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INTEGRATION OF AQUACULTURE AND ARID LANDS AGRICULTURE FOR WATER REUSE AND REDUCED FERTILIZER DEPENDENCY

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SUMMARY

Field irrigation is costly in arid regions, and over-fertilization of farmland can lead to high groundwater nitrate levels and significant environmental challenges. Integrative aquaculture and agriculture (IAA) systems allow the reuse of water and nutrients to offset production costs while promoting greater sustainability. The aim of this study was to test the effectiveness of an IAA system using treatments formed from one water source, groundwater (GRND) or fish pond effluent (EFF), and one chemical fertilizer regime, eliminated (ELIM) or historical (HIST). Treatments were applied to field plots of barley or cotton. There were typically positive effects of EFF applications on crop growth and yield relative to GRND applications under identical fertilizer regimes. However, GRND-HIST almost always outperformed EFF-ELIM, suggesting that substituting effluent irrigations for a historical fertilization regime without pond biosolid or reduced fertilizer applications could be detrimental to crop production.

INTRODUCTION

The integration of aquaculture with agriculture has been proposed as a means to optimize the use of limited water resources (Ingram *et al.*, 2000; Prinsloo and Schoonbee, 1993), decrease dependency upon chemical fertilizers (Fernando and Halwart, 2000; Stevenson, 2003) and increase economic return per unit of water. In the southwestern deserts of the USA and Mexico, there are strong benefits to implementing an integrative agriculture and aquaculture (IAA) system. Frequent droughts increase the cost of irrigation on cotton and small grains farms, while nitrate loading from overuse of chemical fertilizers affects groundwater quality, presenting serious environmental concerns. Implementing IAA at some level allows for the reuse of water through the production of an aquaculture crop that would offset the high cost of irrigation while simultaneously generating nutrient-rich effluent that could be

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applied to agricultural fields and thereby reduce the cost and overuse of inorganic fertilizers.

Integrative systems can increase crop production, net income and sustainability (Edwards, 1998; Hopkins and Bowman, 1993; Hosetti and Frost, 1995; ICLARM, 2000; Lightfoot *et al.*, 1993; McIntosh and Fitzsimmons, 2003; Mosher, 1996; Shereif *et al.*, 1995), and they have been shown to have positive ecological and environmental effects (Edwards, 1993; Fernando and Halwart, 2000; Jamu and Piedrahita, 2002; Prein, 2002). Integrative agriculture and aquaculture systems can also alleviate the pressure of terrestrial pests, reduce numbers of aquatic pests and reduce vectors of human and livestock disease (Fernando and Halwart, 2000). In Arizona alone, over a trillion litres of irrigation water per year are used in agriculture that could be used for aquaculture first. Farmers in arid regions who used aquaculture effluent to maximize farm production without increasing water consumption could make an important contribution to their industry (McIntosh and Fitzsimmons, 2003). Furthermore, fish and algal waste in effluent have the potential to sustain crop growth and yield while lowering the cost and overall use of chemical fertilization. Integrative agriculture and aquaculture systems can take many forms. For example, a cotton grower might decide to apply tilapia pond biosolids to his cotton fields before planting. A farmer growing winter wheat or barley could introduce catfish into irrigation canals and use the effluent to water his fields. A farm simultaneously producing both a brackish water shrimp crop and an olive crop might use the water and nutrient outputs of the former as inputs for the latter.

In many IAA systems, pond sludge and effluent can be valuable agricultural by-products that represent sustainable resources (Hosetti and Frost, 1995), whether applied over an open field or applied routinely during irrigation. Pond mud adsorption of nitrogen (N) and phosphorous (P) or poor spatial distribution of sludges can cause the benthic regions of aquaculture ponds to become untapped nutrient sinks (Boyd and Tucker, 1998; Hepher, 1958), but the implementation and use of pond-based IAA systems is not prevalent in the southwestern USA. However, the increasing success of aquaculture in the USA and elsewhere indicates opportunities for its integration with agriculture in the Southwest.

Globally, aquaculture has steadily increased in the past decade to a production rate of over 47 million t per year (FAO, 2006). It has also become a multi-billion dollar per year industry in the USA. There is strong potential for growth in the southwestern USA, as the largest sectors of aquaculture and agriculture are uniquely situated in that many necessary resource input requirements of field agriculture can be provided by the waste outputs of aquaculture.

In Arizona and other arid regions where water costs are high and crop values can be marginal, there is evidence that it could be beneficial for fish to be cultured in pre-irrigation water prior to field discharge (Budhabhatti, 1991; Fitzsimmons, 1988; Fitzsimmons, 1992). Olsen *et al.* (1993) also found that integrating tilapia and channel catfish farming with cotton farming resulted in an increase of total N and P in irrigation water, but that effluent irrigations did not produce higher cotton yields or increase soil N and P. Isotope labelling has also been used to show the efficiency of N transfer from fish food to plant crop tissue in a small integrated system (Azevedo *et al.*, 1999), although no indication has been given as to whether effluent alone would be able to supply sufficient nutrients within a larger-scale system.

The aim of this study was to test the effectiveness of different irrigation sources and fertilizer treatments on the growth and yield of field crops. We evaluated the efficacy of four treatments that comprised groundwater (GRND) or pond effluent (EFF) as the water source combined with an eliminated (ELIM) or historical (HIST) fertilizer regime.

Three comparisons were made. First, crops treated with GRND-ELIM and EFF-ELIM were compared to determine the effect of fish effluent irrigations alone. Second, crops treated with GRND-HIST and EFF-HIST were compared to determine whether fish effluent irrigations could function as a positive supplement to chemically fertilized field crops. Third, crops treated with EFF-ELIM and GRND-HIST were compared to determine whether fish effluent irrigations alone might be able to replace historical fertilization practices without compromising crop growth or yield. The growth patterns and overall health of the three species of fish used in our research pond were also monitored to determine whether the irrigation scheduling and practices of this system were compatible with production of a profitable fish crop. Although pond mud and residual biosolids were not collected and applied to fields in this study, we measured their end product nutrient levels to estimate a potential benefit of their application between cropping seasons.

MATERIALS AND METHODS

We rotationally farmed three species of fish, tilapia (*Oreochromis niloticus*), catfish (*Ictalurus punctatus*) and koi (*Cyprinus carpio*), along with two field crops, upland cotton (*Gossypium hirsutum*, DP-458 BR variety) and winter barley (*Hordeum vulgare*, Poco variety) for 18 months in Maricopa, Arizona. The fish species were selected because of their importance to aquaculture in US arid lands as food and ornamental crops. We rotationally cropped late-season cotton with winter small grains, as this practice has been used throughout the desert southwest to maximize economic gain.

