Aquaculture International **12:** 539–553, 2004.

A comparison of reciprocating flow versus constant flow in an integrated, gravel bed, aquaponic test system

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Received 20 October 2003; accepted 20 January 2004

Abstract. Murray cod, *Maccullochella peelii peelii*, and Green oak lettuce, *Lactuca sativa*, were used to test for differences between two aquaponic flood regimes; reciprocal flow (hydroponic bed was periodically flooded) and constant flow (hydroponic bed was constantly flooded), in a freshwater aquaponic test system, where plant nutrients were supplied from fish wastes, while plants stripped nutrients from the wastewater before it was returned to the fish. The Murray cod had FCRs and biomass gains that were statistically identical in both systems. Lettuce yields were good and a significantly greater amount of both biomass and yield occurred in the constant flow treatment. Constant flow treatments exhibited greater pH buffering capacity, required fewer bicarbonate (buffer) additions to control pH and maintained lower conductivity levels than reciprocal flow controls. Water consumption in the two systems was statistically identical. Overall, results suggest that a constant flow flooding regime is as good as, or better than, a reciprocating flooding regime in the aquaponic test system used.

Key words: Aquaponics, Flood regime, Hydroponics, Lettuce, Murray cod

Introduction

Aquaponics is the integration of hydroponic plant production into recirculating aquaculture systems (RAS), and has been proposed as a method to control the accumulation of waste nutrients from fish culture (Rakocy and Hargreaves 1993), in a way that consumes less water (McMurtry et al. 1997) and produces additional, saleable crops (Rakocy and Hargreaves 1993). Early researchers showed that waste nutrients could be 'stripped' from fish culture waters using hydroponically-grown plants (Naegel 1977; Lewis et al. 1978; Waten and Busch 1984), with the hydroponic component generally using a sand/gravel/aggregate culture bed (Lewis et al. 1978; Waten and Busch 1984; McMurtry et al. 1993). A reciprocating flooding and draining cycle

for the hydroponic bed was thought to be essential to the efficient operation of the system (Lewis et al. 1978; Nair et al. 1985; McMurtry et al. 1997), as reciprocation provides uniform distribution of nutrient rich waters within the media during the flood phase and improved aeration in the media during the drain component of the cycle due to effective atmosphere exchange of gases in the drained hydroponic bed (McMurtry et al. 1997). In these studies, the ratio of 'flooding' times to 'draining' times varied, from 5 min (Sutton and Sutton 1983) to 30 min (McMurtry et al. 1990) or more. The number of flood cycles per day also varied, from as low as 5 times a day (McMurtry et al. 1997) to as high as 6 times an hour (Sutton and Sutton 1983). Although reciprocation of flood/drain cycles may have potential advantages (such as increased aeration of hydroponic media), no evidence within the scientific literature can be found that compares reciprocating flooding with a constant flood flow or cycle.

This experiment was devised to test a reciprocating flood/drain cycle in the hydroponic component of an aquaponics system against a constant flow (through the hydroponic bed and back to the fish culture component). The fish species used was the Australian native Murray cod, *Maccullochella peelii peelii*, and the hydroponic vegetable was lettuce, *Luctuca sativa* (Green oak variety). The two systems were compared for fish growth, plant growth and nutrient levels in the recirculating water.

Methods

Fish origin and holding

Murray cod were obtained from Australian Aquaculture Products Pty. Ltd., Victoria, Australia. Fish were held indoors at the RMIT University Aquaculture Annex and ranged in size from 120 to 220 g. All fish were kept in 1000 L, cylindrical tanks receiving flow-through water at a flow rate of 3000 L day^{-1}, until required for experimentation. Water was of domestic origin, carbon filtered and heated to approximately 22 °C.

Experimental aquaponic system description

The experimental aquaponic testing system consisted of 12 individual, identical aquaponic units, designed to allow for replication of experimental situations.

