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Article *in* Journal of Applied Aquaculture · July 2011

DOI: 10.1080/10454438.2011.600629

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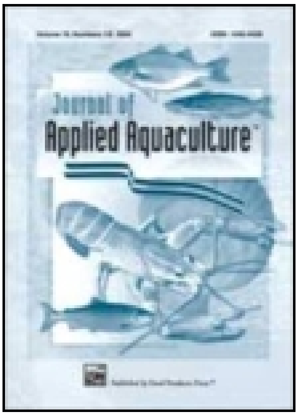

Journal of Applied Aquaculture
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/wjaa20

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Available online: 20 Sep 2011

Journal of Applied Aquaculture, 23:212–230, 2011

ISSN: 1045-4438 print/1545-0805 online
DOI: 10.1080/10454438.2011.600629

Improving Water Use Efficiency in Semi-Arid Regions through Integrated Aquaculture/Agriculture

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*Two experiments were performed in the Bekaa plain in Lebanon to evaluate the feasibility of integrating aquaculture with established agriculture production in order to increase water productivity. Both experiments consisted of four plant management treatments: 1) Aquaculture effluent irrigation and no fertilizer; 2) aquaculture effluent irrigation and inorganic fertilizer; 3) well water irrigation and no fertilization; and 4) well water irrigation with inorganic fertilizer. In the first experiment, tilapia growth and radish production using aquaculture effluent were evaluated. All fish survived and grew, and radish production was improved by irrigating with aquaculture effluent. In the second experiment, maize (*Zea mays*) in large plots was irrigated with aquaculture effluent. Irrigation with effluent water improved maize production and improved soil nitrogen availability. In both experiments, fish production improved water value index and water use efficiency. Results suggest that aquaculture effluent can supplant inorganic fertilizers and could actually yield better crop production.*

KEYWORDS *Integrated agriculture/aquaculture, IAA, water value index*

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INTRODUCTION

During the next 50 years, problems associated with a lack of water will affect virtually everyone on the planet (Gleick 1992). At least one-third of the world's population lives in countries experiencing medium to high water stress (Stockholm Environment Institute (SEI) 1997). In the Middle East (ME), the water situation is precarious. Middle Eastern countries have experienced rapid population growth during the past few decades, while technical and institutional development in the water sector has been slow (Dillman 1989; Haddadin 1989; Gleick 1992; Arlosoroff 1995; Haddad & Mizyed 1996). The result has been reduced per capita fresh water availability. In the Mediterranean region, agriculture consumes about 72% of available freshwater resources (Hamdy & Lacirignola 1999) and thus will be the economic sector most affected by freshwater shortages (Water and Environmental Studies Center 1995). Lack of adequate supply is compounded by the fact that seasonal rains do not coincide with agricultural need (Hiessl & Plate 1990). Added to these is inefficient use of available water resources. Because irrigated agriculture uses more than 70% of available freshwater resources, any water-saving solution should start with improving irrigation water usage, mainly by implementing a "more crop per drop" approach (Seckler 1996). A possible method to increase crops per drop would be to integrate aquaculture into existing agriculture systems.

Integrated agriculture–aquaculture (IAA) allows for efficient use of water, particularly in arid and semi-arid regions (Hussain & Al-Jaloud 1998; Palada, Cole, & Crossman 1999; McIntosh & Fitzsimmons 2003). It potentially reduces cost of water and amount of fertilizer needed for crops and increases water productivity (Al-Jaloud et al. 1993; D'Silva & Maughan 1994, 1995; Azevedo 1998). Integrating agriculture with fish farming could improve fish pond water quality, reduce environmental impact of nutrient rich water discharge, reduce cost of water and amount of chemical fertilizer needed for crops, diversify farm production, increase income, and thus increase water efficiency (Billard & Servrin-Reyssac 1992; Ghate & Burtle 1993). If aquaculture is added to existing agriculture systems, it becomes a non-consumptive productive segment that does not compete with irrigation. Moreover, the long-term performance of diversified farms is better than non-diversified enterprises for various reasons. Just as with monocrop agriculture, monoculture fish farms operate at higher levels of risk from diseases, water quality, and price fluctuations (Naylor et al. 2000; Pant, Demaine, & Edwards 2005).

Various researchers have demonstrated the benefits of integrating agriculture with existing aquaculture facilities (Naegal 1977; Lewis et al. 1978; Watten & Buch 1984; Zweig 1986; McMurtry et al. 1990; Parker, Anouti, & Dickenson 1990; Olsen 1992; Al-Jaloud et al. 1993; McMurtry et al. 1993; Racocy, Hargreaves, & Bailey 1993; Seawright 1993; D'Silva & Maughan 1994, 1996; Palada, Cole, & Crossman 1999; Cruz et al. 2000; Al-Ahmed 2004). The present work evaluated the feasibility of increasing water productivity in semi-arid regions through integrated tilapia and crop production.

MATERIALS AND METHODS

The experiment was conducted during the summers of 2007 and 2008 at the Agricultural Research and Educational Center (AREC; 33°56' N, 36°05' E; 1000 m above sea level) of the American University of Beirut (AUB) in the North Central Bekaa plain of Lebanon. This being a semiarid region, almost all rainfall occurs during the cold and wet winter seasons (November–April), and summers are typically hot and dry in the daytime and cool at night. A weather station placed 200 m from the experimental unit indicated that average maximum temperature from July to September 2007 was 34.88°C, and average minimum temperature was 15.02°C. Relative humidity was 55.9%. Soil in the study area is alkaline (pH 8.0), clayey, vertic xerochrept formed from fine-textured alluvium derived from limestone (Ryan, Musharrafieh, & Barsumian 1980).

