USE OF FLOATING WETLANDS TO TREAT NUTRIENT ENRICHED LAKE WATER

James P. S. Sukias • Chris C. Tanner • Jason Park • Thomas R. Headley*

National Institute of Water and Atmospheric Research Ltd, PO Box 11-115 Hamilton, New Zealand.

**** Current address: Helmholtz Centre for Environmental Research – UFZ, Environmental- and Biotechnology Centre, Permoserstr. 15, 04318 Leipzig, Germany.***

ABSTRACT

The nutrient attenuation performance of floating treatment wetlands (FTWs) planted with emergent wetland macrophytes was investigated in 4 one-week long batch mesocosm studies using artificial eutrophic lake water. The FTWs were made from buoyant polyester mats (0.6 x 0.6 m squares) planted with one of three native wetland species, *Cyperus ustulatus*, *Juncus edgariae* or *Schoenoplectus tabernaemontanii*. Three of each FTW type were each placed in 0.7 m^3 mesocosm tanks and dosed with artificial eutrophic lake water with nutrients at concentrations relevant to eutrophic Rotorua lakes. In addition, three Control mesocosms without FTWs but with shading equivalent to the FTWs were also monitored. Mean areal mass attenuation rates of the FTWs ranged from 638 to 762 mg m^{-2} d^{-1} for total nitrogen, however the Controls which simply shaded the surface, had removal rates of 379 mg m^{-2} d^{-1}. Thus the average net TN removal attributable to the FTWs was 339 mg m^{-2} d^{-1}. This rate is similar to that for equivalently loaded conventional constructed wetlands with sediment-rooted vegetation. Mean areal mass attenuation rates for TP and DRP ranged from 54 to 58 and from 57 to 64 mg m^{-2} d^{-1} respectively. In the Controls the rates were 39 and 44 mg m^{-2} d^{-1}, resulting in net FTW removal of 30 and 16 mg m^{-2} d^{-1} respectively. Attenuation mechanisms appeared to be dominated by plant and algal uptake and subsequent algal settling beneath the FTWs. Denitrification within the FTW matrix was also apparent when nitrogen was supplied as nitrate, but was limited by a lack of organic carbon available for microbial processing. Direct investigation of these mechanisms will be necessary to determine their long-term sustainability, as they include uptake into temporary and/or finite storage pools. Furthermore, the nutrient attenuation rates recorded in the present study during summer are likely to be higher than would be expected in winter. The FTWs have however demonstrated considerable potential to reduce nutrients from eutrophic lake water. They may be a suitable option for targeted application in smaller lakes, in polluted lakes embayments, or at the mouth of streams or point sources that are important inputs of nutrients into lakes.

KEYWORDS

Floating treatment wetlands FTW- Bioremediation – Constructed wetlands, nitrogen, phosphorus

1 INTRODUCTION

Several lakes within the Bay of Plenty region of New Zealand are considered eutrophic, with reports of algal booms in the media and scientific literature (Edgar, 2009; Scoop Independant News, 2009). Anthropogenic sources such as agricultural runoff and discharges of domestic sewage have been implicated as the sources of the eutrophication (Burger et al., 2008; Rutherford et al., 1996).

A relatively novel approach to achieve wetland remediation processes along-side or within the lake/water body is using floating wetlands (Hubbard, 2010). Floating wetlands consist of rooted emergent wetland plants growing on a buoyant mat or raft which provides a floating platform for plant growth on the water surface of a pond or lake (Figure 1). Such systems have been termed Floating Emergent Macrophyte Treatment Wetlands by Fonder and Headley (2010), however the abridged term Floating Treatment Wetland (FTW) shall be used here. FTWs integrate the nutrient attenuation capabilities of wetlands while incorporating the flexibility of a deeper pond system that can accommodate large and rapid fluctuations in water inflow and depth. Because they float, they can be incorporated into lake areas where water depth would otherwise preclude the use of emergent macrophytes. Thus, FTWs show potential as a passive technological option for improving the water quality of eutrophic lakes. Conventional constructed wetlands remove nutrients primarily by plant uptake and microbial transformations. However, the sediment-rooted vegetation used in conventional treatment wetland systems are susceptible to chronic die-back if they experience excessive water depths for extended periods of time. For the treatment of lake water, conventional treatment wetlands are therefore restricted to the shallower areas of the lake margins (littoral zone) and deltaic stream inflows, or need to be constructed on adjacent land. In contrast, FTWs can be installed in relatively deep water, or areas experiencing fluctuating water levels (e.g. stormwater ponds, water supply reservoirs, irrigation dams or lakes with significant wetting and drying cycles), without risk of drowning the plants, or indeed dessication during extended dry periods.

Figure 1: ***Schematic longitudinal cross-section through a typical Floating Treatment Wetland system. Note that the water depth can vary appreciably in such a system without affecting plant growth (Source: Headley & Tanner, 2006).***

The dense hanging root mat that forms beneath the FTW provides close interaction between the plant roots (and attached biofilm, see Figure 2) and nutrients in the water column. As the plants are forced to meet their nutrient requirements from the water column rather than the soil, they are likely to experience greater uptake of nutrient and other contaminants from the water than conventional sediment-rooted wetlands (Headley & Tanner, accepted pending minor revisions Feb 2010). In addition, the large root area provides a surface for the development of biofilms (predominantly bacterial) which can contribute to nitrogen and phosphorus attenuation. Organic exudates released from the plant roots have the potential to provide organic carbon to denitrifying bacterial organisms promoting transformation of nitrate (NO_3-N) to N_2 gas under anoxic conditions. Sasser et al (1991) reported consistently low dissolved oxygen concentrations (0.2-1.0 ppm) in the floating wetland mat and underlying free-water zone of a natural floating marsh in Louisiana. Tanner and Headley (In Prep) also found reduced oxygen saturation beneath planted floating mats. Contributing mechanisms potentially include reduced re-aeration, increased oxygen consumption, and inhibition of algal photosynthetic oxygen production. This would suggest that a dense cover of floating wetland over a pond will impede oxygenation of the water column more than an uncovered pond, thereby promoting conditions suitable for heterotrophic denitrification around the biofilm.

Another nutrient attenuation process associated with this approach is the removal of suspended particulates from the water column via trapping within the root mat and enhancement of sedimentation processes. Settling is an important process in slow-moving water bodies such as lakes and ponds and FTWs are likely to enhance this effect by reducing wind induced mixing of the water body, buffering wave energy and trapping fine suspended particles within the hanging root-biofilm matrix (Smith & Kalin, 2000). The shading provided by a FTW will also make the water-body less conducive for algal survival. Deposited algal biomass may also become an important source of organic carbon for removal of oxidised nitrogen via bacterial denitrification within the sediments or root biofilms of the FTW.

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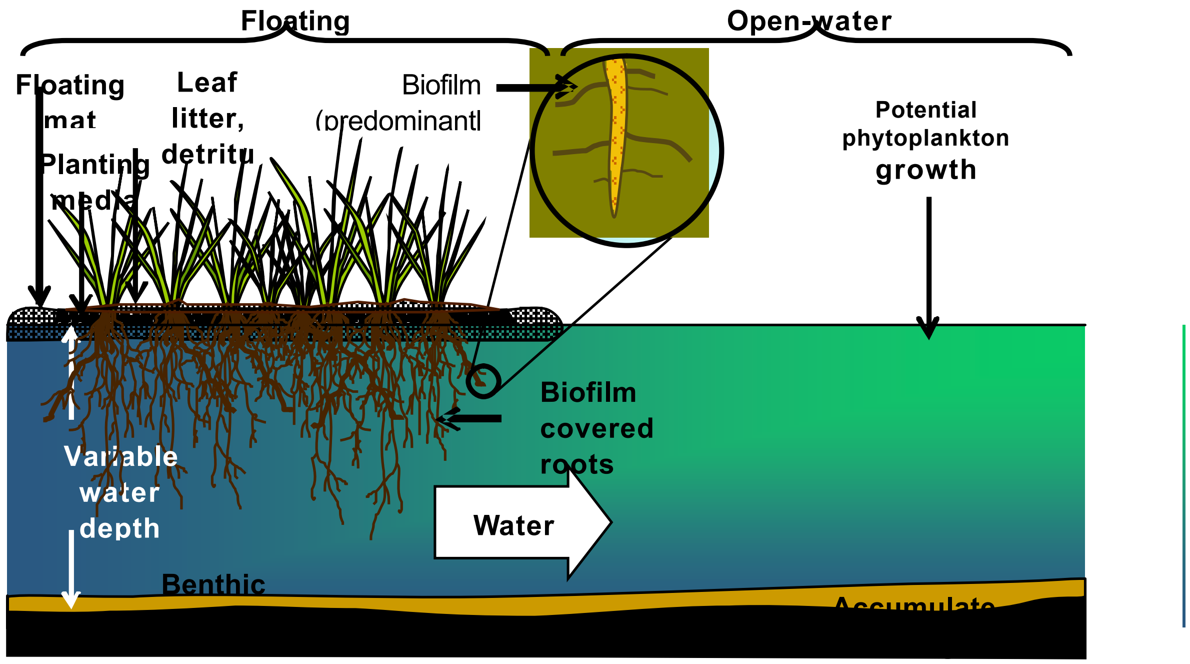