Each aquaponic unit consisted of one fish holding tank, an associated biofilter and a hydroponic growth bed (Figure 1). The fish tank consisted

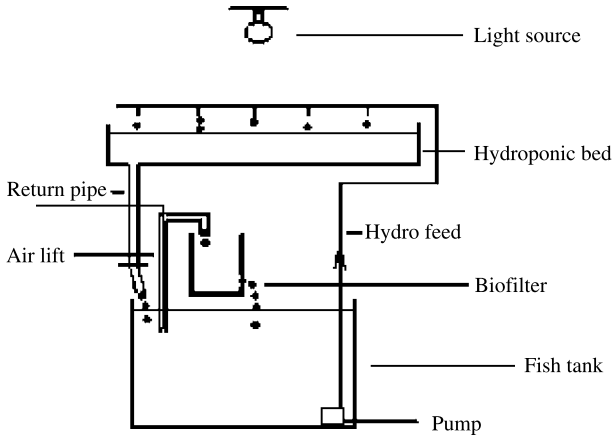

Figure 1. Schematic representation of the aquaponic test system.

of a round 100 L, opaque, white plastic tank (570 mm diameter × 460 mm deep). Other than fish, the tank contained an airlift pipe (see biofilter section), a submersible water pump (see hydroponic bed section) and a 100 W (240 V), thermostatically controlled electrical resistance aquarium heater. A plastic 'core flute' (3 mm) lid covered the tank to lower evaporation and prevent fish from jumping from the tank.

Each tank had an associated, 20 L biofilter (360 mm L × 330 mm W × 290 mm D), made from a plastic storage box. This biofilter sat above the fish tank and was of a wet/dry trickling design. Water entered the biofilter by way of a 50 mm airlift pipe (at an average of 250 L h^{-1}), running from the base of the fish tank and into the top of the biofilter. Water from the airlift entered the top of the biofilter via a 'spray bar', then trickled across the biological filter medium (polystyrene 'bean bag' beads at approx. 300 m^2 m^{-3}: area/volume) and out a series of 6 × 10 mm holes (drilled in the bottom, front area of the biofilter) and back into the fish tank.

Each tank and biofilter unit had an associated hydroponic plant growth bed with gravel media. This bed, rectangular in shape (780 mm L × 670 mm W × 220 mm D), was placed above the fish tank/biofilter unit on a separate shelving system. The hydroponic bed was filled with approximately 80 L of 7 mm, washed river gravel. A submersible water pump (Rio 1700, 1200 L h^{-1} at 1.2 m head) in the fish tank delivered water to the hydroponic bed via a 25 mm pipe when activated. Water from the hydroponic bed was returned to the fish tank via a 50 mm drainpipe, situated at the opposite end of the hydroponic bed from the water inlet.

The aquaponic unit operated continuously with a known density of fish biomass. Fish lived, were fed and defecated entirely within the fish tank.

Water from the fish tank was continuously (24 h day^{-1}) pumped to the biofilter via the airlift, thus biological filtration of the culture water was constant. At a determined time interval (see below) a timed electrical switch supplied energy to the submersible pump, pumping water from the fish tank up to the hydroponic bed. Thus, the hydroponic bed was flooded with fish tank culture water at regular intervals. The valve in the hydroponic bed drain line was used to control the rate of the return water flow so as to produce a water level in the hydroponic bed that completely saturated the gravel media. Water eventually returned to the fish tank via the hydroponic bed drain line. Water for all tanks was supplied from the aquaculture lab water supply system.

Lighting (for plant growth in the hydroponic beds) consisted of 6×400 W metal halide lamps. Lights were situated above the hydroponic beds at a height of 700 mm above the gravel surface, with one lighting unit located at the interface between two hydroponic growth beds. Lights were controlled by a digitally timed electrical switch (timer).

Biofilters were pre-conditioned for 3 weeks prior to experimentation. Preconditioning consisted of daily additions of ammonium chloride (NH_4Cl) at a rate of 20 mg L^{-1} (2 g $tank^{-1}$). Daily ammonia and nitrite levels were taken to determine the degree of oxidation of ammonia to nitrate, evidence that the biological filter was working. This also allowed the establishment of a steady-state bacterial biomass in the biofilter in order to minimise net nutrient uptake by bacteria at the beginning of the hydroponic trials.

Experimental methodology

This experiment was designed to ascertain whether aquaponically grown lettuce plants grew successfully using a constant flow regime (roots constantly inundated with water), as opposed to a flood and drain regime (reciprocating flood). Two separate test regimes were operated in triplicate:

1. *Reciprocating control*; fish in tank, plants in the hydroponic bed, flood regime of 10 min every 70 min (pump on 10 min in every 70 min) – this was a control regime based on previous research.
2. *Constant flow*; fish in tank, plants in the hydroponic bed, flood regime of constant flow (pump permanently on) – this was a test regime to compare plant growth and other parameters to the control (flood and drain) regime.

The lighting regime for plant growth was 10 h on:14 h off, with lights coming on at approximately 08:30 hours (AEST) and going off at 18:30 hours (AEST).