Experiment 1, 2007

Aquaculture

Six round 1-m^3 fiberglass tanks with central drains were stocked with size-sorted (17.9 ± 1.3 g; mean ± SE) Nile tilapia, *Oreochrormis niloticus,* fingerlings at 10 fish per tank. Fingerlings were spawned at the AUB aquaculture laboratory, and all came from a single brood. An air blower and submersible air diffusers provided continuous aeration and mixing of water. Fish were offered a commercial floating pelleted feed (35% crude protein; 5% lipid; Zeigler Bros. Inc. Gardner, PA, USA) at 5% body weight daily, divided into a morning (07:00–08:00) and afternoon (18:00–19:00) feedings. All fish from every tank were weighed biweekly to determine fish growth and to adjust ration. Every day about 10 liters of water from each tank were used for irrigation, and tanks were refilled with fresh well water to replace water lost due to irrigation and evaporation. Additionally, half of the water volume in each tank was replaced once a week. No filtration or other water treatment methods were used.

Water quality parameters were tested twice daily in the morning (07:00–08:00) and in the afternoon (18:00–19:00). Water temperature was measured using a pocket hygro-thermometer (EXTECH Instruments, London, United Kingdom). Dissolved oxygen (DO) concentrations and pH were determined using a portable pH and DO meter Model HQ-20 (Hach Company, Loveland, CO, USA). Total ammonia-nitrogen (TAN) and nitrite-nitrogen (NO_2-N) were determined twice a week using a fresh water test kit (Model AQ-2, La MOTTE Chemical Company, Washington, USA).

On termination of the experiment (after 60 days), fish in each tank were harvested and counted. All fish were group weighed and then weighed individually to the nearest 0.01 g. Specific growth rate (SGR) was calculated as: $SGR = 100 \times (\ln W_f - \ln W_i)/D$, where W_f is the final mean weight of the fish, W_i is the initial mean weight, and D is number of days. Feed conversion ratio was calculated as $FCR = F/(W_f - W_i)$, where F is the dry weight of feed offered to the fish, W_f is the final biomass of the fish, and W_i is biomass of fish at stocking.

Agriculture

A plot of soil adjacent to the tanks was ploughed with moldboard twice then rototilled. Before planting, clods, rocks, and plant debris were removed. Twelve 1-m^2 plots were demarcated with flag markers. Seventy-six radish seeds (ASGROW Vegetables Seeds, Oxnard, USA) were planted per plot. Seeds were planted in four rows 100 cm in length and 20 cm apart, with seeds placed every 5 cm within each row. Radish was chosen as a test crop because radishes are easy to grow, have a short cultivation cycle of 30 to 40 days, and have a good market in the region where both the roots and the leaves are sold for human consumption. Biological insecticide (Bacill, Certis, USA) and selective insecticide (Marshal, FMC, USA) were applied at recommended doses. Plots were randomly divided into four treatments with three replicates per treatment. Treatments were: T1 = fish tank water irrigation with no additional fertilizer; T2 = fish tank water irrigation with fertilizer; T3 = well water irrigation with no additional fertilizer; and T4 = well water irrigation with fertilizer. Inorganic fertilizer NPK (15:15:15) at the rate of 100 kg/ha used commonly in the study area was applied to T2 and T4. Ten liters of fish effluent were applied every day at 6 pm to T1 and T2 using a sprinkling bucket, whereas T3 and T4 were irrigated using well water.

Plant growth was assessed by measuring plant height, new leaf number, and leaf length at 15 and 25 days after planting (DAP). At the end of the experiment, all plants in an area of 0.5 m^2 in the center of each plot were harvested. Average yield per plot was determined. Also fresh weight, total length, root length, tuber length, tuber diameter, leaf length, and leaf number were determined. Leaves and roots were dried at 70°C until constant weight and dry matter yield per treatment were determined.

A simple evaluation of water economics was performed. In a well-maintained system, water loss is mainly due to evaporation and fish biomass, which were negligible. Accordingly, consumptive water use (CWU) from the integrated system was due mainly to radish irrigation, which was calculated as m^3/m^2. Water use efficiency was calculated as: WUE kg/m^3 = total yield/CWU, and was used to evaluate efficiency for fish and radish integration. Finally, water productivity WP $\$/m^3$ = WUE $kg/m^3 \times$ price $/kg, was calculated for fish and radish using an estimated fair market value for fish and radish.

Experiment 2, 2008

The second experiment was performed on a larger scale than the previous experiment to evaluate feasibility of an IAA system in reducing water use and increasing crop productivity on a small-holding farm scale. Fish growth was not evaluated. The crop used was 80-day maize to be used as silage.

Aquaculture

The five tanks used in the previous experiment were supplemented with a sixth tank that was filled with well water that was then used for irrigation with no fish or feed inputs (Figure 1). Two of the fish tanks were stocked with 60 fry (1.3 g) each, and two tanks were stocked with 10 male and 20 female brood stock tilapia each (biomass approximately 13.5 kg in each tank). The brood stock were offered 500 g of feed daily, and the fry were offered the same feed (ground to suitable size) to apparent satiation twice daily. Water quality parameters were measured daily in the morning (08:00) after irrigation and in the evening (20:00) as described above.