Figure 2: Cross-section of a typical floating treatment wetland showing main structural elements in comparison with an open-water lake or pond (Source: Headley & Tanner, 2006).

Because FTWs are a relatively recent treatment concept, there are few studies available that enable quantitative assessment of their nutrient-removal performance. Kansiime et al. (2005) measured TN and NH_4-N reductions of 80-90%, and TP and ortho-phosphate reductions of 70-80% in a small mesocosm study (30 L buckets, 7 day hydraulic retention time (HRT)) using floating papyrus plants receiving secondary treated sewage. The floating papyrus nutrient attenuation generally exceeded that of rooted papyrus plants. In a similar mesocosm study using *Phragmites mauritianus* (40 L buckets, 5 days HRT) receiving daily loadings of sewage pond effluent, Sekiranda and Kiwanuka (1998) noted little difference between the gravel-rooted and floating mesocosms in terms of nitrogen attenuation (both >97% NH_4-N removal), however control buckets without plants or gravel also achieved high attenuation of NH_4-N (92.5%). They also found that the gravel rooted systems removed significantly more TP and PO_4-P than the floating systems, associated with a greater amount of P associated with plant biomass in the gravel-rooted plants.

Boutwell and Hutchings (1999) found the FTWs removed around 80% of oxidised nitrogen within 7 days in mesocosms receiving eutrophic lake water, and in a follow-up study Boutwell (2002) commonly recorded nitrate reductions of up to 50% in waters flowing beneath FTWs deployed in a lake, although he also recorded some increases. Laktos (1998) also measured high reductions of TN (85%) and TP (40%) in trials where FTWs received nutrient enhanced river waters, however performance declined in winter.

Studies of floating mats vegetated with vetiver grass in northern New South Wales (Hart et al., 2003) reported TN removal rates of 1.8 g m^{-2} d^{-1} and TP removals of ~0.1 g m^{-2} d^{-1} from septic tank effluents (240 L static hydroponic systems). These removal rates were more than doubled in subsequent trials with recirculated effluents.

In small mesocosm (76 L) trials carried out in a glasshouse in Montana, nitrate removal rates as high as 114 g N m^{-2} d^{-1} were reported for unplanted FTW mats with recirculation and addition of organic carbon. Phosphate removals of 4.6 g P m^{-2} d^{-1} were reported for unplanted systems with artificial aeration. These trials were carried out at 27 ºC and used high nutrient levels, similar to those present in livestock wastewaters (Stewart et al., 2008).

Tanner and Headley (In Prep) using 0.7 m^3 mesocosms found FTW's substantially improved removal of turbidity and dissolved copper when treating artificial urban stormwater. Most other reports regarding use of artificial floating wetland systems for nutrient removal focus primarily on their ecosystem and habitat values (e.g. Nakamura et al., 2000).

This paper provides a comparative assessment of the dissolved nitrogen and phosphorus attenuation potential of floating treatment wetlands vegetated with three emergent wetland macrophyte species based on a series of batch-loaded mesocosm trials undertaken in Hamilton, New Zealand.

2 METHODS

Surface water quality data of the three lakes regarded as eutrophic in the Bay of Plenty region of New Zealand (Lakes Rotorua, Okaro and Rotoehu) were compared to determine appropriate initial nitrogen and phosphorus concentration for the FTW studies (CBER, 2010). Based largely on the high concentrations of Lake Okaro and our desire to examine a "worst case" scenario, the initial concentration of nutrients for FTW studies were 1000 mg N m^{-3} for ammonium and/or nitrate, and 180 mg P m^{-3} for phosphorus. Although the majority of dissolved N in the lake water is in the form of ammonium, relatively high levels of oxidised nitrate were also used because oxidised nitrogen is generally the main form of nitrogen entering these lakes from the surrounding watersheds. Thus, oxidised nitrogen concentrations can be locally high adjacent to stream inflows and other contaminant sources, which may form target areas for application of FTWs. The addition of both nitrate and ammonium also enables a more complete picture of the nitrogen transformations within a FTW system to be examined.

The FTW treatments consisted of three native emergent wetland macrophyte species (*Cyperus ustulatus*, CU, a sedge; *Juncus edgariae* JE, a rush; and *Schoenoplectus tabernaemontani*, ST, a rush) which were selected for the trial based on a previous study (Tanner & Headley, In Prep) that found these species grew well and showed vigorous root growth under waterlogged conditions.

FTWs consisted of squares of a commercially available fibrous polyester matrix with injected expanded polyurethane for additional buoyancy (0.6 m × 0.6 m, BioHaven™ floating islands produced by Floating Islands International, Shepherd, Montana, USA; Figure 1), which were filled with a growth medium (8 cm deep) consisting of sand, peat and compost in a 1:2:1 ratio, with a small amount of lime added to balance the pH. They were then planted with propagules of one of the three wetland species (Figure 1). Plants were allowed to establish for 20 months on the FTW matrixes prior to undertaking the trials, by which time the plants had grown to 0.5-0.8m high. Their roots grew through the fibrous matrix forming a dense root mass extending ~0.5 m into the water beneath.

Biomass dry weight of the plant species measured 7 months before the trials (Tanner & Headley, In Prep) were in the range of 834 to 1528 g m^{-2} (above-mat biomass) and 184 to 329 g m^{-2} (below-mat biomass). Total root length and root surface area ranged from 1000 to 3200 m m^{-2} and from 4.6 to 7.7 m^2 m^{-2} respectively.

2.1 EXPERIMENTAL APPROACH AND SET-UP

A series of batch-loaded mesocosm experiments were conducted at the Ruakura Agricultural Research Centre, Hamilton, New Zealand (37°46'31"S, 175°18'45"E) during the summer period from December 2007 to February 2008 to investigate the potential of FTWs to attenuate nutrients at concentrations found in eutrophic lakes. Timing and nutrient additions for each trial are shown in Table 1. Experiments 1 and 2 were standard batches where the full ranges of nutrients were added to each mesocosm in accordance with Table 1. In order to uncover more information about specific nitrogen transformation processes ammonium was not added during Experiments 3 and 4.

Glucose was added at a rate of 300 g of glucose (120 g carbon) to the mixing tank (~10 g C per treatment) during Experiment 4 to determine whether denitrification had been limited in the previous trials due to a lack of readily available organic carbon. In addition, two litres of sewage effluent taken from an anaerobic digester was also added to seed heterotrophic bacteria into the tank to facilitate reduction of DO concentrations in the artificial lake water. Water was mixed within the tank for three days prior to the start of the experiment. The mixing tank was also bubbled with nitrogen gas for one day to remove oxygen.