At the initiation of the experiment, systems were flushed and refilled with fresh, aquaculture system water to 100 L and initial nutrient levels (nitrate

and phosphate) were recorded. Fish were added to each system up to the treatment biomass of approximately 1000 g (fish biomass was recorded on an individual tank basis). Twenty lettuce plantlets (*L. sativa*, Green oak variety) were planted using an evenly distributed planting scheme in each of the replicate hydroponic beds. The individual initial weight (biomass) of these 20 plantlets was recorded (weight with attached soil plug). Because plantlets had attached plugs of soil, initial leaf weight was estimated by recording the weights of an additional 15 plantlets with and without attached soil plugs. These weights were used to establish a mean ratio of leaf only to leaf + plug weight. This ratio was then used to estimate the initial leaf only weight of the hydroponic tested plantlets.

Fish were fed at a percentage of the total initial fish biomass per day (for 6 out of 7 days per week) with a 9 mm, sinking pellet (43% protein) (Skretting Classic SS, Skretting Pty. Ltd., Australia). Fish feeding rates were incrementally increased over the duration of the experiment, in order to avoid the shock loading of the biofilters. Feeding rates were set at 1.0% of fish biomass (per day) for the first 6 days, then adjusted to 1.5% for the remaining 15 days of the experiment.

Six out of 7 days a week (at the same time every day – 9:30 hours, AEST; Monday to Saturday, inclusive), the amount of fish feed fed (g), air temperature (°C), water replaced per tank (L) (to adjust for evapotranspiration), sodium bicarbonate added (to adjust pH between 6.80 and 7.40) (g), pH, temperature of the tank water (°C), conductivity ($\mu s\,cm^{-1}$) and dissolved oxygen ($mg\,L^{-1}$) were recorded. Twice a week, tanks were sampled for ammonia ($mg\,L^{-1}$), nitrite ($mg\,L^{-1}$), nitrate ($mg\,L^{-1}$) and phosphate ($mg\,L^{-1}$).

The amount of feed fed and the bicarbonate added per tank were measured using a top loading balance (A.N.D. HL-200). The amount of water replaced per tank was determined by re-filling the tank to a pre-measured 100 L mark and recording the amount of water added (fresh aquaculture annex water). Temperature (tank water), pH, conductivity and dissolved oxygen were determined using a meter and Sonde probe (Grant YSI 3851 Sonde; Grant YSI 3800 Data Logger). Ammonia was determined using a Hanna, C203 Multiparameter ion specific meter (H025463) and Hanna Ammonia LR reagent (HI 93700-01). Nitrite was determined using a Hanna, C203 Multiparameter ion specific meter (H025463) and Hanna Nitrite LR reagent (HI 93707-01).

Phosphate was determined using a Merck spectroquant colour reagent test (ammonium vandate and ammonium heptomolybdate in H_2SO_4, code: 1.1482.0001), read against a standard curve (a new curve was determined every determination) and read using a spectrophotometer at 400 nm (Varian Cary 50 Bio UV–Vis). Nitrate was determined using a Hanna, C203 Multiparameter ion specific meter (H025463) and Hanna Nitrate HR reagent (HI 93728-01).

The entire experiment ran for 21 days from water flushing and planting to harvesting of the mature lettuce. At the end of the experiment, fish biomass was determined by weight (Wedderburn, Tanita-1581) and lettuce plant (leaf only) biomass was determined by weight (A.N.D. HL-200). Gains in both fish biomass and plant biomass per replicate were determined by the differences between initial and final biomasses. Fish biomass was determined on a per replicate basis, whilst plant biomass (leaf only) was determined on an individual, per plant basis.

Comparisons between treatments and controls at the end of the experimental period for fish biomass, fish FCR, fish SGR, nitrate and phosphate were analysed using Mann–Whitney, two independent population, non-parametric analysis. Comparisons between all other parameters were analysed using ANOVA and least significant difference (LSD) post-hoc analysis where appropriate. All statistical analysis was performed using SPSS (Version 10.0) software.

Results

Fish

Survival of Murray cod in all replicates (for both constant flow and reciprocating control treatments) was 100% for the 21-day trial. Table 1 shows the increase in fish biomass, specific growth rate (SGR) and food conversion ratio (FCR) for both treatments. There were no significant differences ($P > 0.05$, $n = 3$) detected between the two treatments (constant flow and reciprocating control) for any of the parameters measured (biomass gain, SGR and FCR).