Agriculture

A 500-m^2 field was tilled and prepared as described for experiment 1 and planted with rows of maize (*Zea mays*) with 70 cm between rows and 20 cm between seeds within each row. Half the field was fertilized at the locally common rate for NPK (17:17:17) of 100 kg/ha. Four 100-m^2 plots (5 m × 20 m) were delineated within the field, each containing eight rows

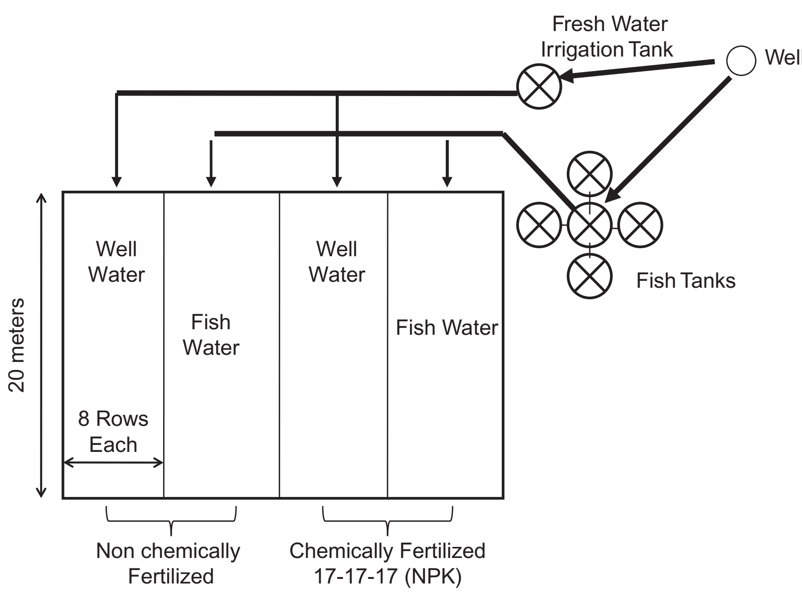

FIGURE 1 Schematic representation of the experimental setup used in Experiment 2.

of maize, with two plots in the fertilized section and two outside the fertilized section (Figure 1). Maize plants between rows were removed by hand after emergence. The whole field was irrigated with sprinklers and well water until emergence and then drip irrigation was fitted to every row. Treatments were: T1 = fish tank effluent/fertilized; T2 = well water/fertilized; T3 = fish tank effluent/unfertilized; T4 = well water/unfertilized. Fish tank water was pumped out of the sedimentation tank at 30 cm above bottom. The same irrigation pump was used for all treatments, and valves were used to separate well water from fish effluent. Each 100-m^2 plot was irrigated every second day with 1 m^3 of water.

Plant growth parameters measured were plant height, plant weight, and number of leaves per plant. Experimental time was recorded as number of days after sowing (DAS). To achieve replications at sampling and harvest, four 1-m^2 quadrants were randomly delineated within each treatment plot, and plant height and number of leaves of all plants within the quadrant were measured weekly. At 54 DAS and every two weeks thereafter, all the plants within the quadrants were cut at ground level and aboveground biomass measured.

Soil samples were collected at a 15 to 30 cm depth prior to maize seeding, at maize seeding, and then every two weeks until harvest to measure nitrogen, phosphorous, and potassium concentrations. All soil samples were air-dried, ground, and sieved through a 1-mm mesh. A 5-g sample of air-dried soil was used to estimate soil P as described by Watanabe and Olsen (1965). Five-gram soil samples were treated with ammonium acetate (NH_4OAc) to extract potassium, after which K^+ concentrations were determined by flame photometry. Nitrogen content in the soil was determined using an elemental nitrogen analyzer (Thermo Finnigan/EA1112 elemental analyzer, Thermo Electron Corporation, Madison, WI, USA) with aspartic acid as a calibration standard.

Statistical Analysis

All statistical analyses were performed using SPSS statistical software (V.12 for Windows, SPSS Inc., Chicago, IL, USA). Means of parameters were estimated using one-way ANOVA and Student Newman-Keuls multiple-range test to determine significant differences ($P < 0.05$) among treatment means. Significant differences were considered when $P < 0.05$.

RESULTS

Experiment 1, 2007

Aquaculture

Fish survival was 100%, daily weight gain was 0.6 ± 0.02 g/fish/d (mean ± SE), average FCR was 2.78, and SGR was 1.9%/d. There were no differences in tilapia growth among the six culture tanks (Table 1), and

TABLE 1 Stocking Density, Initial Weight, Survival, Final Weight, Specific Growth Rate (SGR), and Feed Conversion Ratio (FCR) for Tilapia Reared in 1 m^3 Tanks in the Bekaa Plain During Summer Season. Data are Means (±SE) of all Tanks. No Significant Differences were Observed Among Tanks