Mesocosms consisted of one of twelve polyethylene tanks (~1.0 m × 1.0 m × 1.15 m deep with an operational water depth of 0.7 m; tanks were slightly tapered towards the base, water volume = 0.7 m^3, Figure 3) set-up under a clear horticultural plastic shelter (≈90% transmission of photosynthetically active radiation). Treatments consisted of a FTW (floating matrix planted with one of the selected wetland species), one of which was added to each of nine mesocosms (3 of each species). Each matrix was supported with fibreglass rods attached to the sides of the mesocosm to ensure uniform submergence (half the depth of the matrix) as well as holding the FTWs during emptying and re-filling procedures (see below). Controls consisted of three mesocosms which did not contain a FTW matrix. Instead, a black polyethylene sheet the same size as a matrix was suspended above the water surface of these mesocosms to provide an equivalent amount of shading to that of the floating mats.

Table 1: Trial dates, nutrient additions and experimental rationale

Trial	Dates	Nutrient additions	Experimental rationale
Experiment 1	4th - 11th December 2007	Nitrate, ammonium & phosphate	Assess preferred N form of floating island biota
Experiment 2	11th - 18th February 2008	Nitrate & ammonium	Assess preferred N form when P is limiting
Experiment 3	18th - 25th February 2008	Nitrate & phosphate	Assess background denitrification rate
Experiment 4	25th February - 3rd March 2008	Nitrate, phosphate & glucose (25 g ~ 10 g C per treatment)	Assess maximum denitrification potential

The mesocosms were connected to a central mixing tank (10 m^3 capacity), from which they were simultaneously filled with artificial lake water (approx. 700 L each) on Day 0 of each experiment, which usually ran for 7 days. Between experiments the mesocosms were emptied and the sides of the plastic tanks cleaned to remove any sediment or biofilm that had accumulated. The artificial lake water comprised nutrient salts added into 9.8 m^3 of Hamilton City tap water in the central mixing tank, which was continuously mixed with a pump for at least a day prior to the start of each experiment.

2.2 Water quality sampling and analysis

Water quality sampling was conducted on Day 0, 1, 3 and 7 of each trial. Depth-integrated samples were collected from the mesocosms using a 700 mm length of 50 mm diameter PVC pipe submersed vertically into the upper 500 mm of the water column immediately adjacent to the hanging root network of the FTWs but not from within the root interstices. The upper end of the pipe was capped with a rubber bung, the pipe drawn up and the lower end capped before being withdrawn from the water and decanted into a sample bottle. This provided a depth-averaged sample of the upper 500 mm of the 700 mm water column. Samples were analysed at the NIWA-Hamilton water quality laboratory after filtration (0.45 µm) for ammonium-N, measured colourimetrically using automated flow injection analysis (QuikChem 8000 FIA+, Lachat Instruments, Milwaukee, WI, method 31-107-06-1-1-B, Revision date 26 April 2001), and for combined nitrate and nitrite N (oxidised nitrogen denoted as NO_x-N) and reduction to nitrite in a copperised cadmium column (QuikChem Method 31-107-04-1-A, Revision date 27 Feb 2001). Total N was analysed using the same method on an unfiltered sample which had first undergone digestion using an alkaline persulphate solution (modified from APHA, 2005, 4500N). Detection limits were 1 µg L^{-1} for oxidised nitrogen and ammonium-N and 10 µg L^{-1} for total N. Organic nitrogen (OrgN) was calculated by subtraction (TN – NH_4-N and NO_X-N).

Samples for dissolved reactive phosphorus (DRP) were filtered (0.45 µm) and analysed colourimetrically using QuikChem Method 31-115-01-1-I, while total phosphorus (TP) was analysed on an unfiltered sample using the same method after first undergoing acid hydrolysis using persulphate (modified from APHA, 2005, 4500P). Dissolved organic carbon (DOC) was analysed using high temperature catalytic oxidation with IR detection according to APHA (2005, method 5310B) with a detection limit of 0.2 μg L^{-1}.

In-situ measurements of pH, dissolved oxygen (DO) and temperature were also made approximately 200 mm below the water surface within each mesocosm on each sampling day. pH was measured using a TPS™ WP-81 portable meter, while DO and temperature were measured using a TPS™ WP-82Y portable meter. In addition during Experiment 1, temperature, pH and DO in one representative tank of each FTW treatment were monitored at 15 minute intervals using 4 multiprobe DataSonde 4a (Hydrolab, HACH, USA).

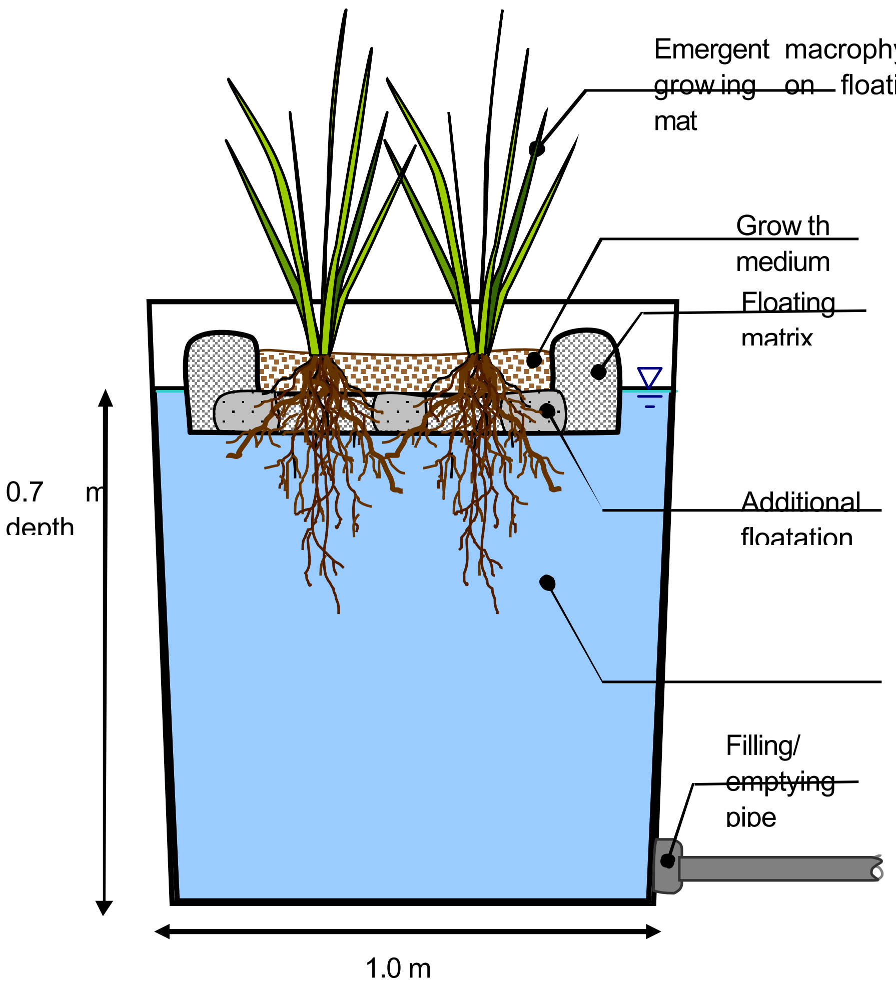

Figure 3: Cross-sectional diagram through mesocosm showing a planted 0.6 x 0.6 m polyester floating matrix used in the experiments.

2.2.1 STATISTICAL TREATMENT OF DATA

Residuals from ANOVA analyses were plotted and examined for non-normality and, as much of the data was non-normal, a natural log transformation was performed, which reduced non-normality in residual plots. Data from each batch were analysed using one way ANOVA (each batch separately) and two way ANOVA (combined across batches). Removals of nutrients within a batch, as measured on each sampling date, were calculated as a proportion of the initial concentration and log-transformed to reduce non-normality prior to analysis. Where a variable contained some zero values, an appropriate constant (the minimum analytical value) was added to all data before undertaking the log transformation.

Data were tested for the significance of the differences between (1) all 4 means, (2) the Control versus the other 3 Treatments (planted FTW's), and (3) the differences between the 3 planted treatments. Where significant differences were identified a post-hoc Tukey range test (Hsu, 1996: Tukey-Kramer method; Sokal & Rohlf, 1981) was applied to determine between which treatments the differences existed.