Lettuce

The gain in plant biomass (wet weight) for the constant flow test treatment differed significantly ($P < 0.05$, $n = 60$) from the reciprocating control treatment (Table 1). Similarly, both yields ($\mathrm{g\,plant^{-1}}$ and $\mathrm{kg\,m^{-2}}$) showed a significant difference ($P < 0.05$, $n = 60$) between the constant flow test treatment and the reciprocating control (Table 1).

Metabolites, nitrates and phosphates

Ammonia ($NH_3\,NH_4^+$) and nitrite (NO_2) were recorded twice weekly to ascertain biological filter conversion efficiency. All replicates in both treatments showed minimal initial (day 1) ammonia concentrations, but these dropped to zero ($0\,\mathrm{mg\,L^{-1}}$) after the first week of the experiment. Nitrite levels remained at zero ($0\,\mathrm{mg\,L^{-1}}$) for all replicates in both treatments for the entire duration of the experiment.

Table 1. Murray cod wet weight gain, specific growth rate (SGR), food conversion ratio (FCR) and food consumption; lettuce mean biomass gain and mean yield ($g\,plant^{-1}$ and $kg\,m^{-2}$); and mean net phosphate and nitrate concentrations for reciprocal control and constant flow treatments at the end of the 21 day trial

Parameter	Reciprocating control	Constant flow
Fish		
Wet weight[1] (g/replicate)	$173.3^{a} \pm 15.3$	$210.0^{a} \pm 17.3$
SGR[1] (%/replicate/day)	$0.78^{a} \pm 0.04$	$0.92^{a} \pm 0.05$
FCR[1]	$1.25^{a} \pm 0.06$	$0.92^{a} \pm 0.05$
Feed fed (g/replicate)	215.0	215.0
Lettuce		
Biomass gain[1] (g/replicate)	$2269.0^{a} \pm 23.7$	$2599.6^{b} \pm 11.9$
Yield[1] ($g\,plant^{-1}$)	$113.45^{a} \pm 5.31$	$129.98^{b} \pm 2.65$
Yield[1] ($kg\,m^{-2}$)	$4.34^{a} \pm 0.20$	$4.97^{b} \pm 0.10$
Nutrients		
Phosphate[1] ($mg\,L^{-1}$)	$4.04^{a} \pm 0.39$	$3.87^{a} \pm 0.71$
Nitrate[1] ($mg\,L^{-1}$)	$13.30^{a} \pm 2.05$	$11.80^{a} \pm 1.78$

[1] Values are means ± S.E.
[a,b] Values showing the same letter are not significantly different ($P > 0.05, n = 3$) (Mann–Whitney).
SGR: specific growth rate (% day^{-1}): [(ln final wt. − ln initial wt.)/(time (days))] × 100.
FCR: food conversion ratio: feed fed/wet weight gain.

Final net phosphate (PO_4) concentrations are represented in Table 1. Concentrations averaged 4.04 and 3.87 $mg\,L^{-1}$ for reciprocating control and constant flow treatments respectively with no significant difference detected ($P > 0.05, n = 3$).

Final net nitrate (NO_3) concentrations are represented in Table 1. Concentrations averaged 13.30 and 11.80 $mg\,L^{-1}$ for reciprocating control and constant flow treatments respectively with no significant difference detected ($P > 0.05, n = 3$).

Physical/chemical parameters

Air temperature was measured daily and remained steady at 24 °C. Reciprocating control tank temperatures averaged 21.9 °C, whilst constant flow tank temperatures averaged 22.0 °C (data not shown).

Mean daily dissolved oxygen (DO) concentrations were significantly higher in the constant flow treatment ($P < 0.05, n = 54$) (Figure 2). DO concentrations dropped over the length of the experiment in all replicates, but

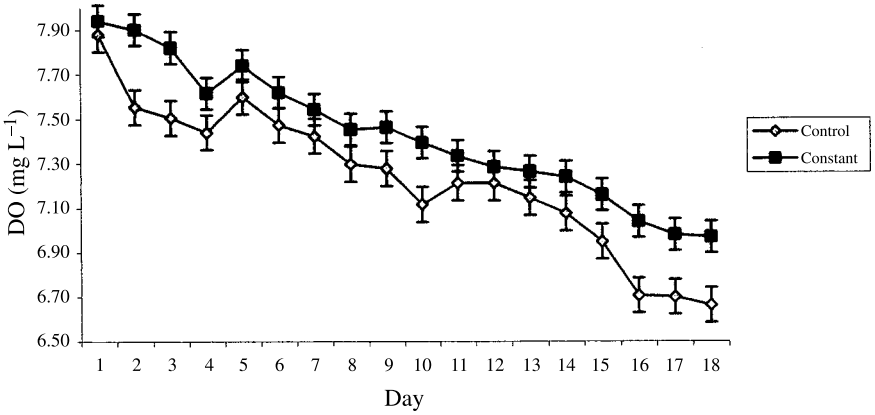

Figure 2. Mean daily dissolved oxygen concentrations for reciprocating control and constant flow treatments. Error bars represent standard errors.