Treatments were formulated by combining a water sources with a fertilizer regime. Water sources were GRND, which contained high nitrate levels, and EFF, which contained varying levels and forms of N and P. Fertilizer regimes were ELIM, in which no chemical fertilizers were applied, and HIST, which is used by the Maricopa Agricultural Center in farming upland cotton and winter barley, and consists of applications of monoammonium phosphate and ammonium sulphate (Table 1).

The field agriculture portion of the study used a randomized complete block design with 2 × 2 factorial treatment analysis. The four treatments (GRND-ELIM, EFF-ELIM, GRND-HIST and EFF-HIST) were assessed in four repetitions each, thereby providing a total of 16 testable plots.

A diagram of the experimental IAA system is shown in Figure 1. Each field agriculture plot contained six rows that were 1 × 40m in length and had a surface area of 0.025 ha. Soil in each plot was a sandy loam. Cotton was planted in single

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Table 1. Field management practices for Maricopa Agricultural Center (December 2001–April 2003). The listed fertilization practices cumulatively reflect the historical (HIST) regime.

Date	Treatment	Classification	Field management practice
2001/2002 barley			
21 Dec 01	HIST plots	Fertilization	Monoammonium phosphate (11-52-0), 278.0 kg ha^{-1}
21 Dec 01	All plots	Maintenance	Conservation till, laser, disc hip, bed shape
21 Dec 01	All plots	Plant	Poco©, 122 kg ha^{-1}, 18 cm spacing, rows and furrows (MF-4263 Monosoem© planter)
21 Dec 01	All plots	Herbicide	2,4-D, manufacturer's recommended dose
25 Feb 02	HIST plots	Fertilization	Ammonium sulphate (21-0-0), 192.2 kg ha^{-1}
25 Mar 02	HIST plots	Fertilization	Ammonium sulphate (21-0-0), 145.1 kg ha^{-1}
13 May 02	All plots	Harvest	5.5 m width axial flow combine (International© 1440) and weigh wagon
2002 cotton			
15 May 02	All plots	Herbicide	Prowl©, 2.34 L ha^{-1}
15 May 02	All plots	Maintenance	Conservation till, laser, disc hip, bed shape
15 May 02	All plots	Plant	DP458-BR©, 83 kg ha^{-1}, 1m apart, single line, center of rows (John Deere© 8200 planter)
17 Jun 02	HIST plots	Fertilization	Ammonium sulphate (21-0-0), 67.3 kg ha^{-1}
25 Jun 02	All plots	Herbicide	Post©, manufacturer's recommended dose
17 Jul 02	HIST plots	Fertilization	Ammonium sulphate (21-0-0), 67.3 kg ha^{-1}
14 Aug 02	HIST plots	Fertilization	Ammonium sulphate (21-0-0), 44.8 kg ha^{-1}
19 Aug 02	All plots	Pesticide	Knack©, Courier©, manufacturer's recommended doses
3 Sep 02	All plots	Pesticide	Vidate©, manufacturer's recommended dose
1 Oct 02	All plots	Defoliation	Ginstar©, manufacturer's recommended dose
5 Nov 02	All plots	Harvest	4-row spindle picker and boll buggy (SK-Crust Buster©)
6 Nov 02	All plots	Pull Roots	Root puller
Barley 2002/2003			
19 Dec 02	HIST plots	Fertilization	Monoammonium phosphate (11-52-0), 278.0 kg ha^{-1}
19 Dec 02	All plots	Maintenance	Conservation till, laser, disc hip, bed shape
19 Dec 02	All plots	Plant	Poco©, 122 kg ha^{-1}, 18 cm spacing, rows and furrows (MF-4263 Monosoem© planter)
12 Feb 03	HIST plots	Fertilization	Ammonium sulphate (21-0-0), 192.2 kg ha^{-1}
31 Mar 03	HIST plots	Fertilization	Ammonium sulphate (21-0-0), 145.1 kg ha^{-1}
29 Apr 03	All plots	Harvest	5.5 m width axial flow combine (International© 1440) and weigh wagon

rows on the tops of beds, while barley was planted both on beds and in furrows. Of the six rows in each plot, only plants in the centre four rows were measured and harvested to eliminate fringe effects. Monoammonium phosphate (11-52-0) and ammonium sulphate (21-0-0) fertilizers were applied both by side-dressing and manual techniques, depending on the crop, crop height and time of year (Table 1). After each field harvest, a conservation tillage system was implemented (tilling parallel to rows) to reduce cross-plot contamination of soils.

An elevated, oval-shaped pond was used as an irrigation reservoir and housed the fish for this experiment. The pond was lined with black plastic and consistently held 1800 m^3 of water. To collect sludges and other biosolids from the total pond area uniformly, a collection pipe was built along the bottom of the pond. A gasoline-powered pump was used to discharge water from the fish pond via flex hose connected to a

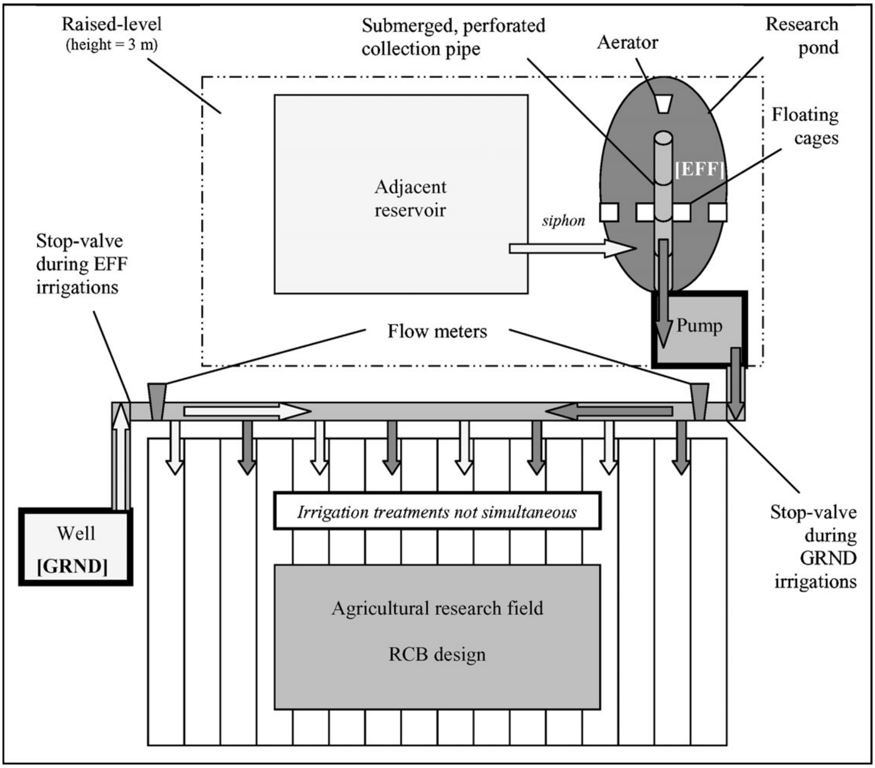

Figure 1. The IAA system implemented at the University of Arizona's Maricopa Agricultural Center in Maricopa, Arizona, USA. GRND: groundwater; EFF: effluent; RCB: randomized complete block.