3 RESULTS

3.1 EXPERIMENT 1 – SIMULATED EUTROPHIC LAKE CONDITIONS

Temperatures in the mesocosms remained between 17° and 24°C, with a mean value of 20.3°C (±1.4) (Table 2, Figure 4). The mean daily diurnal variation in water temperature was 2.8°C. The lowest water temperature was around 7:00 a.m., and peaked at around 5:00 p.m. There was little variation in water temperature between the wetland Treatments including the Controls.

The water pH for the Control mesocosms increased from around 7.0 up to pH 8.0. In contrast, the pH for all planted Treatments (JE, ST and CU) declined from around 7.0 down to 6.5 (approximately 0.5 pH scale drop, Figure 4), although the mesocosms also displayed a small diurnal cycle of 0.1 - 0.2 pH units with a peak at 5:00 p.m. and a minimum at around 7:00 a.m. when they were exposed to direct sunlight.

Table 2: ***Summary statistics for temperature, pH, DO and DOC during Experiment 1. For each treatment, the data has been grouped for the entire batch.***

Parameter	Temp (°C)				pH				DO (%)				DOC (mg m^{3})			
	Contro	JE	ST	CU	Contro	JE	ST	CU	Contro	JE	ST	CU	Control	JE	ST	CU
Mean	20.3	20.1	20.2	20.2	7.54	6.54	6.50	6.37	73.5	63.3	72.2	60.3	0.7	0.9	0.7	0.8
Standard deviation	±1.4	±1.4	±1.3	±1.2	±0.32	±0.11	±0.13	±0.11	±6.1	±9.5	±7.8	±8.7	±0.2	±0.2	±0.1	±0.3
Max.	24.2	23.7	23.8	23.7	8.04	6.91	7.01	6.71	100.2	95.1	102.5	91.8	1.0	1.1	0.9	1.1
Min.	17.1	16.8	17.3	17.4	6.89	6.39	6.37	6.29	64.9	48.3	62.4	50.5	0.6	0.7	0.6	0.6

Dissolved oxygen in all Treatments remained above 50% saturation during this experiment (Figure 4), but exhibited a rapid reduction in DO on Day 1, decreasing from 90% down to 65 – 69% saturation for all planted Treatments. There were strong diurnal variations from 50% to 80% DO saturation (~ 30% variation) for all Treatments, with minima between 6 and 7 a.m. and peaks in the late afternoon (6-7 p.m.).

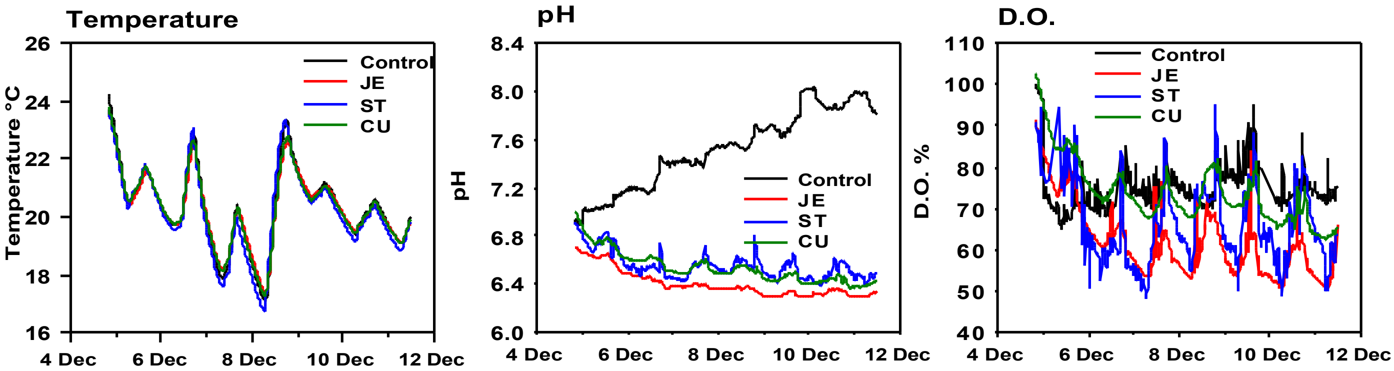

Figure 4: ***Temperature, pH and DO for FTW's and the control during Experiment 1.***

Dissolved organic carbon (DOC) concentrations remained low and stable throughout the experiment (Table 2 ~0.8 mg m^{-3}).

3.1.1 NITROGEN ATTENUATION

The mean concentrations of TN, ammonium, and oxidised nitrogen are presented in Figure 5. Initial nitrogen removal was predominantly of ammonium. The highest ammonium attenuation occurred in the planted Treatments during the first three days of the experiment (64% for JE, 82% for ST and CU), although concentrations continued to decrease until Day 7 (82% for JE, 99% for ST and CU) at a reduced rate. The ammonium concentration in the Control was also significantly reduced by 66% by Day 7.

Mean reductions of oxidised nitrogen, which occurred mainly in the latter days of the trial, were lower than for ammonium, at 38% for JE, 83% for ST and 74% for CU by Day 7. Oxidised nitrogen concentrations in the Control were also reduced by 17%.

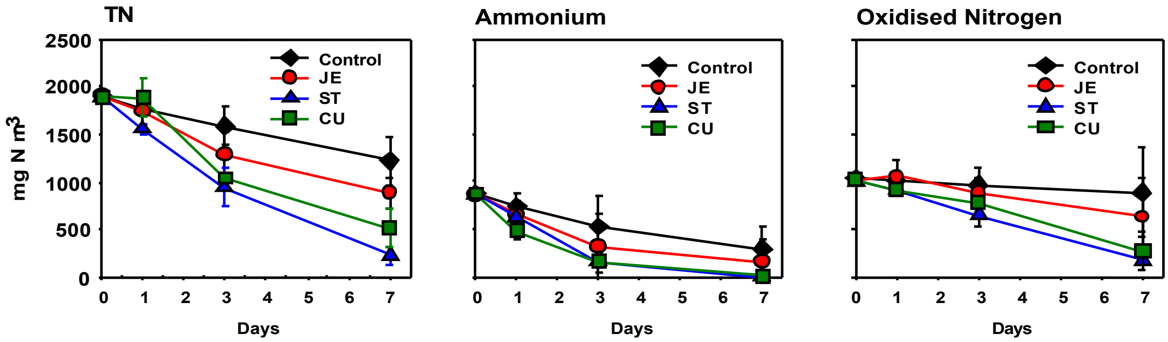

Figure 5: Mean concentration reduction of Total Nitrogen (TN), Ammonium (NH_4^+-N), and Oxidised nitrogen-N (NO_X-N) during Experiment 1 (error bars are one standard deviation).

3.1.2 PHOSPHORUS ATTENUATION

The mean concentrations of total phosphorus (TP) and dissolved reactive phosphorus (DRP) are presented in Figure 6. Dissolved reactive phosphorus was reduced by 37% over the 7 day batch in the Control. Higher rates of attenuation were apparent in the planted Treatments (57% for JE, 84% for ST and 59% for CU).

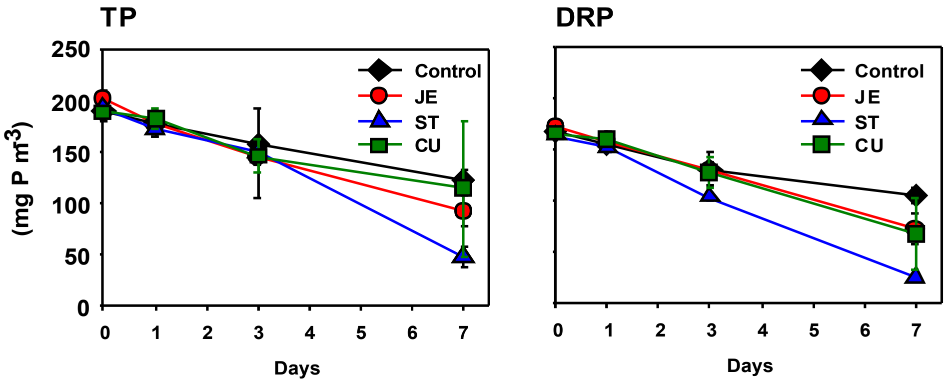

Figure 6: ***Mean reductions of TP and DRP concentration during Experiment 1.***

3.1.3 STATISTICAL ANALYSIS

Table 3 shows average concentrations of nutrients at the end of the experiment after addition of the minimum correction factor (to all data points) where zero values were present in the data set, log transformation to remove bias and back-transforming of the log means. Total nitrogen, ammonium, TP and DRP concentrations were significantly different (P <0.05) in the floating emergent wetland treatments compared with the controls. In addition, for both TP and DRP, there was a difference between the various FTW treatments, with concentrations in the ST treatment significantly less than in the other two FTW types.