averaged 7.24 mg L^{-1} for reciprocating control replicates and 7.43 mg L^{-1} for constant flow replicates.

Bicarbonate additions were used to maintain pH levels between 6.80 and 7.40, hence, bicarbonate addition and pH are integrally linked. Figure 3 represents mean daily bicarbonate additions per treatment replicate for reciprocating control and constant flow treatments. There was no significant difference ($P < 0.05, n = 51$) detected between reciprocating control treatment replicates (mean $= 1.1 \pm 0.15$ g day^{-1}) and constant flow (mean $= 0.8 \pm 0.14$ g day^{-1}) treatment replicates.

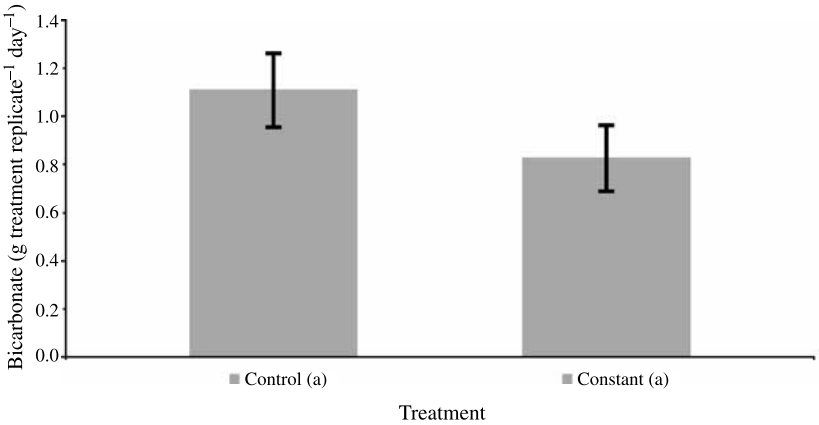

Figure 3. Mean daily bicarbonate additions (per treatment replicate) for reciprocal control and constant flow treatments. a and b: treatments showing the same letter are not significantly different ($p > 0.05, n = 51$). Error bars represent standard errors.

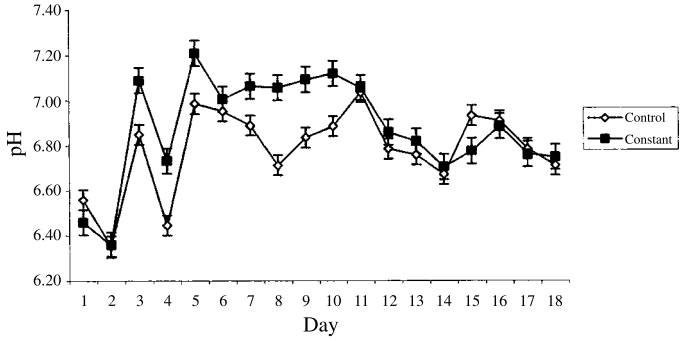

Figure 4. Mean daily pH readings for reciprocal control and constant flow treatments. Error bars represent standard errors.

Mean daily pH readings are represented in Figure 4. Mean daily pH levels differed significantly ($P < 0.05$, $n = 54$) between reciprocating control (mean $= 6.8 \pm 0.05$) and constant flow (mean $= 6.9 \pm 0.06$) treatments, the reciprocating control treatment recording lower average pH levels.

Mean daily conductivity readings are represented in Figure 5. Reciprocating control replicates exhibited significantly higher ($P < 0.05$, $n = 54$) mean daily conductivity readings compared to constant flow replicates, due to the increased additions of bicarbonate over the length of the experiment. However, the curves for both treatments follow a very similar slope and conductivities levelled out in both treatments approximately half way through the trial, as the increased size of the 10-day-old lettuce plants removed more nutrients.