Item	Average
Stocking Density/m^3	10 ± 0.0
Initial Weight/Fish (g)	17.8 ± 1.3
Survival (%)	100
Biomass at Harvest (kg/m^3)	1.11 ± 0.07
Final Weight (g/fish)	55.8 ± 3.1
Final Length (cm)	13.5 ± 0.4
SGR (%/day)	1.9 ± 0.09
Feed Offered (g)	1052.1 ± 0.0
FCR	2.78 ± 0.22

growth curves in all tanks were similar to each other throughout the study period (Figure 2). Water quality parameters remained within the safe limits for tilapia growth during the study. Maximum TAN concentration was 1.76 ± 0.26 mg/L (mean ± SE), and nitrite-N concentration was 0.61 ± 0.03 mg/L. Morning water temperature (at 7:00 h) averaged 19.67 ± 0.58°C, and evening water temperature (at 19:00 h) averaged 25.87 ± 0.53°C. Dissolved oxygen concentration (DO) ranged from 5 mg/L to 8.5 mg/L, and pH ranged from 7.6 to 8.6. Lowest values of dissolved oxygen, water temperature, and pH were routinely observed in early morning and high values in the evening. Effluent pH was 0.4 points greater than incoming well

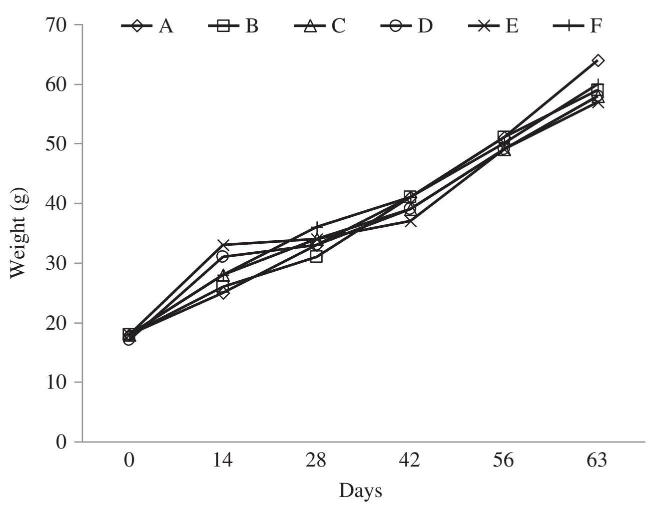

FIGURE 2 Growth performance of tilapia reared in 1 m^3 tanks in the Bekaa plain during summer season. Data points are means of 10 fish. Model average of all tanks is: $y = 7.99x + 10.2$; $R^2 = 0.989$.

water, and ammonia and nitrite nitrogen levels in well water were below detectable limits using the La Motte kit.

Agriculture

Radishes in all treatments grew well and produced tubers. Growth parameters were not significantly different from each other among treatments at 15 and 25 days after planting (DAP), thus data are not reported nor discussed. At harvest (35 DAP), leaves in non-fertilized treatments irrigated with fish effluent (T1) were significantly larger than leaves in other treatments. Leaves in fertilized plots irrigated with well water (T4) and in fertilized plots irrigated with fish effluent (T2) showed no significant differences from each other. No significant differences in root length were observed among treatments. Both treatments irrigated with fish effluent produced tubers with significantly larger diameters than treatments irrigated with unfertilized well water. Plant length in fish effluent treatments was significantly larger than plant length in well water treatment (Table 2).

Significant differences in plant biomass and plant dry weight were observed among treatments. Leaf and tuber fresh weight in plots irrigated with fish effluent was significantly greater than those irrigated with well water. Non-fertilized plants irrigated with aquaculture effluent yielded greater leaf and tuber production than fertilized plants irrigated with well water. Tuber biomass of plants irrigated with fish effluent and treated with inorganic fertilizer (T2) were greater than tuber biomass of plants that received fish tank water only (T1), although not significantly different (Table 3).

In fish effluent treatments, total yield of radish plants was significantly greater than yield in both well water treatments. There were no significant differences in total dry and total fresh weights of plants between fertilized fish effluent treatments and non-fertilized fish effluent treatments.

TABLE 2 Tuber Length, Tuber Diameter, Root Length, Leaf Length, and Total Plant Length of Radish Grown in 1 m^2 Plots in the Bekaa Plain During Summer Season. Data are Means of 48 Radish Plants (±SE), and Values in the same Column Having Different Superscripts are Significantly Different ($P < 0.05$) from Each Other. Data were Collected 35 Days after Planting

Treatment	Tuber L (cm)	Tuber D (cm)	Root L (cm)	Leaf L (cm)	Total L (cm)
T1[1]	4.82 ± 0.1[a]	3.83 ± 0.07[a]	10.53 ± 0.44[a]	14.96 ± 0.3[a]	30.32 ± 0.53[a]
T2[2]	4.73 ± 0.09[a]	3.76 ± 0.07[a]	11.36 ± 0.55[a]	13.96 ± 0.31[b]	30.07 ± 0.79[a]
T3[3]	4.58 ± 0.15[a,b]	3.48 ± 0.09[b]	10.15 ± 0.42[a]	12.57 ± 0.3[c]	27.32 ± 0.62[b]
T4[4]	4.35 ± 0.1[b]	3.47 ± 0.06[b]	9.96 ± 0.51[a]	13.8 ± 0.27[b]	28.12 ± 0.72[a, b]
PSE[5]	0.12	0.10	0.26	0.20	0.3

[1]T1: Fish tank water irrigation and no fertilizer in plots.
[2]T2: Fish tank water irrigation with fertilizer in plots.
[3]T3: Well water irrigation and no fertilizer in plots.
[4]T4: Well water irrigation with fertilizer in plots.
[5]PSE: Pooled standard error.