Table 3: Back transformed mean concentrations of nutrients (mg m^{-3}) for Experiment 1 on day 7. Results from one-way ANOVA analyses between controls and treatments, and between treatments are shown.

	Control	*Juncus edgariae* (JE)	*Schoenoplectus tabernaemontani* (ST)	*Cyperus ustulatus* (CU)	Anova *P* values between Control and Treatments	Anova *P* values between planted Treatments
Total Nitrogen	1180	892	253	546	**0.044**	0.061
Ammonium	340	110	6.8	17	**0.028**	0.108

Oxidised nitrogen	870	651	196	212	0.084	0.188
Total phosphorus	124	92[b]	48[a]	77[ab]	**0.004**	**0.014**
Dissolved reactive phosphorus	109	75[b]	26[a]	61[ab]	**0.017**	**0.028**
Dissolved organic carbon	0.95	1.13	0.94	1.15	0.392	0.387

Where ANOVA indicated a statistical difference exists ($P<0.05$), these have been highlighted in bold. Where they exist between the treatments, these have been confirmed using post-hoc Tukey-Kramer method, and shown using superscripted letters using a convention that no difference was apparent if treatments bear the same letter. Note: a significant Treatment:Batch interaction was only present for ammonium on two occasions (results not shown).

3.2 EXPERIMENT 2 – PHOSPHORUS LIMITED EUTROPHIC CONDITIONS

The procedure of Experiment 2 was the same as that for Experiment 1, except phosphate was not added into the artificial lake water in order to investigate the potential for nitrogen attenuation where low phosphorus availability was likely to limit plant and algae growth.

3.2.1 TEMPERATURE, PH AND DO

Mean water temperatures during the batch decreased from 29.1 to 20.2°C through the experimental period (Figure 7). pH variations of the treatment mesocosms were similar to Experiment 1, decreasing from 7.6 to 6.5. pH increased in the Control mesocosm from 7.6 to 9.7, along with DO increases up to 148% saturation. All the planted Treatments maintained >25% DO saturation.

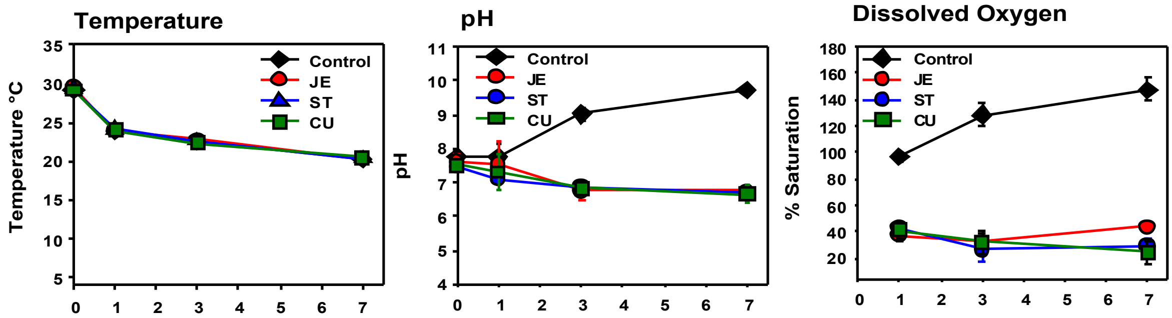

Figure 7: Temperature, pH and DO for FTW's and the control during Experiment 2.

3.2.2 NITROGEN ATTENUATION

The mean reductions in concentration of TN, ammonium, and oxidised nitrogen for the treatments are presented in Figure 8. The initial concentrations of these parameters in the artificial lake water were 1,380 mg N m^{-3}, 772 mg N m^{-3} and 579 mg N m^{-3} respectively. Almost complete ammonium attenuation (<5 mg N m^{-3}) occurred in all the planted Treatments as well as the Control within the first three days of the experiment. The mean ammonium concentration remained below 3 mg N m^{-3} until the end of the experiment.

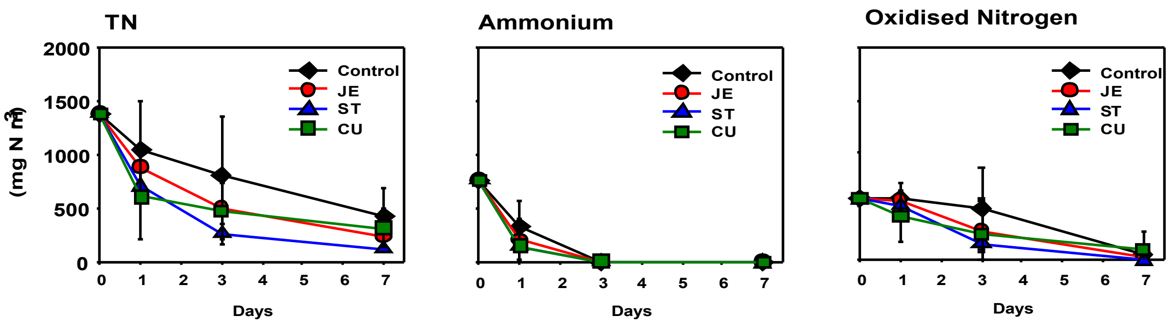

Figure 8: Mean concentration reductions of TN, ammonium and oxidised nitrogen during Experiment 2.

Unlike the previous batch experiment, mean oxidised nitrogen concentrations were reduced by 93% in all mesocosms, although this occurred once the ammonium was depleted. Although oxidised nitrogen and ammonium were almost completely removed, some TN remained as organic nitrogen. No statistical differences were apparent between the Controls and Treatments, nor within the 3 Treatments (Table 4).

Table 4: ***Back transformed mean concentrations of nutrients (mg m^{-3}) for Experiment 2 on day 7. Results from one-way ANOVA analyses between controls and treatments, and between treatments are shown.***

	Control	*Juncus edgariae* (JE)	*Schoenoplectus tabernaemontani* (ST)	*Cyperus ustulatus* (CU)	Anova *P* values between Control and Treatments	Anova *P* values between planted Treatments
Total Nitrogen	399	237	141	311	0.203	0.366
Ammonium	3.8	3.2	2.7	3.0	0.299	0.814
Oxidised nitrogen	35	83	10	71	0.937	0.391

No statistical differences were apparent between the control and treatments.

3.3 EXPERIMENT 3 – N SUPPLIED AS NITRATE

The procedure of Experiment 3 was the same as that for Experiment 1, except that in this experiment we omitted ammonium as a nitrogen source to investigate plant uptake and denitrification of oxidised nitrogen in the FTWs.

3.3.1 TEMPERATURE, PH AND DO

Mean water temperature, pH and DO throughout Experiment 3 are presented in Figure 9. Mean water temperature ranged from 20.4 to 23.4°C throughout the experiment. In the Control, pH increased from 7.57 to 8.56 by Day 7, while DO rose to 137% saturation. Mean pH and DO for all the planted treatments declined to 6.56 and 40.4% saturation respectively.