segmented field irrigation pipe (15.2 cm diameter), which had adjustable, slotted flow outputs running the width of the field and perpendicular to crop rows. Water discharge occurred only during irrigation events. Half of the randomized plots received effluent and the others received groundwater. Analogue volume flow meters were fastened onto the irrigation pipe nearest to each incoming water source adjacent to the stop valves in order to estimate irrigation water volume. Each plot was dyked along its edges and corners to allow for equal distribution of water and nutrients within the plots and to eliminate treatment contamination between plots. A floating aerator was anchored in the pond to maintain healthy dissolved oxygen levels. Six cube-shaped floating cages (volume 1 m^3) were fastened to the edges of the pond using rope and iron stakes to facilitate rotational multi-crop fish harvests.

Irrigation

Irrigation scheduling was determined using data from the Arizona Meteorological Network for the city of Maricopa and AZSCHED, a software program designed to manage and schedule watering events. Irrigation typically occurred at 50% depletion of plant available water in the rooting zone unless delayed by poor weather. In Arizona, short-season barley typically requires one to three irrigations after watering up and plant emergence, whereas late season cotton can require between eight and ten. Multiple water samples were collected at randomly assigned times from each irrigation source to determine the nutrient concentration of the water applied to the field. At the beginning of each irrigation event the pond effluent was concentrated and black in colour, but then became slightly less concentrated over time. Time trials conducted in August 2002 determined that this initial spike in nutrients lasted only a few minutes before subsiding to normal levels (Stevenson, 2003). There were three and four irrigation events for barley in 2001/2002 and 2002/2003, respectively, and nine for cotton in 2002. The volume of water applied during each irrigation event (EFF and GRND events combined) was approximately 2520 ± 260 m^3 ha^{-1} for barley (both seasons averaged, first two events of 2001 removed) and 1620 ± 170 m^3 ha^{-1} for cotton.

Water and pond biosolid analysis

Concentrated H_2SO_4 was added to all but one water sample from each source to eliminate metabolism by algae. All samples were frozen at -20 °C for future analysis. Samples with added H_2SO_4 were analysed for total Kjeldhal nitrogen, ammonia (NH_4-N), organic nitrogen (N-Org), nitrate (NO_3), total N and phosphate (PO_4). Electrical conductivity (EC), total dissolved solids (TDS) and pH were all determined from the sample not containing H_2SO_4. Samples of pond biosolids (i.e. the residual pond sludge and sediment remaining after draining) were collected from different depths and locations in the research pond after the final fish harvest and were analysed at IAS Labs in Phoenix, Arizona, to determine N and P content.

Fish cropping

The three farmed fish species were stocked and harvested at different times throughout the study. Koi fingerlings were stocked into the research pond at the start of the study. Additional juvenile and adult koi were added at different times during the season to increase the total pond biomass. Juvenile tilapia and catfish were raised on site at the University of Arizona Maricopa Agricultural Center, stocked into the floating cages of the research pond and harvested seasonally. All fish were weighed prior to stocking and at post-harvest. Caged fish were weighed mid-study for additional health and growth assessment and given floating feed through openings in the tops of cages. Fry, juvenile and adult koi swam freely in the pond and were fed the same floating feed. The target range for feeding was 2–3% of the total fish biomass once per day, as recommended by Tucker and Robinson (1990). The feed had a nutritional content of 32% crude protein (min), 4% crude fat (min), 6% crude fibre (max), 0.5% phosphorus (min) and 9% ash (max). Fish also fed upon pond algae, which were prolific during the summer.

Field crop data collection and analysis

Stand counts were taken at the start of each barley and cotton season to ensure uniform planting and emergence. Barley plants were randomly selected at different growth stages, and plant heights were measured from the ground to the apical kernel of fully-stretched plants. Because of heavy rains in winter during the 2002/2003 season, one less irrigation was used than in the 2001/2002 season. Conditions also never improved enough in the 2002/2003 season to permit a scheduled application of 2,4-D herbicide, and weed abundance among barley stands was greater in the second season. Cotton plants were selected at random for growth and fruiting measurements during five different growth stages. We measured plant height from the cotyledonary node to the apical meristem, the number of open fruiting positions (aborts) on each fruiting branch, the number of the first fruiting branch above the cotyledonary node, the number of total nodes per plant and the number of nodes above the highest white flower. On 14 August 2002, ten cotton plants from each plot were randomly selected for petiole nutrient content analysis. The fifth petiole below the apical meristem was collected and analysed to determine [NO_3] and [PO_4] in leaves.

Barley was harvested using a small research combine, while cotton was harvested using a spindle picker and boll buggy. Each plot was harvested individually and weighed at the conclusion of the growing season to calculate crop yield (kg ha^{-1}). Ginned samples (400 g) of harvested cotton were analysed at US Department of Agriculture laboratories in Phoenix, Arizona, for fibre quality and were tested for colour grade (cotton whiteness), micronaire (fibre thickness or fineness), staple (fibre length), strength (how difficult it is to break a single fibre) and uniformity (consistency and similarity between cotton fibre). One-way ANOVAs with Bonferroni post-hoc tests ($\alpha = 0.05$) were used in treatment comparisons (SPSS software).

RESULTS

Water nutrient and pond biosolid analysis

From December 2001 to April 2003, the cumulative adjusted N added to the field through the EFF and GRND irrigations alone were 92.3 kg N ha^{-1} and 109.9 kg N ha^{-1}, respectively. The cumulative adjusted levels of P added to the field through EFF and GRND irrigations alone were 1.7 kg P $ha^{-1}$and 0.0 kg P ha^{-1}, respectively. The pH of the pond ranged between 7.66 and 8.01, and TDS levels increased slightly over the course of the study because of evaporation and replacement of water without complete draining. All water quality data are provided in Table 2.

