg Soil)	Organic Phosphorus (mg P/kg Soil)
	Summer soil samples	
Ditchwater-irrigated field	23.3 [b]	9.0 [a]
Fishpond-water-irrigated field	34.3 [a]	8.6 [a]
t-test (p = 0.05)	0.0	0.8
	Winter soil samples	
Ditchwater-irrigated field	14.4 [b]	7.4 [b]
Fishpond-water-irrigated field	17.1 [a]	8.7 [a]
t-test (p = 0.05)	0.00	0.0

Same letter = no difference at p = 0.05.

3.5. Soil Microbial Respiration and Total Microbial Biomass

After almost two decades of applying irrigation water from the fishpond, soil microbial respiration and biomass have increased when compared to direct irrigation with only ditchwater (Table 5). In the summer months soil samples, the total microbial biomass, total bacterial biomass, total fungal biomass, and soil respiration increased by 13%, 27%, 29%, and 59%, respectively, under fishpond irrigation when compared to ditchwater irrigation. In the winter soil samples, the total microbial biomass, total bacterial biomass, total fungal biomass, and soil respiration increased at 12%, 11%, 30%, and 47%, respectively, under fishpond irrigation when compared to ditchwater irrigation. Comparatively, summer samples had higher microbial activities than the winter samples (Table 5 and [27]).

Table 5. Effects of ditch and fishpond irrigation water on semi-arid vineyard soil's total soil microbial biomass, bacterial biomass, fungal biomass, and microbial respiration.

	Total Microbial Biomass (PLFA ng/g)	Total Bacterial Biomass (PLFA ng/g)	Total Fungal Biomass (PLFA ng/g)	Soil Respiration (mg CO_2-C /kg Soil)
		Summer soil samples		
Ditchwater-irrigated field	1807.0 [a]	652.7 [a]	101.5 [a]	88.7 [b]
Fishpond-water-irrigated field	2041.2 [a]	826.1 [a]	131.0 [a]	141.0 [a]
t-test (p = 0.05)	0.6	0.1	0.1	0.0
		Winter soil samples		
Ditchwater-irrigated field	1064.1 [a]	340.1 [a]	5.9 [a]	38.2 [b]
Fishpond-water-irrigated field	1189.9 [a]	378.4 [a]	7.7 [a]	56.2 [a]
t-test (p = 0.05)	0.5	0.5	0.8	0.0

Same letter = no difference at p = 0.05.

4. Discussion

Irrigation water and soil health are major challenges for sustainable and profitable crop production in the Southwest United States and semi-arid regions in general, especially among small-to-medium-sized farms due to increasing temperatures, drought, and reduced aquifer and reservoir levels. The Southwest United States can be more resilient in food production using circular agricultural systems by using waste streams more efficiently, closing nutrient loops, regenerating soils, and minimizing environmental impacts [9]. This study highlights the effects of recycling fishpond irrigation water as a catalyst for improving soil health and biodiversity in a circular agricultural model vineyard in Northern Arizona.

The study results reveal that watering with fishpond water for almost two decades has positively affected grape yields compared to irrigating with just ditchwater (Figure 2), which is consistent with similar studies from other locations and systems. In different studies, fishpond water increased paddy rice [21,22,28] and wheat [29] yields. The positive yield effects from fishponds relate to soil fertility and health improvements, as observed by others [28,29], which is also consistent with the findings of this study. Irrigating with fishpond water improved soil health compared to irrigating with just ditchwater (Tables 1–4).

Yuan et al. reported higher paddy rice yields [28], while Abdelraouf and Ragab reported a yield increase in wheat [29] from using fishpond water compared to freshwater, which was associated with increases in nitrogen and phosphorus and was also confirmed by this study (Tables 3 and 4). Recall that both ditchwater- and fishpond-water-irrigated fields receive compost and manure from the geese on the farm. Thus, the additional nitrogen and phosphorus from fishpond-water-irrigated fields are mainly related to droppings and organic matter from fish and other living organisms such as moss, as well as the migratory birds visiting the pond during the winter. Therefore, these systems represent a classical integration of fish farming into semi-arid agriculture, where nutrients are sustainably recycled from biodiversity and integrated into agroecosystems with the extra benefits of harvesting fish from the pond for food or household income.

Similarly, the highest amount of organic and inorganic phosphorous recorded was in the soil irrigated with fishpond water (Table 4). Phosphorus in the soil system is mainly available as non-labile P, labile P, and solution P [30]. However, the highest amount of phosphorous was in the summer for all treatments, which is related to organic matter and carbon that is mostly in the mineralized form during the summer (Table 4). Not only did this integration benefit major nutrient cycles from the increased biodiversity, but the organic matter content of the soil also increased in the fishpond-irrigated fields (Table 2). Organic matter and carbon have a linear correlation with nitrogen and phosphorus availability [11], which could be why more nitrogen and phosphorus were observed in the field irrigated with fishpond water. The higher organic matter and carbon in the soils of fishpond-irrigated fields could be attributed to the fish and bird feces and moss plants in the pond, which supports soil health for more biomass in those areas. Though no differences were observed in the soil pH, the slightly lower pH of the pond water (Table 1) could support the higher P availability observed in Table 4.