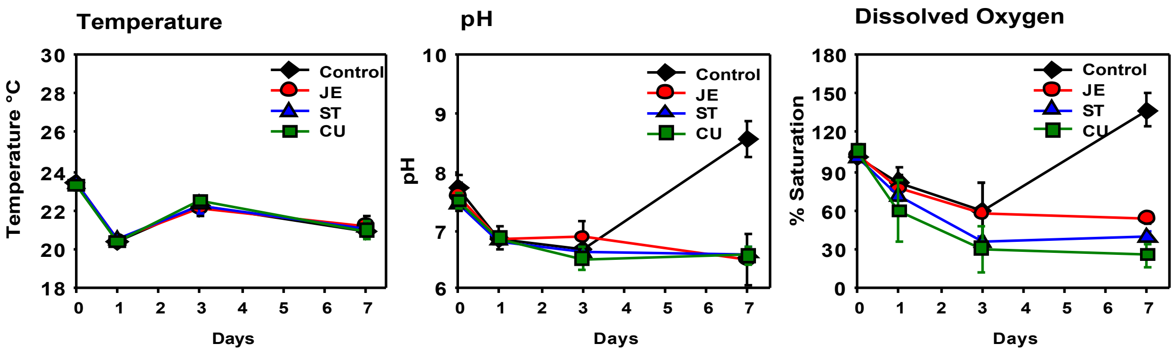

Figure 9: Mean Temperature, pH and DO levels for FTWs and the control during Experiment 3.

3.3.2 NITROGEN ATTENUATION

The initial concentrations of TN, ammonium, and oxidised nitrogen in the artificial lake water were 1,070 mg N m^{-3}, 4 mg N m^{-3} and 1,025 mg N m^{-3} respectively (Figure 10).

Table 5: ***Back transformed mean concentrations of nutrients (mg m^{-3}) for Experiment 3 on day 7. Results from one-way ANOVA analyses between controls and treatments, and between treatments are shown.***

	Control	*Juncus edgariae* (JE)	*Schoenoplectus tabernaemontani*	*Cyperus ustulatus* (CU)	Anova *P* values between	Anova *P* values between

			(ST)		Control and Treatments	planted Treatments
Total Nitrogen	709	352	152	316	0.076	0.375
Ammonium	4.5	4.4	4.2	5.3	0.916	0.816
Oxidised nitrogen	622	86	19	54	0.165	0.772
Total phosphorus	91	58	54	56	0.407	0.996
Dissolved reactive phosphorus	49	28	47	37	0.688	0.837

No statistical differences were apparent between the control and treatments.

Mean ammonium concentrations for all mesocosms of FTW Treatments remained low (<5 mg N m^{-3}, Table 5). As in the previous experiments, faster oxidised nitrogen attenuation occurred in the Treatment FTWs over the first 7 days, 81.5% for JE, 99.7% for ST, 90.9% for CU, although attenuation was also substantial within the Control mesocosm at 51.8%. Mean reductions of TN concentration for the planted Treatments and the Control paralleled oxidised nitrogen attenuation. Despite the high removal of nitrogen in the Treatments, the differences between them and the Controls were not statistically significant for oxidised nitrogen or TN (Table 5) although *P* values were close to significant for TN.

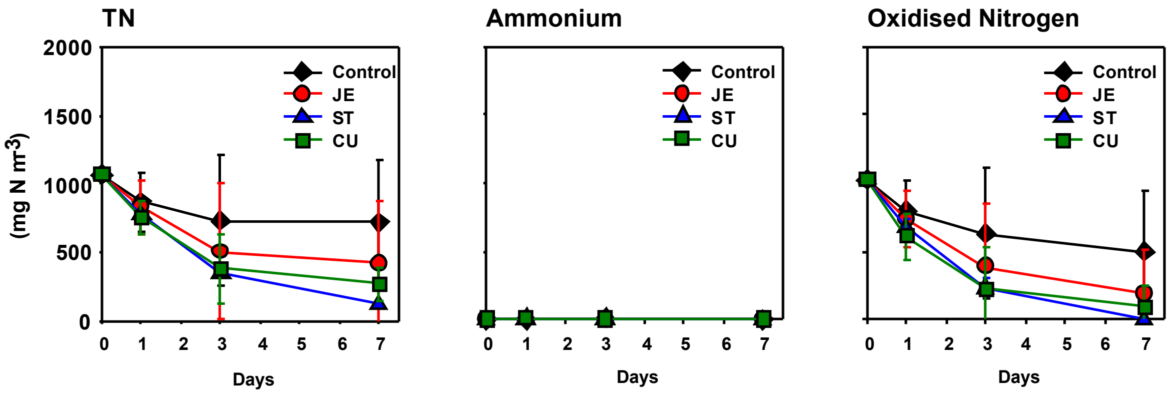

Figure 10: Mean concentration reduction of TN, ammonium and oxidised nitrogen during Experiment 3.

3.3.3 PHOSPHORUS ATTENUATION

The mean concentrations of TP and DRP are presented in Figure 11. The initial concentrations of TP and DRP in the artificial lake water were 165 and 163 mg P m^{-3} respectively.

DRP in FTW Treatments decreased steadily over time by 87% for JE, 78% for ST, and 74% for CU. These were not significantly different from the Control, at 62%. TP and DRP reduction were comparable to that in Experiment 1.

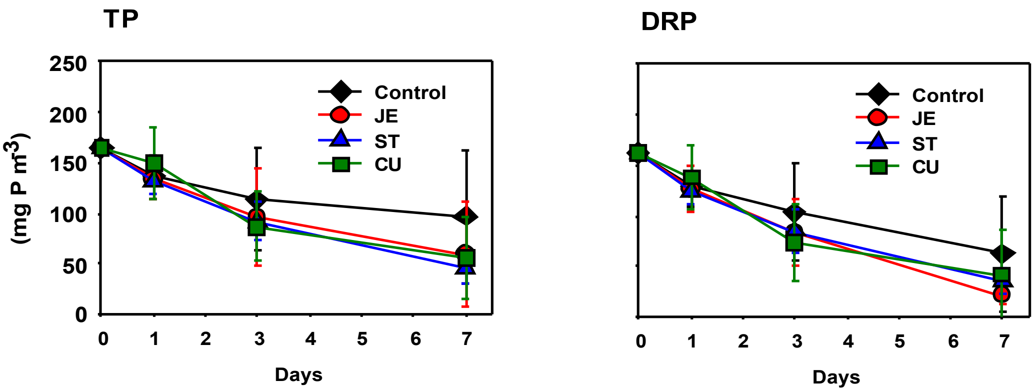

Figure 11: ***Mean concentration reductions of TP and DRP during Experiment 3.***

3.4 EXPERIMENT 4 – NITRATE WITH CARBON ADDITION

In this experiment we investigated the potential for oxidised nitrogen removal using FTWs where available organic carbon, essential for microbial denitrification, was not limiting.

3.4.1 TEMPERATURE, PH, DO AND DOC

Mean water temperature, pH and DO throughout the experiment are presented in Figure 12. Mean water temperatures were in the range of 21.1 to 23.4°C. As seen in the previous experiments, mean pH declined in the planted treatment mesocosms from 7.54 to 6.26 after 7 days. Unlike the previous experiments, however, mean pH also declined for the Control mesocosms, from 7.57 to about 6.30 on Day 7.

Initial mean DO concentrations were low (~14% DO saturation) compared to ~100% DO saturation for the previous experiments. Mean DO levels for the Treatment mesocosms temporarily increased to 39% saturation on Day 1, but thereafter reduced to near anoxic conditions (<5% DO saturation) following the addition of glucose to each mesocosm on Day 2.

Mean DOC concentrations measured at Day 0, 1, 3 and 7 are also shown in Figure 12. The initial mean DOC concentration for all Treatment mesocosms was 2.1 mg C m^{-3}. This level was considered insufficient to sustain denitrification. Thus, a further 17.5 g of glucose was added to each mesocosm on Day 2. Mean DOC concentrations were raised to 6.2 mg C m^{-3} on Day 3, decreasing to 2.8 mg C m^{-3} by Day 7.