TABLE 3 Tuber Fresh Weight, Leaf Fresh Weight, and Total Fresh Weight of Radish Grown in 1 m^2 Plots in the Bekaa Plain During Summer Season. Data are Means of 48 Radish Plants (±SE), and Values in the same Column Having Different Superscripts are Significantly Different ($P < 0.05$) from Each Other. Data were Collected at 35 DAP

Treatment	Tuber F Wt (g)	Leaf F Wt (g)	Total F Wt (g)
T1[1]	28.56 ± 0.65^a	8.76 ± 0.14^a	37.3 ± 0.78^a
T2[2]	28.83 ± 0.15^a	8.5 ± 0.02^a	37.33 ± 0.14^a
T3[3]	24.86 ± 1.14^b	6.06 ± 0.2^c	30.93 ± 1.32^b
T4[4]	25.66 ± 0.2^b	7.43 ± 0.07^b	33.03 ± 0.27^b
PSE[5]	0.30	0.13	0.33

[1]T1: Fish tank water irrigation and no fertilizer in plots.
[2]T2: Fish tank water irrigation with fertilizer in plots.
[3]T3: Well water irrigation and no fertilizer in plots.
[4]T4: Well water irrigation with fertilizer in plots.
[5]PSE: Pooled standard error.

Water productivity in IAA treatments (T1 and T2) was higher than in non-integrated treatments (T3 and T4). In integrated treatments, WVI was \$10.3/m^3 for radish and \$1.5/m^3 for fish, whereas in non-integrated or conventionally irrigated treatments (T4) WVI was \$9.11/m^3 for radish alone. Consequently, radish-fish culture yields gross incomes that are 23% greater than radish monoculture (Table 4). WVI was increased by 12% for IAA treatments (T1 and T2) in comparison with well water treatment with NPK fertilization (T4) and by 17% in comparison with well water treatment without NPK fertilization (T3) after price of fertilizer is taken into account (Table 4). Water use efficiency based on plant biomass was 8.24 kg/m^3 for aquaculture effluent treatments (T1 and T2), 7.29 kg/m^3 for fertilized and well water-irrigated radishes (T4), and 6.83 kg/m^3 for well water-irrigated but unfertilized radishes (T3) (Table 4).

TABLE 4 Water use Efficiency and Water Productivity for Radish Grown in 1 m^2 Plots and for Tilapia Reared in 1 m^3 Tanks in the Bekaa Plain During Summer Season. The Price of Radish and Tilapia were Calculated at \$1.25/kg for Radish and \$7/kg for Tilapia

Treatment	WUE (kg/m^3)	(WP \$/m^3)
T1	8.24	10.3
T2	8.24	10.3
T3	6.83	8.53
T4	7.29	9.11
Tilapia	0.22	1.54

T1: Fish tank water irrigation and no fertilizer in plots.
T2: Fish tank water irrigation with fertilizer in plots.
T3: Well water irrigation and no fertilizer in plots.
T4: Well water irrigation with fertilizer in plots.

Experiment 2, 2008

Aquaculture

Tilapia fry survived and grew well. Two of the brood stock jumped out of their tank and were found dead and a third fish was not accounted for at harvest. All other fish survived and had no external signs of stress at harvest. The largest fish was 690 g, and the smallest fish was 210 g. Water temperature averaged 19.4 ± 0.02°C (mean ± SE) at 08:00, 18.4 ± 0.03°C (mean ± SE) immediately following irrigation and water replacement, and 27.5 ± 0.02°C (mean ± SE) at 20:00. Dissolved oxygen (DO) was 6.3 ± 0.05 mg/L at 08:00 and 5.2 ± 0.00 mg/L at 20:00. Total ammonia-N (TAN) and nitrite-N concentrations averaged 0.6 ± 0.1 mg/L and 0.4 ± 0.2 mg/L, respectively, throughout the experiment except from July 20, 2008, to July 23, 2008, when TAN levels increased above 3.0 ppm and nitrite-N levels were above 0.8 ppm. Water in the system was changed and water quality parameters then remained stable within acceptable limits for the remaining of the experiment.

Agriculture

Maize plants fertilized and irrigated with fish tank effluent appeared taller with greater numbers of leaves than plants in all other treatments throughout most of the experimental period (Table 5; Figure 3A, B). At 20 DAS, there were no significant differences in maize plant height among treatments. During the rest of the experimental period, average maize plant height remained significantly greater in maize plants irrigated with fish effluent and fertilized (T1) than maize plant height in all other treatments (Figure 3A). The lowest plant height was observed in maize plants irrigated with well water and unfertilized. A similar trend was observed for number of leaves over the experimental period, where maize plants that were fertilized and irrigated with fish tank effluent had a greater number of leaves than all other treatments throughout the experimental period (Figure 3B). At harvest, weights of maize plants irrigated with fish effluent and unfertilized (T3) were significantly greater than the weights of maize plants in all other

TABLE 5 Growth Parameters (mean ± SE), Yield, and Water use Efficiency (WUE) of Maize Plants Irrigated with Different Sources of Water (Fish Effluent and Well Water and Fertilization)