The research pond was drained for final fish harvest in April 2003. As expected, wet sludge depth was shallow near the centre pipeline, but rapidly became deeper and thicker at further distances. Sludge depth ranged from 7 cm to 61 cm, and the range of total retention over three cropping seasons was roughly estimated to be between 50 m^3 and 400 m^3. Subsamples of pond sludges were 46.0 ± 13.3% water, and contained 29.3 ± 18.4 ppm PO_4 and 1807.5 ± 1078.9 ppm N (mean ± *s.d.*). The overall N content of these biosolids was characterized as 95.8% N-Org, 4.0% NH_4, and 0.2% NO_3.

Fish cropping

Koi freely swam in the pond year-round, while tilapia and catfish were housed in floating cages during summer and winter, respectively. Fish showed healthy growth

Table 2. Water quality data for groundwater (GRND) and pond effluent (EFF) treatments during irrigation (2001–2003). Values are averages of three water samples collected at random intervals ($\geq$ 5 minutes after the start of irrigation). Average values per treatment are reported as the mean ± 1 *s.d.*

Date of irrigation	EC	TDS (ppm)	TKN (ppm)	NH_4-N (ppm)	Org-N (ppm)	NO_3-N (ppm)	PO_4-P (ppm)	Total N (ppm)
GRND								
22 Dec 2001†								
24 Jan 2002	1.28	819	0.00	0.00	0.00	5.43		5.43
9 Mar 2002	1.48	945	0.13	0.00	0.00	6.10		6.10
30 Mar 2002	2.31	838	0.00	0.00	0.00	5.27		5.27
18 May 2002	1.15	736	0.00	0.00	0.00	4.42		4.42
27 May 2002	1.04	663	0.00	0.00	0.00	4.64		4.64
18 June 2002	1.00	640	0.00	0.00	0.00	3.08		3.08
9 July 2002	1.26	817	0.61	0.00	0.61	2.31		2.92
22 July 2002	1.32	843	0.00	0.00	0.00	4.21	0.00	4.21
5 Aug 2002-	0.92	589	0.00	0.00	0.00	3.99	0.00	3.99
15 Aug 2002	0.94	603	0.00	0.00	0.00	4.44	0.00	4.44
26 Aug 2002	1.11	612	1.02	0.00	1.02	3.67	0.00	4.69
5 Sept 2002	1.01	646	0.79	1.05		4.01		
20 Dec 2002						5.16		5.16
7 Mar 2003	2.30		2.53		1.91	3.70		5.60
31 Mar 2003	1.34	858	0.33	1.45	0.68	5.51		7.64
EFF								
22 Dec 2001†								
24 Jan 2002	1.39	892	0.00	0.00	0.00	5.30		5.30
9 Mar 2002	1.52	973	0.37	0.00	0.27	1.97		2.24
30 Mar 2002	1.40	894	0.07	0.00	0.07	1.80		1.87
18 May 2002	1.32	842	1.14	0.48	0.66	2.54		3.69
27 May 2002	1.34	856	0.74	0.38	0.36	1.72		2.46
18 June 2002	1.25	802	1.99	0.10	1.89	0.50		2.48
9 July 2002	1.48	909	1.86	0.00	1.86	1.03		2.89
22 July 2002	1.36	870	2.51	0.26	2.25	0.00	0.15	2.51
5 Aug 2002-	1.11	708	3.37	0.00	3.37	0.00	0.21	3.37
15 Aug 2002	0.70	448	5.02	0.57	4.44	0.00	0.20	5.02
26 Aug 2002	1.35	864	3.00	1.19	1.81	1.87	0.17	4.86
5 Sept 2002			3.34	0.19	3.16	0.00	0.20	
20 Dec 2002			3.57	0.66	2.91	2.78		6.35
7 Mar 2003	1.77	1132	2.21	0.51	2.69	2.04	0.15	5.24
31 Mar 2003	1.62	1037	5.13	1.30	3.83	2.58		7.71
Average values per treatment								
GRND	1.32 ± 0.45	739 ± 119	0.39 ± 0.71	0.19 ± 0.48	0.32 ± 0.59	4.39 ± 1.00	0.00 ± 0.00	4.83 ± 1.21
EFF	1.35 ± 0.26	864 ± 163	2.29 ± 1.64	0.38 ± 0.42	1.97 ± 1.44	1.61 ± 1.44	0.18 ± 0.03	4.00 ± 1.76

†No data are available from initial irrigation in December 2001.

EC: Electrical conductivity; TDS: Total dissolved solvents; TKN = Total Kjeldahl nitrogen.

rates and survived well in the research pond with no visible signs of stress or ammonia toxicity around the gills, although acclimation to the research pond was the cause of some mortality for each species. With the exception of some early fingerling mortality during acclimation on a cold day in December 2001, koi were the most durable fish. The parasite *Ichthyophthirius multifiliis* ('ich'), which commonly targets catfish in Arizona from February to April, caused considerable harm in our catfish crop. Some carcasses

Table 3. Stocking, growth, and harvest of fish in the Maricopa Agricultural Center research pond (2001–2003).

Species	Date	No. stocked	No. harvested	Stocking biomass (kg)	Harvested biomass (kg)	Duration in pond (d)	Total % increase (kg)	Daily percent increase (%d^{-1})
Koi	27 Dec 01	1250		5.63		477		
	24 May 02	88		11.61		329		
	25 Sep 02	5		7.15		205		
	17 Dec 02	26		53.44		122		
	17 Apr 03		896		286.39			
	Total	1369	896	77.83	286.39	1133	270%	†
Tilapia	3 May 02	280		55.25		126		
	25 Sep 02		249		107.63			
	Total	280	249	55.25	107.63	126	97%	0.81
Catfish	17 Dec 02	149		25.75		122		
	17 Apr 03		122		35.38			
	Total	149	122	25.75	35.38	122	68%	0.56

†Data unavailable.

were found floating in cages prior to harvest, and many fish had visible signs of external lesions and skin deterioration. Results of all fish cropping are summarized in Table 3.

Field cropping

Statistical comparisons using combined yields from the two barley seasons could not be made because of unrelenting rains in 2003, which prohibited herbicide treatment and encouraged heavy weed cover in the field. These weeds affected the grain hopper during that year's harvest (albeit consistently across plots), and the yields of the two barley seasons were thus evaluated independently ($n = 4$ per group in 2001/2002 and in 2002/2003). The most notable growth differences were in barley and cotton height and yield, cotton petiole nutrient content and number of nodes per cotton plant. There were negligible differences in the other plant growth characteristics tested, including cotton fibre quality. Three comparisons were made in this study. The first compared EFF-ELIM v. GRND-ELIM, the second compared EFF-HIST v. GRND-HIST, and the third compared EFF-ELIM v. GRND-HIST.