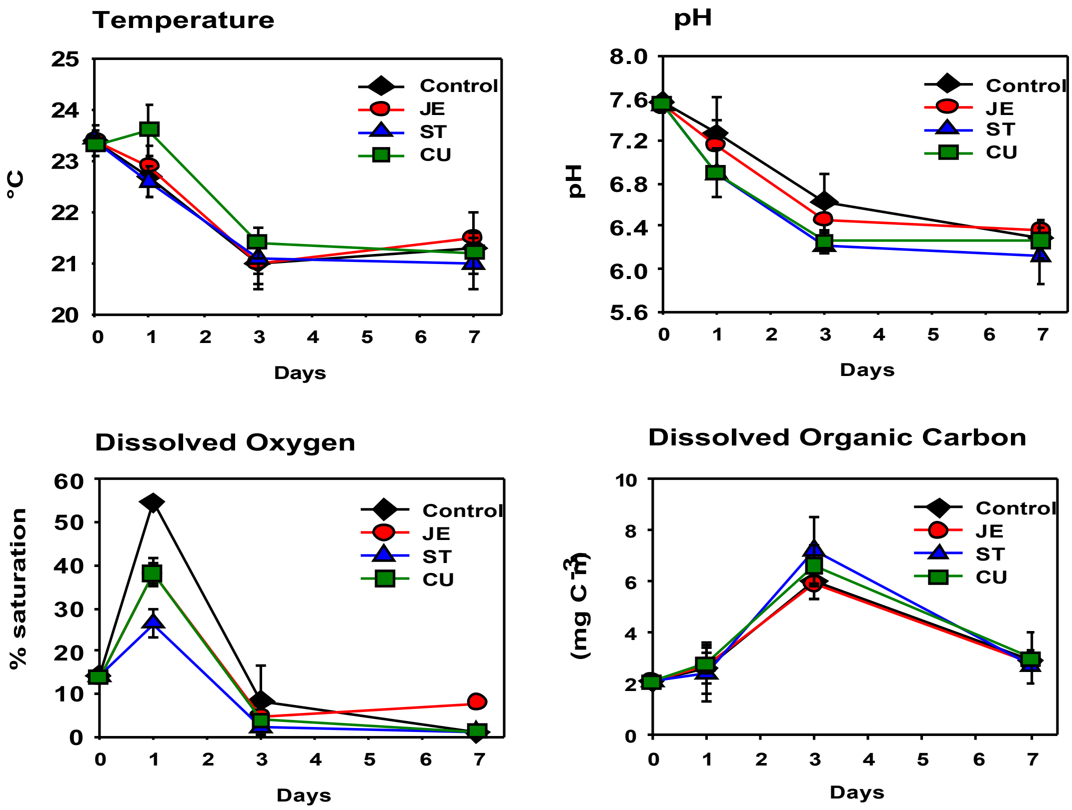

Figure 12: Mean Temperature, pH and DO, and DOC levels for FTWs and the controls during Experiment 4.

3.4.2 NITROGEN ATTENUATION

The initial concentrations of TN, ammonium, and oxidised nitrogen on Day 0 were 815 mg N m^{-3}, 9 mg N m^{-3} and 812 mg N m^{-3} respectively (Figure 13). Low concentrations of ammonium (<5 mg N m^{-3}) were maintained for all Treatment mesocosms until Day 7, except JE, where concentrations reached 12 mg N m^{-3}, significantly higher than in the other Treatments, although still low compared with TN (Table 6). While almost all oxidised nitrogen was removed from all mesocosms after 3 days (<3 mg N m^{-3}), TN attenuation was lower than previously observed, at around 25% in the Controls, increasing in the various Treatments to nearly 50% for JE. Differences between the Treatments were however insufficient for them to be statistically significant (Table 6).

Table 6: ***Back transformed mean concentrations of nutrients (mg m^{-3}) for Experiment 4 on day 7. Results from one-way ANOVA analyses between controls and treatments, and between treatments are shown.***

	Control	*Juncus edgariae* (JE)	*Schoenoplectus tabernaemontani* (ST)	*Cyperus ustulatus* (CU)	Anova *P* values between Control and Treatments	Anova *P* values between planted Treatments
Total Nitrogen	576	386	588	637	0.766	0.420
Ammonium	3.0	11.5^{b}	2.5^{a}	3.3^{a}	0.183	**0.006**
Oxidised nitrogen	1.6	2.1	1.1	1.1	0.739	0.504
Total phosphorus	98	60	98	108	0.727	0.436
Dissolved reactive phosphorus	6.6	10.2^{b}	2.2^{a}	5.7^{ab}	0.358	**0.008**
Dissolved organic carbon	2.9	2.8	2.7	2.9	0.823	0.892

There were no statistical differences apparent between the control and treatments. Where differences exist between the treatments, these have been shown using superscripted letters using a convention that no difference was apparent if treatments bear the same letter.

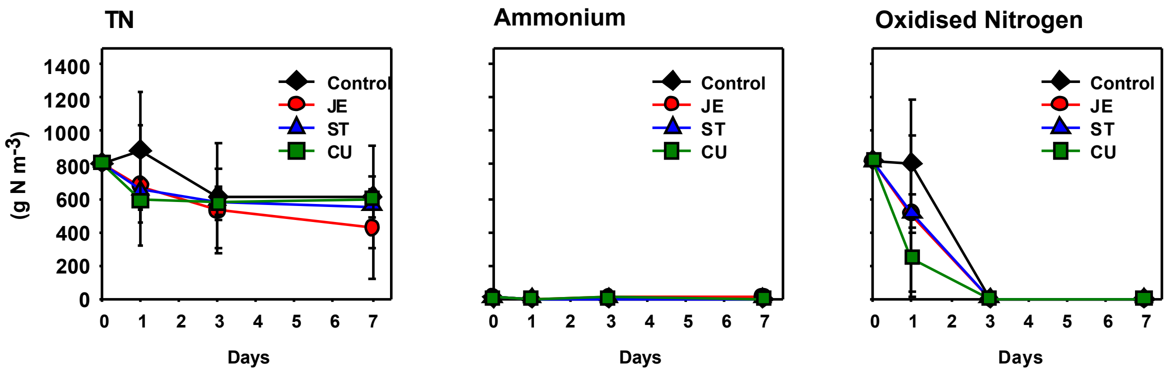

Figure 13: *Mean concentration reduction of TN, ammonium, and oxidised nitrogen during Experiment 4.*

3.4.3 PHOSPHORUS ATTENUATION

The mean concentrations of TP and DRP during Experiment 4 are presented in Figure 14. Initial concentrations of TP and DRP were 125 and 121 mg P m^{-3} respectively.

In all mesocosms DRP was almost completely removed in the first 3 days. A statistical difference was apparent between the various Treatments (Table 6), although these were not considered meaningful. TP attenuation was much lower than for DRP, ranging between 19% for CU and 42% for JE.

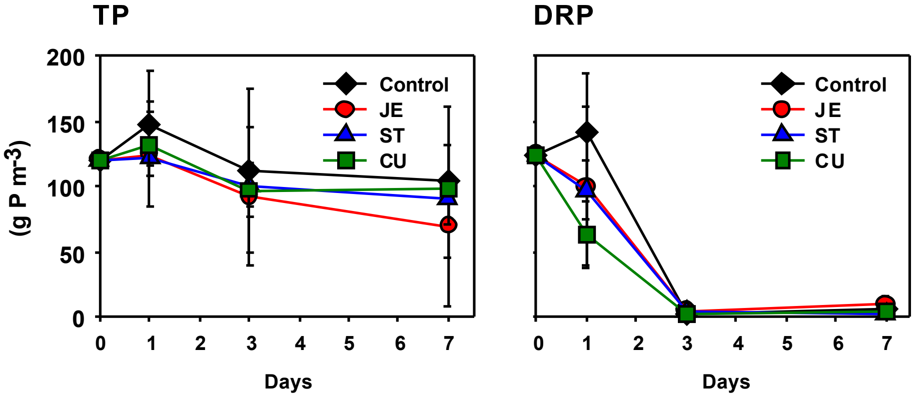

Figure 1: ***Mean concentration reduction of TP and DRP during Experiment 4.***

3.5 COMBINED DATA FROM ALL FOUR EXPERIMENTS

The results from the combined data were also analysed for overall statistical significance (Table 7). The FTWs gave significantly higher TN removal than the controls. In addition, it was apparent that FTWs planted with ST resulted in significantly higher TN attenuation than those planted with the other two emergent wetland species (JE and CU). While attenuation of TP and DRP were higher in the FTWs than the controls, high variability within treatments meant the differences were not statistically significant.