Treatment	Plant height (cm)	Number of leaves per plant	Plant weight (g)	Yield (kg/m^2)	WUE (kg/m^3)	WVI ($\$/m^3$)
T1	276.3 ± 0.73a	18.7 ± 0.16a	870.3 ± 2.30b	6.96b	1.91b	0.50b
T2	244.9 ± 0.71c	17.2 ± 0.14c	769.1 ± 2.22c	6.15c	1.69c	0.44c
T3	262.3 ± 0.86b	17.8 ± 0.12b	884.0 ± 2.91a	7.07a	1.94a	0.51a
T4	213.9 ± 1.32d	16.4 ± 0.11d	526.2 ± 3.25d	4.21d	1.16d	0.30d

T1 = drip irrigation with fish tank effluent/fertilized; T2 = drip irrigation with well water/fertilized; T3 = drip irrigation with fish tank effluent/unfertilized; T4 = drip irrigation with well water/unfertilized. Values in the same column sharing the same letter are not significantly different from each other ($\alpha = 0.05$).

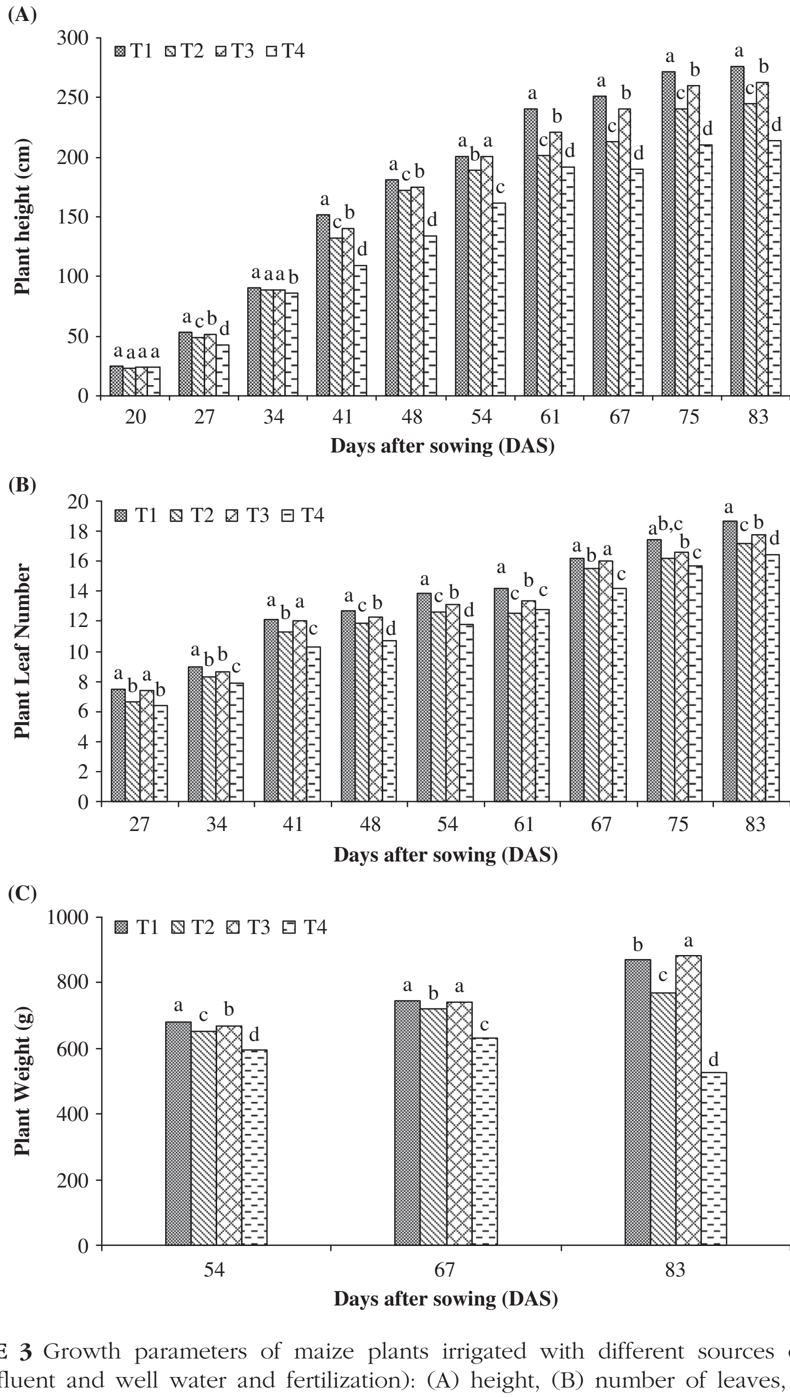

FIGURE 3 Growth parameters of maize plants irrigated with different sources of water (fish effluent and well water and fertilization): (A) height, (B) number of leaves, and (C) weight during experimental period of three months. T1 = drip irrigation with fish tank effluent/fertilized; T2 = drip irrigation with well water/fertilized; T3 = drip irrigation with fish tank effluent/unfertilized; and T4 = drip irrigation with well water/unfertilized. Data followed by the same letter do not differ significantly from each other ($\alpha = 0.05$).