We tested the effect of four treatments on crop growth and yield over two barley seasons and one cotton season. For all cropping seasons, no significant differences in yield were observed in our three treatment comparisons ($p > 0.05$), but EFF-treated plots always produced slightly higher yield values than GRND-treated plots grown under the same fertilizer regime. Significant differences in yield might have been observed in our comparisons had the study continued for additional seasons, had sample size been increased, or had dried pond biosolids been collected and utilized as additional fertilizer. Comparisons of crop height (Figure 2), petiole nutrient content (Figure 3) and crop yield (Figure 4) are shown. All results are summarized in Table 4.

Comparison 1 (EFF-ELIM v. GRND-ELIM): Petiole NO_3 and PO_4 concentrations were not significantly different between treatments, although EFF-ELIM crops had

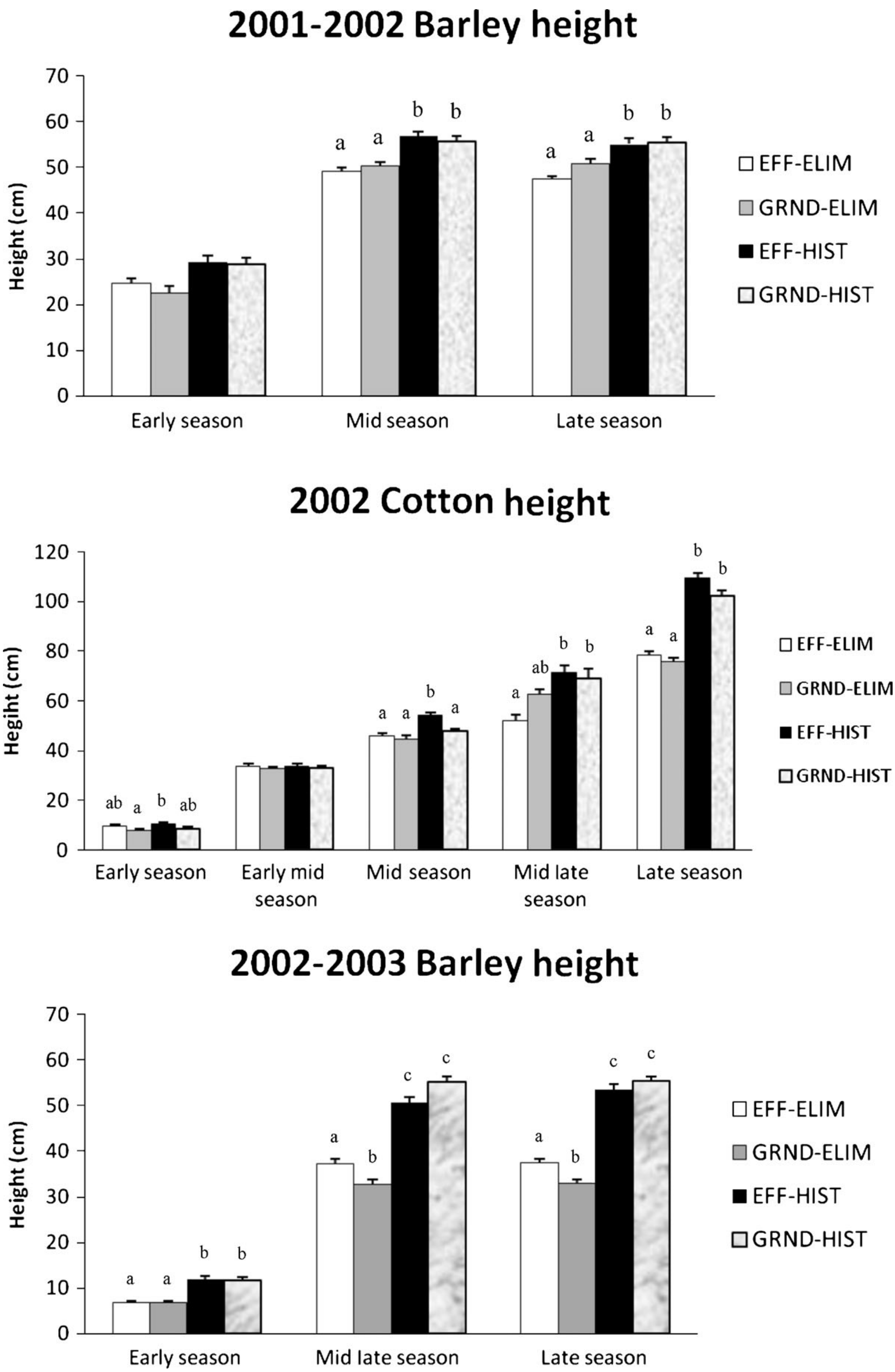

Figure 2. Effect of four treatments on barley and cotton plant height. Each treatment utilized one water source, either fish effluent (EFF) or groundwater (GRND), and one fertilizer regime, either eliminated (ELIM) or historical (HIST). Means and standard errors are reported. Within each sub-season, bars that share the same letter are not significantly different.

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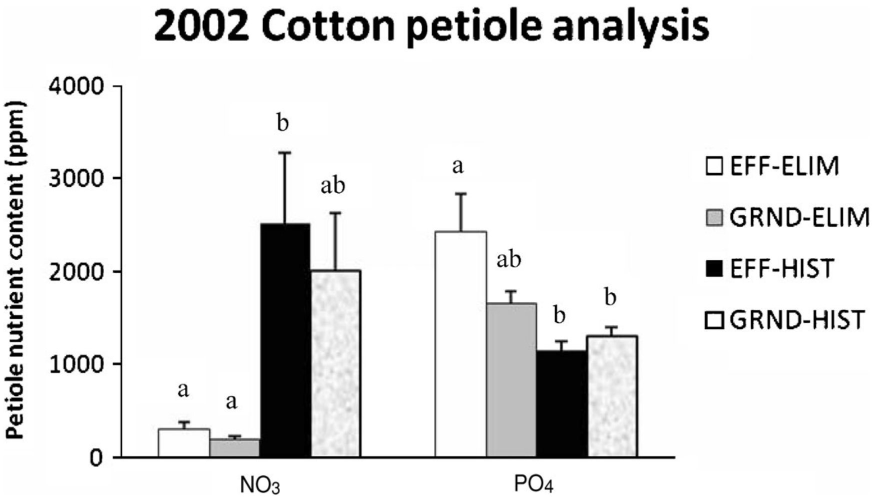

Figure 3. Effect of four treatments on cotton petiole nitrate [NO_3] and phosphate [PO_4]. Means and standard errors are reported. Within each nutrient category, bars that share the same letter are not significantly different

slightly higher levels of each (Figure 3). A significant effect of the EFF treatment was identified in the 2002/2003 barley season in that EFF-ELIM treated plants were significantly taller than GRND-ELIM plants in mid-season (ANOVA, $p < 0.001$) and late-season ($p < 0.001$, Table 4, Figure 2). Crop yield was also slightly (although not significantly) higher in plots treated with EFF-ELIM in all three growing seasons (Figure 4). Overall, EFF-ELIM performed slightly better than GRND-ELIM.