Water was replaced daily to compensate for evapotranspiration. Figure 6 represents mean daily water replacement (per treatment replicate) for both

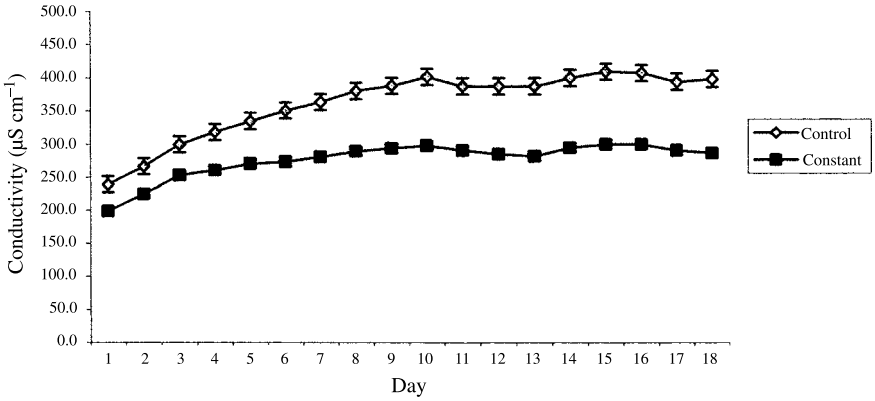

Figure 5. Mean daily conductivity readings for reciprocal control and constant flow treatments. Error bars represent standard errors.

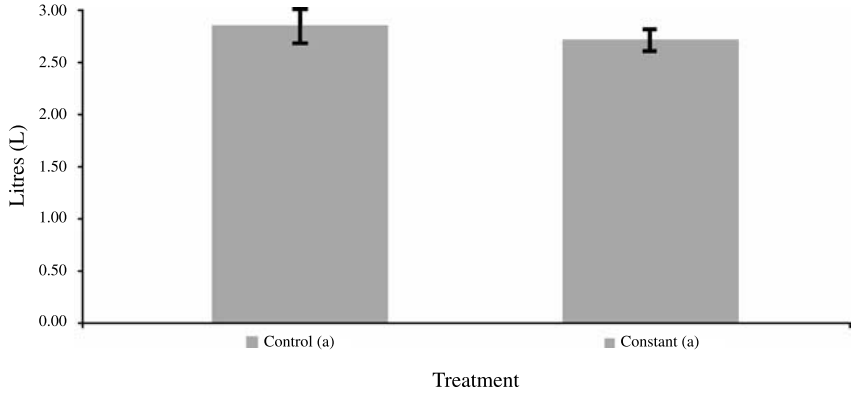

Figure 6. Mean daily water replacement (per treatment replicate) for reciprocal control and constant flow treatments. a and b: treatments showing the same letter are not significantly different ($P > 0.05, n = 51$). Error bars represent standard errors.

treatments. Overall, total water replacement averaged 47.67 L replicate tank^{-1} for the reciprocating control treatment and 47.00 L replicate tank^{-1} for the constant flow treatment, with no significant difference ($P > 0.05, n = 54$) detected between the two treatments. The mean amount of water replaced per replicate tank per day was 2.86 and 2.72 L for reciprocating control and constant flow treatments respectively, which equates to 2.86% (100 L volume – reciprocating control) and 2.43% (112 L volume – constant flow).

Discussion

Past studies of aquaponic technologies (Sutton and Lewis 1982; Sutton and Sutton 1983; McMurtry et al. 1997; Dontje and Clanton 1999) have argued that reciprocal flow through the hydroponic bed component is better than constant flow (constant flooding of the sand/gravel bed) because the draining of the hydroponic media bed assists the bed to acquire fresh, atmospheric air, and remain aerobic. It has been argued that constant flows of water would lead to lower dissolved oxygen levels (McMurtry et al. 1997), or anoxic 'pockets' within the substrate (Rakocy and Hargreaves 1993) with lower oxygen levels for plant roots and generation of anoxic microbial metabolites which may be deleterious to fish and plant growth (McMurtry et al. 1997). This study was designed to test whether a constant flow of water (from the fish rearing compartment) delivered to the hydroponic, plant-growth bed could be as effective in an experimental aquaponic system, as opposed to reciprocal flow (a flood and drain cycle) that intermittently supplies water to the hydroponic growth bed.