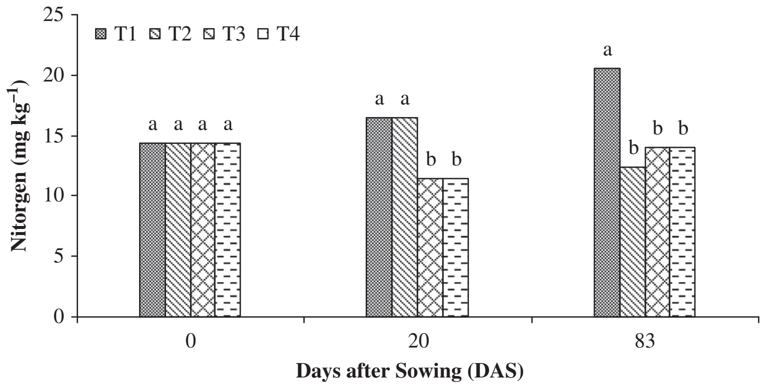

FIGURE 4 Effect of water sources for irrigation (fish effluent and well water) and fertilization (T1 = drip irrigation with fish tank effluent/fertilized; T2 = drip irrigation with well water/fertilized; T3 = drip irrigation with fish tank effluent/unfertilized; and T4 = drip irrigation with well water/unfertilized) on nitrogen (N) levels in soil samples. Data followed by the same letter do not differ significantly from each other ($\alpha = 0.05$).

treatments. Weights of maize plants irrigated with well water and unfertilized were significantly less than weights of maize plants in all other treatments (Table 5; Figure 3C).

Prior to crop planting and fertilizing, there were no significant differences in soil N, P, and K levels among plots. At the start of drip irrigation, (20 DAS), soil N in plots T1 and T2 was greater than soil N in T3 and T4 ($P < 0.05$). After the crop was harvested (83 DAS), the soil irrigated with fish effluent and fertilized (T1) had significantly greater levels of nitrogen than soils in all other treatments (T2, T3, and T4) ($P < 0.05$) (Figure 4). Mean soil phosphorus and potassium concentrations were above 20 mg/kg and 500mg/kg, respectively, in all treatments and thus cannot have affected plant growth results (FAO 2006).

Maize yield, water use efficiency, and water productivity data are shown in Table 5. Mean yield ranged from 4.21 kg/m^2 for T4 (well water and no fertilizer) to 7.07 kg/m^2 for T3, which was significantly greater than yield in all other treatments. The mean WUE and WVI of maize ranged between 1.16–1.94 kg/m^2/m^3 and 0.30–0.51 \$/m^3, respectively. In T3, WUE (1.94 kg/m^2/m^3) and WVI (0.51\$/m^3) were significantly greater than in all other treatments.

DISCUSSION

Experiment 1, 2007

Aquaculture

Growth performance and feed conversion efficiency were within normal limits for tilapia aquaculture. The FCR average of 2.78 obtained in the present study was similar to the average of 2.61 reported by Suresh and Lin (1992) for tilapia and was greater than the range of 1.45–2.40 reported by Yi & Diana (1996) for Nile tilapia in cages and also greater than 1.01–1.6 reported by Diana & Lin (2004) in ponds. FCR was probably high because constant change of water reduced primary productivity available to the fish. Moreover, daily temperature variations coupled with temperature changes during water exchange may have affected feeding behavior and growth rate, thus increasing FCR. Tilapia stocking density and production were low for aerated systems, but specific growth rates (1.8%/day) were good in comparison with other commercial scale aquaculture systems (McMurtry et al. 1990; Rakocy & Hargreaves 1993). The mean daily weight gain of 0.6 g/fish was lower than that obtained by Guerrero (1980) in ponds (0.56 to 1.60 g/fish) and lower than that obtained by Coche (1982) in cages (1.05 to 2.33 g/fish). However, fish in the reported studies benefited from natural productivity while fish in the present study did not.

Fish (55.86 ± 2.95 g; mean ± SE) did not reach market size. This was probably due to the relatively small stocking size (17.9 ± 1.3 g; mean ± SE) and short growout period (63 days). Balarin and Haller (1981, 1982) recommended stocking tilapia fingerlings (20 to 50 g) in commercial tanks and suggested a total production cycle duration of 205 days to produce market-size fish of 250 g average body weight. Such a growout period is not available in the Bekaa region, but fish stocked at 30 g have attained 160 g in 180 days (unpublished data). Moreover, individual fish growth is not only influenced by the initial size of the fish, but also by gender (Saoud et al. 2005), where all male tilapia fingerlings grow faster than females (Fitzsimmons 2000). Fish in the present study were not monosex, and size variability was apparent in all tanks. An all-male monosex culture would probably have yielded better average growth values. Nonetheless, the present study demonstrated that tilapia can be successfully grown in the Bekaa valley, and if cold tolerant strains, genetic variants such as GIFT tilapia, and/or greenhouses were used, harvest size could be attained in a shortened season.

Radish growth and biomass

Plants irrigated with aquaculture water grew better than those irrigated with well water. Radish tuber biomass, stem and leaf biomass, plant length, and root diameter (Tables 2 and 3) were higher when irrigated with aquaculture effluent compared to plants irrigated with well water. The low yields observed in the well water treatments suggest a lack of nutrients for adequate plant growth. The improved yields observed in the fish water treatments suggest that nutrients present in aquaculture effluent contributed significantly toward crop growth by meeting partial crop nutrient requirements. Results suggest that, even at low levels of nutrients present in aquaculture effluent, repeated applications yield better growth than a single large application of inorganic fertilizers at planting (Table 2). The fact that nutrients were available to plants in small amounts throughout the entire crop cycle allows for efficient on-time use by plants, increasing productivity (Pinto 1997). Results of the present experiment suggest that using aquaculture effluent for irrigation could reduce fertilizer use and increase economic returns. Differences in plant biomass were not significant ($P > 0.05$) among treatments treated with fish effluent, meaning that the use of fish effluents as irrigation and fertilizer source without application of inorganic fertilizer can produce crops equal in mass to crops treated with fish effluent and application of inorganic fertilizer (NPK). The lack of a significant difference between T1 and T2 can be attributed to constant availability of NPK in fish effluent, while fertilization only supplied NPK early and excess fertilizers might have leached into the ground due to repeated irrigation.