Comparison 2 (EFF-HIST v. GRND-HIST): The EFF-HIST treatment produced significantly taller cotton plants than GRND-HIST in mid-season 2002 (ANOVA, $p = 0.003$) and in late-season 2002 ($p = 0.005$). No other significant differences or consistent trends in crop growth were detected in this comparison. Interestingly, EFF-HIST produced plants with the highest petiole NO_3 content, but the lowest PO_4 levels among all four treatments (ANOVA, NO_3 $F_{[3,12]} = 5.709$, $p = 0.12$; PO_4 $F_{[3,12]} = 6.186$, $p = 0.009$). However, neither NO_3 nor PO_4 concentrations in petioles of EFF-HIST plants were significantly different from GRND-HIST plants ($p > 0.05$). The yields of EFF-HIST-treated plants were slightly (but not-significantly) greater than those of GRND-HIST-treated plants in each cropping season (Figure 4, Table 4). Overall, EFF-HIST performed slightly better than the GRND-HIST treatment.

Comparison 3 (EFF-ELIM v. GRND-HIST): GRND-HIST outperformed EFF-ELIM at many levels. Across all growing seasons, plants receiving GRND-HIST grew significantly taller than plants receiving EFF-ELIM ($p < 0.05$, Figure 2, Table 4), and this effect was quite pronounced in the final barley season ($p < 0.001$ for early-, mid-, and late-season). During the 2002 cotton season, plants treated with GRND-HIST also produced significantly more nodes per plant than EFF-ELIM treated plants during mid-late season ($p = 0.004$) and late season ($p = 0.003$). However, these results did not necessarily correspond with yield in only three cropping seasons, as there were no noticeable trends or differences. Cotton plants treated with GRND-HIST had

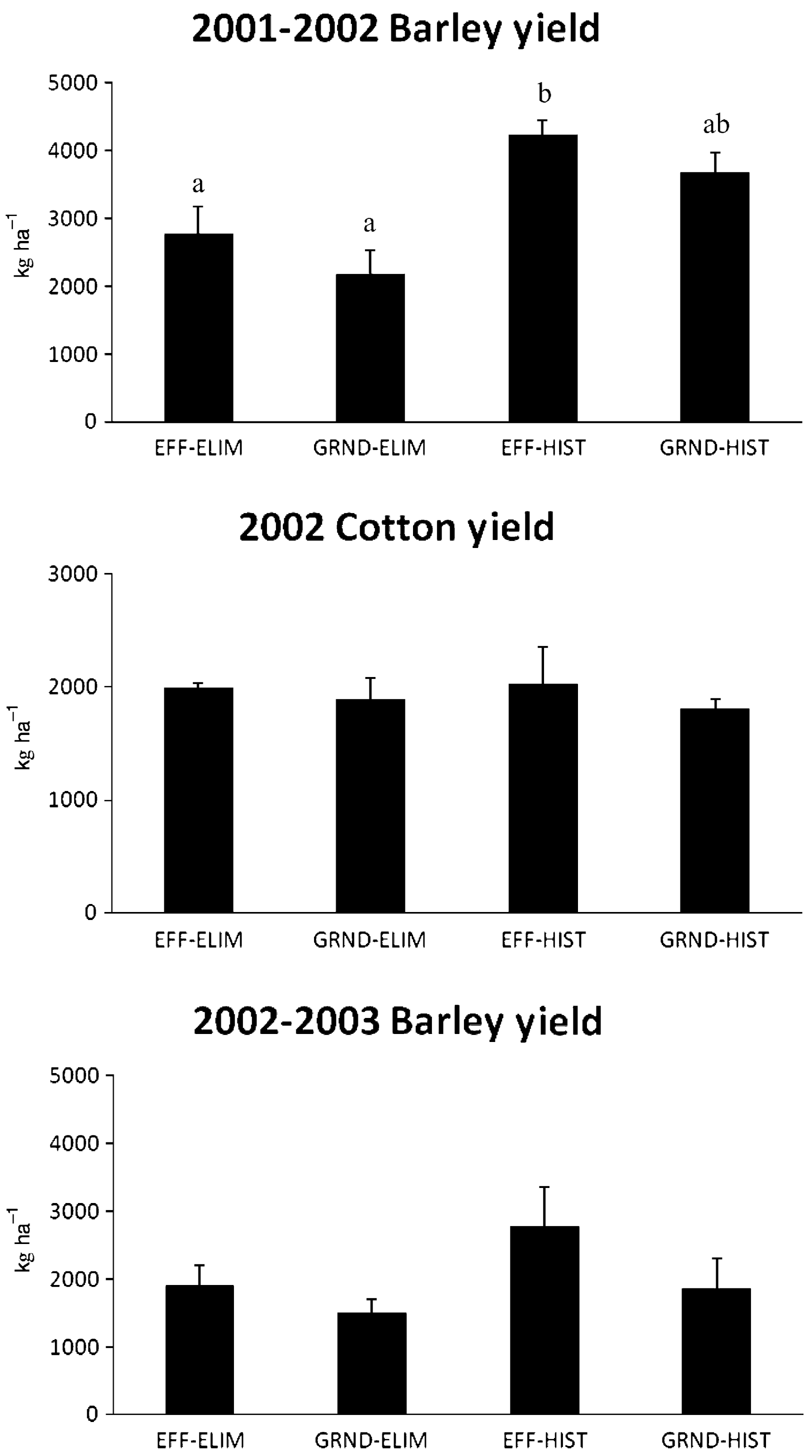

Figure 4. Effect of four treatments on barley and cotton yield. Means and standard errors are represented. Bars that share the same letter are not significantly different ($n = 4$ harvested plots per treatment group).

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Table 4. Effect of water and fertilizer treatments on yield and plant growth characteristics during two barley seasons and one cotton season. Up to 10 randomly selected plant measurements were averaged within each plot (except for yield) to obtain a plot average measurement ($n = 4$ plots per treatment group).