There was no fish mortality in either the reciprocating control or constant flow treatments. Ingram (2002) obtained mortalities of less than 5% for Murray cod exceeding 50 g in weight in culture trials. The lack of mortality in the present study was expected for Murray cod of this size (200–350 g) in standard recirculating aquaculture (Ingram 2002). Food conversion ratios (FCR) were 1.25 and 1.03 for reciprocating control and constant flow treatments, respectively. Ingram (2002) obtained a mean FCR for Murray cod over 150 g in weight of 1.2, therefore the FCR values obtained in this study are comparable to research results using industry standard methods. In terms of biomass gain, FCR and SGR, no significant difference ($P > 0.05, n = 3$) was detected between reciprocating control and constant flow treatments.

Lettuce production within the constant flow replicates (7798.7 kg) was significantly higher ($P < 0.05, n = 60$) than lettuce production within reciprocating control replicates (6806.9 kg) by a total (across all three replicates) of 991.8 g. Similarly, yield within constant flow replicates (mean of 4.97 kg m^{-2}) was higher than control replicates (mean of 4.34 kg m^{-2}). Lettuce growth was, therefore, significantly better within a constant flow environment. Both treatments, however, exhibited good yields compared with other aquaponic studies. Yields were equal to or better than the studies of Burgoon and Baum (1984) (lettuce yield of 3.3–4.5 kg m^{-2}) and Seawright et al. (1998) (Romaine lettuce yield of 2 kg m^{-2}). Lettuce plants in all replicates grew quickly and seemed healthy, with no signs of any nutrient deficiency syndromes, as was similarly seen in a previous experiment using this system (Lennard and Leonard, in press).

In terms of overall nitrate (NO_3) production within the integrated systems, constant flow replicates appeared to remove more nitrate (final $NO_3 = 11.8$ mg L^{-1}) from culture waters than did reciprocating control replicates (final $NO_3 = 13.3$ mg L^{-1}), but no significant difference was detected. Ammonia (NH_4) and nitrite (NO_2) concentrations were not detectable after the first week, showing that all biofilters were working efficiently enough to convert all toxic ammonia quickly to less toxic nitrate. It may therefore be assumed that the difference in final net nitrate concentrations between reciprocating control and constant flow replicates was due to greater assimilation by plants within the constant flow replicates, which also had higher lettuce production. In reciprocating control replicates, plants were only inundated with culture waters for 10 min in every 70 min. Constant flow replicates had more contact time with culture waters, and therefore more contact time to remove nitrates. Similarly, final phosphate levels within reciprocating control replicates (final $PO_4 = 4.04$ mg L^{-1}) were higher than in constant flow replicates (final $PO_4 = 3.87$ mg L^{-1}), but no significant difference was detected.

Again, this was probably due to the higher contact time of plant roots with culture waters within constant flow replicates.

Bicarbonate additions and pH are integrally linked in the aquatic systems. Bicarbonate is a buffer used to counteract the acidification caused by bacterial nitrification within a biofilter (Rakocy and Hargreaves 1993; Masser et al. 1999). Acidification may be counteracted in aquaponic systems without buffer, because plants are known to release either hydroxyl ions (OH^-) or bicarbonate ions (HCO_3^-) when they are actively assimilating nitrate ions (Salsac et al. 1987; Imsande and Touraine 1994). In the present study, pH stability was better in constant flow replicates (higher average pH readings – Figure 4) and the bicarbonate additions required were lower (Figure 3). Again, as for nitrate and phosphate assimilation, this may be due to longer contact times of plant roots with culture waters within constant flow replicates, therefore allowing higher nitrate assimilation by plants, leading to higher OH^- or HCO_3^- production by plant roots (Salsac et al. 1987; Imsande and Touraine 1994), with more stable pH and lower bicarbonate additions.

Water use across treatments was not significantly different (averaging approximately 2.5% of water replaced per day per treatment). Other studies using gravel/sand bed systems report average daily water replacement values of 6.6% (Lewis et al. 1978), 6% (Sutton and Lewis 1982), 7% (McMurtry et al. 1990) and between 1.2 and 4.7% (McMurtry et al. 1997). Therefore, water use in the present study, whether using reciprocal or constant flow flooding, compared favourably with other, similar, integrated studies. Also, the constant flow method required no more water than the reciprocating method, despite higher plant yields.

Dissolved oxygen levels were determined daily. Significantly higher ($P < 0.05$, $n = 54$) DO concentrations were observed in constant flow replicates than in reciprocating control replicates (average of 7.43 mg L^{-1} and 7.24 mg L^{-1}, respectively). In the constant flow system, water was continually cascading into the fish tank via the hydroponic-bed drain line and therefore was aerated constantly. In contrast, the reciprocating control replicates allowed water drainage (and aeration) for a much shorter period (approximately 10 min) in each 70-minute cycle.