Water value index (WVI), water use efficiency (WUE), and profitability

In the IAA treatments, economic productivity of water and water value index were increased. Integrating aquaculture with agriculture increased water value index by 11% in comparison to the well water treatment with NPK fertilization. If we add the potential value of tilapia (1.5 $\$/m^3$) (Table 4) and the reduction of fertilizers needed due to enrichment of water by aquaculture-generated metabolites, we find that an integrated system appreciably increases water value index. Our results were comparable with those reported by Hopkins et al. (1984), which indicated that integrating tilapia culture with agricultural crops would improve the economic viability of both crops by spreading the usefulness of the water systems. The returns on tilapia ($\$1.5\ /m^3$) were low and directly related to stocking density. A greater stocking density would provide greater revenue per integrated treatment as well as more nutrients in the water. However, higher stocking densities would also require more investment in feed and labor by the farmer whose primary source of income is assumed to be the vegetal crop with aquaculture used to increase returns and decrease CWU.

The present study shows that WUE of integrated treatments is greater than WUE of non-integrated treatments. Dey et al. (2004) showed that adoption of IAA technology increased water productivity substantially, improved total farm productivity by 10%, and increased farm income by 28% without additional consumptive use of water. However, we should remember that our calculations of water use do not take into account virtual water embedded in fish feed or other products needed for its production (see Allan 1998).

The amount of water used for fish production in the present study does not represent any additional demand on the existing water pumping rate on the farm. The water would be pumped on a daily basis even without fish production. The amount of fish produced in this system must be considered as an additional crop to other crops being produced. Therefore, aquaculture is a productive, low-consumptive segment of the water use system that does not compete with irrigation. In aquaculture, CWU is usually due to evaporation and leakage. If we assume that leakage is nil in a properly maintained system, then CWU is mainly due to evaporation and what gets incorporated into fish tissue. These elements of CWU equation are insignificant when compared to what gets lost during irrigation. Therefore, adding an aquaculture production unit between water source and agricultural end product increases productivity without significantly increasing CWU.

Experiment 2, 2008

Irrigation with tilapia aquaculture effluent without fertilization increased maize yield (7.07 kg/m^2), water use efficiency (WUE) (1.94 kg/m^3), and water productivity (0.51 \$/m^3) as compared to yield (6.15 kg/m^2), WUE (1.69 kg/m^3), and water productivity (0.44 \$/m^3) of maize irrigated with well water and fertilized at planting. The WUE of IAA irrigated maize was slightly greater than the 1.36–1.89 kg/m^3 reported by Katerji, Mastrorilii, & Rana (2008) for well water drip-irrigated maize in Lebanon. Furthermore, present results support findings of improved WUE using IAA for various other crops in other countries. Dey et al. (2010) reported that IAA farms in Malawi increased water productivity substantially, improved total farm production, and increased farm income without additional consumptive water use. Hussein and Al-Jaloud (1995) reported that irrigation with aquaculture effluents instead of well water significantly increased barley yields in Saudi Arabia.

The improvement in plant crop production in IAA is probably because of an increase in plant nutrients in the water (McIntosh & Fitzsimmons 2003). Seim, Boyd, and Diana (1997) reported a big increase in nitrogen and phosphorus content of aquaculture water over the course of a growout cycle. In the present study, phosphorus and potassium concentrations in the tank water remained very low throughout the study but that is because of constant water exchange when irrigating the maize. Ammonia nitrogen was constantly present in low concentrations. Because the soil in which the maize was planted contained more P and K than necessary for good maize growth (FAO 2006), we believe that growth differential among treatments was a result of continuous nitrogen input with every irrigation event. The increase in soil nitrogen in the treatments irrigated with aquaculture effluent supports such a statement. Nitrogen in the fish effluent must have partially supplied nutrient requirements for maize growth as evident in the improved yield and WUE of maize fertilized with fish effluent only. Apparently, availability of nutrients such as nitrogen in small amounts throughout the crop cycle allows more efficient nutrient absorption by the plants. Hussein (2009) observed that plant nutrient application through fertigation (mixing fertilizer into irrigation water) was much better used by maize as compared to conventional fertilization techniques.

CONCLUSION

As water stress increases in semi-arid non-industrialized nations, water use efficiency and food production will have to improve concurrently. One way of achieving this goal is to integrate aquaculture with agriculture. This should be done in a way that does not upset traditional lifestyles of local populations and increases economic returns to farmers. In the present work, integrating an aquaculture system between water source and traditional vegetable or grain agriculture increased productivity and economic returns without significantly influencing consumptive water use. The integration also decreased fertilizer needs and added animal protein production to the system without imposing a lifestyle change on the farmer. Further research on improving integration and extending fish growout seasons will greatly benefit traditional rural farmers.

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