	Comparison 1			Comparison 2			Comparison 3		
	EFF-ELIM	GRND-ELIM	*p*-value	EFF-HIST	GRND-HIST	*p*-value	EFF-ELIM	GRND-HIST	*p*-value
2001/2002 Barley									
Plant height (cm)									
Early season	24.6 ± 1.1	22.6 ± 1.4	*n.s.*	29.4 ± 1.2	28.8 ± 1.4	*n.s.*	24.6 ± 1.1	28.8 ± 1.4	*n.s.*
Mid season	49.1 ± 1.0	50.2 ± 0.8	*n.s.*	56.8 ± 1.1	55.7 ± 1.3	*n.s.*	49.1 ± 1.0	55.7 ± 1.3	<0.001
Late season	47.4 ± 0.6	50.8 ± 1.0	*n.s.*	55.1 ± 1.4	55.5 ± 1.0	*n.s.*	47.4 ± 0.6	55.5 ± 1.0	<0.001
Final yield (kg ha^{-1})	2779 ± 389	2184 ± 339	*n.s.*	4242 ± 199	3688 ± 270	*n.s.*	2779 ± 389	3688 ± 270	*n.s.*
2002 Cotton									
Plant height (cm)									
Early season	9.7 ± 0.7	7.9 ± 0.5	*n.s.*	10.4 ± 0.7	8.7 ± 0.6	*n.s.*	9.7 ± 0.7	8.7 ± 0.6	*n.s.*
Early-mid season	33.9 ± 1.1	32.7 ± 0.9	*n.s.*	33.7 ± 1.2	33.0 ± 0.9	*n.s.*	33.9 ± 1.1	33.0 ± 0.9	*n.s.*
Mid-season	45.8 ± 1.5	44.8 ± 1.2	*n.s.*	54.2 ± 1.1	48.0 ± 1.0	0.003	45.8 ± 1.5	48.0 ± 1.0	*n.s.*
Mid-late season	52.1 ± 2.6	62.5 ± 2.3	*n.s.*	71.3 ± 3.1	68.9 ± 4.2	*n.s.*	52.1 ± 2.6	68.9 ± 4.2	0.040
Late season	78.2 ± 1.9	75.9 ± 1.6	*n.s.*	109.5 ± 2.2	102.2 ± 2.1	0.005	78.2 ± 1.9	102.2 ± 2.1	<0.001
Nodes per plant									
Mid-late season	18.0 ± 0.5	20.0 ± 0.5	*n.s.*	22.5 ± 1.0	20.5 ± 0.5	*n.s.*	18.0 ± 0.5	20.5 ± 0.5	0.004
Late season	23.8 ± 0.7	24.2 ± 1.3	*n.s.*	28.9 ± 0.5	28.2 ± 0.4	*n.s.*	23.8 ± 0.7	28.2 ± 0.4	0.003
Aborts plant^{-1}									
Mid-late season	17.4 ± 0.7	18.5 ± 1.1	*n.s.*	22.3 ± 0.5	18.9 ± 0.8	*n.s.*	17.4 ± 0.7	18.9 ± 0.8	*n.s.*
First fruiting branch									
Late-season	6.3 ± 0.3	6.7 ± 0.1	*n.s.*	6.9 ± 0.1	7.0 ± 0.1	*n.s.*	6.3 ± 0.3	7.0 ± 0.1	*n.s.*
Nodes above white flower									
Late-season	3.6 ± 0.2	4.7 ± 0.2	*n.s.*	3.7 ± 0.7	4.2 ± 0.4	*n.s.*	3.6 ± 0.2	4.2 ± 0.4	*n.s.*
Fruit per plant									
Late-season	10.9 ± 1.4	9.6 ± 0.9	*n.s.*	12.1 ± 0.7	10.1 ± 1.0	*n.s.*	10.9 ± 1.4	10.1 ± 1.0	*n.s.*
Petiole NO_3 (ppm)									
Late-season	310 ± 73	193 ± 38	*n.s.*	2525 ± 758	2003 ± 632	*n.s.*	310 ± 73	2003 ± 632	0.027
Petiole PO_4 (ppm)									
Late-season	2425 ± 413	1650 ± 133	*n.s.*	1160 ± 87	1300 ± 108	*n.s.*	2425 ± 413	1300 ± 108	*n.s.*
Final yield (kg ha^{-1})	1989 ± 39	1890 ± 183	*n.s.*	2033 ± 315	1808 ± 77	*n.s.*	1989 ± 39	1808 ± 77	*n.s.*
2002/2003 Barley									
Plant height (cm)									
Early season	6.7 ± 0.4	6.7 ± 0.5	*n.s.*	12.1 ± 0.6	11.6 ± 0.7	*n.s.*	6.7 ± 0.4	11.6 ± 0.7	<0.001
Mid season	37.1 ± 1.1	32.7 ± 1.1	<0.001	50.8 ± 1.1	55.1 ± 1.3	*n.s.*	37.1 ± 1.1	55.1 ± 1.3	<0.001
Late season	37.5 ± 0.7	32.9 ± 1.0	<0.001	53.4 ± 1.4	55.3 ± 1.1	*n.s.*	37.5 ± 0.7	55.3 ± 1.1	<0.001
Final yield (kg ha^{-1})	1912 ± 297	1504 ± 197	*n.s.*	2779 ± 562	1860 ± 432	*n.s.*	1912 ± 297	1860 ± 432	*n.s.*

slightly higher NO_3 levels ($p = 0.194$), but significantly lower PO_4 levels than plants treated with EFF-ELIM ($p = 0.027$).

DISCUSSION

The ability of communities in arid lands to maintain food production is critical to their overall resilience and sustainability. However, in many cases, the historical practices of integrated land use have been either forgotten or abandoned in favour of more conventional, 'modern' practices. As water resources become increasingly threatened, both from scarcity and quality, it is imperative that greater attention is paid to the design, promotion and infrastructure associated with IAA. Key variables associated with water quality and water use efficiency, as well as cyclical biomass production, are important to the science and sustainability of these systems.

Water quality

Nitrate is the preferred form of N for plant uptake, but it leaches through the soil column faster than organic N, which can lead to groundwater contamination. Our groundwater source contained much higher NO_3 than the EFF source, which was likely the result of excessive chemical fertilizer loading. In fact, these high NO_3 levels even gave GRND a slight advantage over EFF in total N (+0.83 ppm). Prior to the study, time trial intervals showed that NO_3^- was absent in the initial EFF discharge (0.0 ppm) and minutely present 30 minutes later (1.87 ppm) (Stevenson, 2003). On average, EFF contained NO_3^- levels of 1.61 ± 1.44 ppm. However, this water originated from the same source as the GRND treatment that averaged 4.39 ± 1.00ppm NO_3^-. This suggests that much of the NO_3^- in the open pond reservoir was assimilated by bacteria or algae that were either trapped in pond muds (Boyd and Tucker, 1998; Hepher, 1958) or consumed by fish. The fish effluent (EFF) source contained higher levels of the other forms of N. Total Kjeldhal Nitrogen was generally higher in EFF treatments, along with ammonia, the primary nitrogenous waste product excreted by fish across their gills (Wright, 1995). NH_3 is not likely be sequestered in benthic sludges because it is water soluble, and is often fixed by algae into an organic form (N-Org). The GRND treatment contained no PO_4, while an average of 0.18 ± 0.03 ppm PO_4 was added to the field with each EFF irrigation.