The activity of soil microorganisms is of great importance to soil health [31]. Therefore, irrigation from the pond water not only added substrate in the form of organic matter but also induced respiration and microbial activities such as microbial, fungal, and bacterial biomass. The increase in microbial activities in the fishpond treatment could be related to lower EC values for the fishpond water when compared to the ditchwater's slightly higher values (Table 1). According to Rietz and Haynes, irrigation water with higher EC and salt reduces microbial activities [32], which is similar to the findings of this study, except that the fishpond water in this study seems to have fairly high salt values, which makes it difficult to relate the positive soil health activities to low EC or salt values. Also, Chen et al. reported a higher diversity in the bacterial community they studied in aquaculture-wastewater-irrigated soils compared to freshwater-irrigated soils [33].

Irrigation water sources from fishponds could be a driving tool for healthy semi-arid soils [34] with added benefits such as increased productivity, long-term profitability, and environmental safety. The use of fishpond water for irrigation comes with additional benefits to the soil, plants, farmer's harvest and income, and support to biodiversity and the environment (Figure 3).

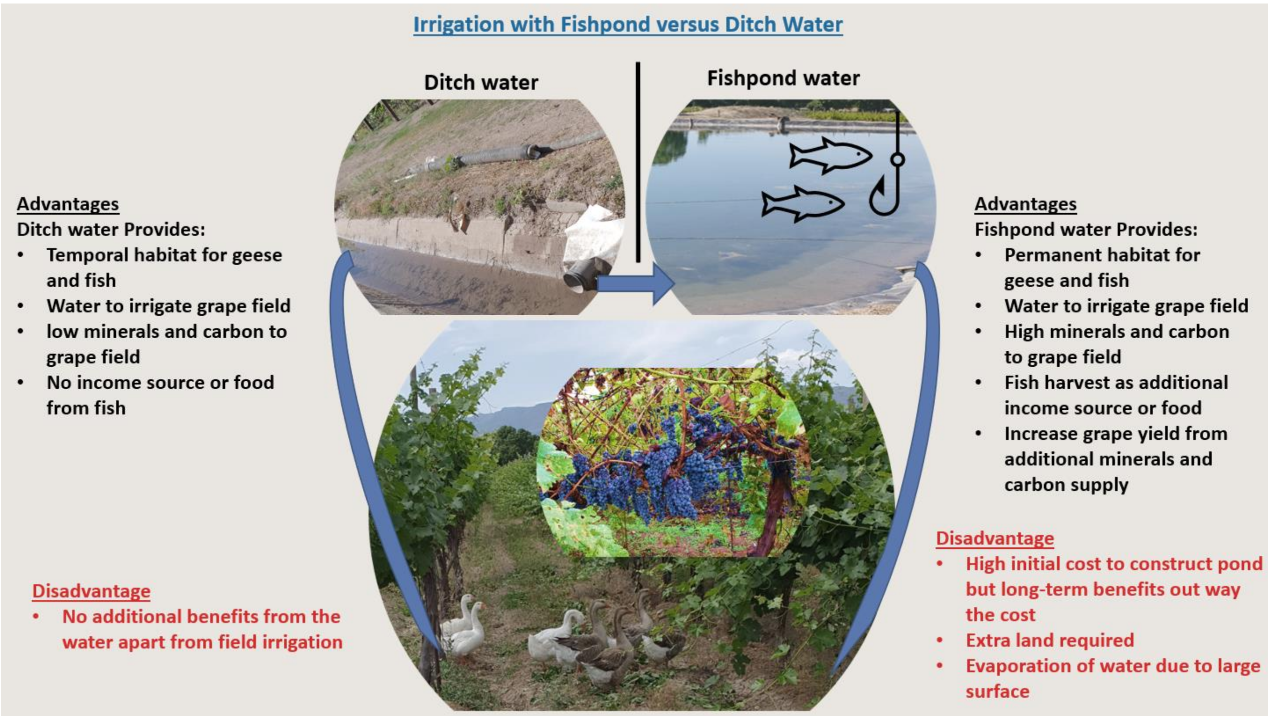

Figure 3. Pros and cons of using ditchwater versus fishpond water for crop irrigation.

Fishponds provide greater habitat for birds, especially during the winter, and aquatic life compared to irrigation ditches that are always flowing fast and may not have water during winter months. The location under study is in a somewhat tempered climate compared to the low desert or more northern climates where water temperatures can be too hot or cold for good year-round fish growth and production. Nonetheless, in areas where geographic and climate conditions are conducive to constructing a fishpond that can water relatively modest-sized fields, a fishpond should be considered for enhanced water, soil, and environmental benefits, even though the initial pond construction costs will be high (Figure 3). The Clear Creek Vineyard owner loves the fishpond not just for the enhanced water, soil, and environmental amenities it provides but also because it makes their property more attractive to tourists, wine tasters, and future potential bidders.

5. Conclusions

In semi-arid regions, integrating circular agricultural practices such as fishponds into cropping systems can enhance the resource use efficiency of water and improve environmental indicators (soil health and biodiversity). Since these ancient practices are regaining attention within agricultural production systems as climate-smart solutions, more research and extension program collaborations should be developed to make these systems more sustainable and resilient for safe food production. Our results suggest that more formal research is warranted on this subject for longer time periods with randomization of more trials to further prove the practice of using fishponds. The limitations associated with the use of fishponds are initial costs and concerns about pond surface evaporations, which we have not addressed. Resource conservation policies need to consider these costs along with the expected benefits before implementation.

Author Contributions: I.K.M., conceptualization, design, data collection, analysis, manuscript drafting, and final editing; T.I., data analysis, first draft writing, and final editing; R.T., critical review, the editing of the first draft, and final draft completion; H.K.D., critical review and the editing and review of the final draft. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: Isaac Kwadwo Mpanga was employed by the Circular Planet Institute LLC. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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