Goto et al. (1996) notes that dissolved oxygen is crucial to good plant production and health in hydroponic culture, including being essential for root growth. Insufficient gas exchange caused by poor aeration tends to result in accumulation of organic acids, ethylene gas and dissolved carbon dioxide (Jackson 1980; Wess and Stuarty 1987), the result being that root metabolic activity and root growth may be restricted (Goto et al. 1987). In trials held to define limits to the requirement of DO in lettuce plants in hydroponic culture, Goto et al. (1996) found that the DO concentration for vigorous

lettuce growth needed to be greater than 2.1 mg L^{-1}. Both reciprocating control and constant flow replicates in the present study easily exceeded this minimum.

Dissolved oxygen maintenance is also important to fish health and biofilter health (i.e., the aerobic bacteria living in biofilters). Dissolved oxygen levels should be maintained above 5 mg L^{-1} for optimum, warm water fish growth (Masser et al. 1999). Similarly, nitrifying bacteria are dependent upon certain DO levels so as to be able to function efficiently and convert harmful, fish-produced, ammonia, to less harmful nitrate. Nitrifying bacteria are known to become inefficient at DO levels below 2 mg L^{-1} (Masser et al. 1999; Alleman and Preston 2002). Therefore, the average DO levels in the present study, in both reciprocating control and constant flow treatments should not have impaired either fish growth or biofilter operation.

Several studies state that reciprocating biofilters (hydroponic gravel/sand beds), which alternately flood and drain, provide uniform distribution of nutrient-laden water within the medium during the flood cycle and improved aeration from atmospheric exchange with each dewatering (Lewis et al. 1978; Nair et al. 1985; Rakocy 1989; McMurtry et al. 1993). Both nitrifying bacteria and plant roots are expected to benefit in this culture system (Lewis et al. 1978; Rakocy 1989; McMurtry et al. 1993). It appears then, that the two most convincing arguments for reciprocating water delivery are:

(A) Uniform distribution (and therefore, uniform use by plants) of nutrient rich waters, and
(B) Improved aeration of the hydroponic medium to aid plant and bacteria metabolism.

In the present study, constant flow replicates assimilated more nitrate and phosphate, and produced higher yields in plant biomass, than reciprocating control replicates. Therefore, in this experimental system, reciprocating water movements provided no advantage over constant flooding of the hydroponic media bed. This suggests that reciprocal flooding/draining does not necessarily provide a more uniform distribution of nutrient rich waters to hydroponic beds. However, the outcomes may depend on the length of run for water along a linear bed. In long hydroponic bed systems, a gradient of nutrient availability may be invoked along the bed and it is possible that in these circumstances reciprocal flood/drain cycles may convey some advantage. In this experimental system, constant flooding actually allowed plants to access more nutrients (through longer root–water contact times) with larger plant biomass production. There was also improved aeration with higher oxygen availability to both plant roots and nitrifying bacteria. This suggests that appropriate design of water delivery systems to hydroponic beds, coupled with

constant flow of sufficiently aerated water, can deliver higher plant yields and more efficient nutrient stripping from fish culture waters.

In summary, past research (Lewis et al. 1978; Nair et al. 1985; Rakocy 1989; McMurtry et al. 1997) has assumed better performance from hydroponic beds in aquaponic studies by using reciprocating water delivery designs. The present study, comparing reciprocating flooding/draining with a constant flood/drain water cycle, in identical test systems, indicates that constant flooding is actually a better methodology. Constant flow replicates were superior in plant nitrate and phosphate assimilation, in pH buffering, in dissolved oxygen concentrations and statistically identical in water and bicarbonate consumption. Constant flow replicates produced a slightly higher fish biomass and more efficient food conversion (lower FCR), although this was not significant. Plant biomass and yield in lettuce was significantly higher for the constant flow system. For the experimental aquaponic system used in this study, constant flooding and draining of the hydroponic component produced better or equal results for all test parameters.

Acknowledgements

This research was partially funded by the Australian Federal Governments Rural Industry Research and Development Corporation (RIRDC). The authors also wish to thank Boomaroo Nurseries (Lara, Victoria, Australia) for the provision of the many lettuce seedlings used to complete this study and Dr. Brett Ingram of the Victorian Institute of Marine and Freshwater Research for his invaluable knowledge of Murray cod culture.

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