Fish cropping

The rotational crop design allowed for year-round intervals of water exchange during crop irrigation events and thus maximized the conservation of water and nutrient resources in the system. The system produced a healthy and profitable crop of fish, and the pond generated large quantities of biosolids for future use as organic fertilizer. Koi were the hardiest fish after initial acclimation, and juveniles and adults were able to survive the year-long temperature extremes. They responded well to handling and were unaffected by seasonal parasite infestations. In southwestern IAA systems, tilapia might generate the greatest net profit because of both their favourable market value as food fish and because they are omnivorous, durable, resistant to common parasites and will eat many small, naturally occurring organisms. They are also incredibly tolerant to high temperatures (up to 42°C) and salinities (up to 29 ppm), and they possess many osmoregulatory mechanisms and unique endocrine characteristics that help to broaden their applicability to IAA systems throughout arid environments (Chervinski, 1982; Prunet and Bornancin, 1989). Although US markets favour whole tilapia, one drawback is that they prefer tropical (non-seasonal) climates, and are typically harvested or kept in a heated area to avoid the potentially harmful effects of cool winters (depending on the specific region). We faced several problems in raising channel catfish in our system. Not only did several die from handling and acclimation stress, but they were susceptible to the parasite, *I. multifiliis*. Every fish became infected, and several showed visible signs of stress. They do not always acclimate well to hot desert temperatures and may not survive handling in the summer. Although market prices for catfish generally produce good returns, they can be a risky investment in the desert.

Field cropping

Depending on fertilizer and soil composition, the N release characteristics of organic fertilizers may actually match N requirements of certain crops more closely than those of inorganic fertilizers (Smith and Hadley, 1989). The organic forms of N and P that are released during EFF irrigations are likely to leach more slowly, be decomposed by soil bacteria near the surface, and be deposited in close proximity to the roots of cotton plants. This may have contributed to the observed trend in crop production in which EFF produced slightly higher yields than GRND under the same fertilizer regime (Comparisons 1 and 2, Table 4). However, the crop growth results from Comparison 3 (EFF-ELIM v. GRND-HIST) suggest that the IAA system tested here, when devoid of dried pond biosolid applications between seasons, would not be competitive with a historical fertilizer regime over longer periods of time. The most notable indicators of this in our study were plant nitrate (but not phosphate) content, plant height and growth markers (e.g. nodes per cotton plant). The results of Comparison 3 generally support the conclusions of a long-term (21 year) organic/inorganic comparison study in which crop yields were found to be approximately 20% lower in organically farmed plots (Mäder *et al.*, 2002). Despite that reduction in yield, however, organic farming practices lead to fertilizer and energy input reductions of 34–53%, pesticide input reductions of 97% and substantial enhancements in soil fertility and biodiversity.

Recommendations for future IAA research and practice in arid regions

Given the limited nutrient contribution to crops from effluent compared with historical practice and background groundwater levels in this study, an alternative approach to analysis might be to use a conceptual mass balance model to investigate the relative contribution and fate of N and P from the fish compared with other sources. In doing so, different scenarios could be considered on the same premise that an IAA system could contribute significantly to crop productivity and water use efficiency.

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Longer and more detailed experiments involving ground water and fertilization treatments, as well as the application of pond biosolid applications between harvests, are likely to improve the current understanding of the sustainability of organic farming practices. We recommend increasing plot sample size, using multiple sites to include a variety of microclimates and soil types, testing effects of treatments different types of field crops, and measuring effects of manually applied pond biosolids on crop yield and soil quality. A comprehensive investigation and evaluation of pond design is also needed for arid regions. For instance, an elevated cone-shaped design with steep slopes and a retractable opening at the bottom point of the pond might allow for more efficient discharge of nutrient-rich sediments while minimizing manual collection or cleaning. Fastening grates above the opening would prevent fish or other aquaculture crops (e.g. freshwater prawns) from being flushed out onto the field and would still allow biosolids to accumulate prior to water discharge. Other pond designs might help to overcome thermal barriers to IAA in highly seasonal environments. For instance a pond design that more effectively utilized ground temperature (e.g. through the use of long, subterranean culverts) might improve the feasibility of IAA in desert regions, creating a buffer zone for fish species that are thermally intolerant to ambient conditions in a given season.

The benefits of IAA both to growers and to environmental quality are very apparent. The use of an arid lands IAA system can successfully and effectively enable the reuse of water, reduce the cost and loading of chemical fertilizers, and support the concurrent production of freshwater aquaculture and field agriculture crops (Fernando and Halwart, 2000; Ingram *et al.*, 2000; McIntosh and Fitzsimmons, 2003; Prinsloo and Schoonbee, 1993; Stevenson, 2003). The positive effect of fish effluent irrigations was well noted in a consistent trend towards increased petiole PO_4 levels and plant yield, (even with ground water containing higher levels of NO_3 and total N). Based on the results of this study, one recommendation for an arid lands IAA system consists of farming tilapia from spring through fall and koi year-round (assuming a market exists for larger ornamentals).

Ultimately, locale-specific adaptations will result in the production of biomass that best serves a community's interests and needs. Production of an instruction manual would help arid lands farmers to adopt IAA. Such a resource would inform them of optimal production species, as well as the timing of cultivation, and it would guide them in determining the best practices in balance with their own desires.

CONCLUSIONS

Sustainability has been promoted as a major benefit of IAA systems (Jamu and Piedrahita, 2002). However, Prein (2002) notes that while on-farm performance of IAA systems has been successful, it has not yet been sustainable within large-scale systems. Here, we show the potential benefit of one type of integrated system. In drought-prone regions, the lack of water reuse and the leaching of fertilizers through soils have been implicated in environmental degeneration. Growers can use IAA to increase diversification, generate higher revenue, conserve resources and promote environmental health. By using irrigation water to raise an aquaculture crop before discharging it onto agricultural fields, desert growers could earn additional income to offset the high cost of irrigating cotton and small grains in the desert, while at the same time reducing inorganic fertilizer use and groundwater pollution.

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