4 DISCUSSION

4.1 EXPERIMENT 1 – SIMULATED EUTROPHIC LAKE CONDITIONS

Variations in environmental variables such as temperature, pH and DO give valuable indications as to processes within the mesocosms. The strong similarity in water temperature between the FTWs and the Controls (Figure 5) indicated that at these scales, the Controls were adequately representing the net shading associated with the FTWs.

The pH increase for the Control mesocosms (from pH 7.0 up to pH 8.0) was likely due to algal assimilation of CO_2 from the water during photosynthesis, causing a shift in the carbon dioxide - bicarbonate – carbonate equilibrium which leads to elevated pH levels (Goldman et al., 1972). The pH decline recorded for the planted Treatments could be due to a variety of mechanisms. Firstly, the shading provided by the planted mesocosms may have been higher than was being achieved simply by using the polythene square suspended over the water, thereby reducing algal photosynthesis within the planted Treatments. The similar temperature changes in the Control and Treatment mesocosms suggest this may not be the most likely mechanism. Secondly, the respiration by the plant root-mat may have exceeded the CO_2 consumed by the algae causing the pH to decrease slightly over time. Alternative processes such as consumption of alkalinity during nitrification in the FTW Treatments are also possible. The extensive area of attachment surfaces provided by the plant root mass could support a substantial microbial nitrifying population. Evidence of nitrification can be seen in some cases by a small increase in oxidised nitrogen in the Treatments (note resulting high s.d. in Figure 6). Any increase in oxidised nitrogen deriving from nitrification is likely to be obscured by the concurrent uptake of the produced nitrate by plants and algae or conversion by denitrification in the mesocosms.

Table 7: Back transformed mean concentrations of nutrients (mg m^{-3}) for combined experiments on day 7. Results from two-way ANOVA analyses between controls and treatments, and between treatments are shown.

	Control	*Juncus edgariae* (JE)	*Schoenoplectus tabernaemontani* (ST)	*Cyperus ustulatus* (CU)	Two-way ANOVA *P* values between Control and Treatments	Two-way ANOVA *P* values between planted Treatments

TN	731	452	262	474	**0.004**	**0.044**
Oxidised nitrogen	317	223	63	126	0.093	0.188
Total phosphorus	106	70	65	79	0.106	0.793
Dissolved reactive phosphorus	49	42	21	35	0.102	0.112
Dissolved organic carbon	1.87	2.01	1.79	2.06	0.658	0.111

Note: Tukey Tests found no “pair-wise” differences.

DO saturation remained above 50% in all mesocosms, with all exhibiting diurnal variability, with reductions during night time, and increases during daylight hours. This suggests increases were due to either algal or macrophyte photosynthetic oxygen production during day light hours. Overall lower DO in the FTW Treatments was likely due to high below-water respiration rates combined with a likely restriction of gas mass transfer through the water surface due to the presence of the floating matrix.

Low DOC concentrations suggested that very little organic carbon, which could have leached from the organic rich soil media or leaked from plant roots as exudates, was actually present in the artificial lake water adjacent to the hanging root mass of the FTWs.

TN removal in the Controls (Figure 6) was 685 mg m^{-3}, largely comprising reduction of ammonium (573 g m^{-3}). As the Controls did not contain FTWs, it appeared this removal was due to algal growth and nutrient assimilation, followed by removal via settling to the base of the mesocosm. The significantly higher ($p < 0.05$) attenuation of ammonium in the FTW Treatments compared to the Controls is likely to be due to plant uptake and/or autotrophic microbial nitrification as noted above, although no accumulation of oxidised nitrogen was observed, possibly due to simultaneous microbial denitrification or uptake by plants and microbes.

Ammonium is known to be a preferred nitrogen source for algae (Larsen, 1977), as well as for many wetland plant species (Brix et al., 1994), explaining the more rapid utilisation of ammonium than oxidised nitrogen in this study. Heterotrophic microbial denitrification in the biofilm on the plant roots of FTW Treatments might have caused reduction of nitrate to N_2 gas, although relatively high DO levels were observed in the planted and Control mesocosms. However, dense hanging roots beneath the FTW treatments could be conducive to the generation of localised anoxic conditions suitable for denitrification either within the FTW matrix or in biofilms attached to the root mass.

Observed reductions in TP and DRP in the Controls are attributed to algae uptake. However, in the planted Treatments the significantly higher ($p < 0.05$) rates of phosphorus attenuation were most likely due to a combination of uptake by wetland plants as well as some uptake by algae. Tanner and Headley (In Prep) reported some increases in DRP concentrations in mesocosms containing floating mats due to the break-down of organic soil media used in their experiments. This was not apparent in the FTW Treatments in the present study, probably because these FTWs had been planted over 20 months previously, and any excess soluble nutrients are likely to have leached out.

4.2 EXPERIMENT 2 – PHOSPHORUS LIMITED EUTROPHIC CONDITIONS

The increases in pH, and DO rising to supersaturation in the Controls from day 3 onwards (Figure 8) strongly suggest algal photosynthetic activity, as observed in Experiment 1. Also similarly to Experiment 1, the FTW Treatments showed a reduction in pH, indicating lower algal photosynthesis caused by shading of the main body of water by the floating island, as well as enhanced nitrification within the plant root-mass (Alexander, 1965) which would reduce alkalinity (Çeçen & Gönenç, 1995; Fritz et al., 1979).

The higher rate of ammonium attenuation observed in Experiment 2 compared to Experiment 1 may be due to enhanced biological activities such as nutrient uptake by wetland plants, assimilation by algae, and ammonium oxidation by autotrophic nitrifying bacteria associated with raised water temperature found during this experiment (mean temperature was 22.2°C compared to 20.3° C in Experiment 1). The generation of organic nitrogen by the end of this batch, as indicated by a difference between TN and dissolved inorganic nitrogen (ammonium + oxidised nitrogen), represented either increases in algal or bacterial biomass.

The fact that a lack of added phosphorus in the water column had no noticeable effect on nitrogen removal in either the FTW Treatments or the Controls has important implications for use of this technology in situations where P limitation is attempted as a means of controlling algal blooms (Schindler et al., 2008). Clearly nutrient attenuation processes within the FTW were operating at undiminished rates, and thus these could be used in environments where P was limited in the water column as any deficiency in P could be overcome by adding controlled amounts to the soil/growth medium within the island matrix. However, the relatively high N removal within the Control treatments, which we presume was due to N uptake and subsequent settling of organic matter, indicates that the P already present in the tap water supplied was sufficient to sustain algal growth, at least where N had been supplied in abundance.

4.3 EXPERIMENT 3 – N IN THE FORM OF NITRATE

Environmental conditions in the Control (high pH and supersaturation of DO) were again consistent with algae growth, and were particularly noticeable between Day 3 to Day 7 when algae had had time to build up. In the FTW Treatments, pH and DO both declined on the first day, but remained stable after that.

The low concentrations of ammonium throughout the experiment indicate that no noticeable conversion of nitrate to ammonium (via dissimilatory nitrate reduction to ammonium, DNRA) occurred. Oxidised nitrogen attenuation in the Control was substantial, at nearly 52% over 7 days, again probably associated with algal uptake and subsequent settling within the mesocosms. In the FTW Treatments, oxidised nitrogen attenuation ranged from 81.5% to 99.7%. The FTW mesocosms did not exhibit similar pH and DO increases to the Controls, suggesting algae growth was markedly lower in the presence of the FTWs, potentially associated with improved algal settling. Thus other removal mechanisms such as uptake by the plants and biofilms on the plant roots as well as denitrification are likely to have been relatively more important for N removal. As the oxygen concentrations measured in the water column adjacent to the hanging root mass were greater than 25% saturation in all planted mesocosms, it seems unlikely that a large amount of denitrification was occurring within the root mass, and that the FTW matrix was a more likely location for this process.

DRP removal in the FTWs (74-87%) was higher than in the Controls (62%). The substantial removal in the Controls indicates a high level of algal uptake and subsequent settling in these mesocosms.

4.4 EXPERIMENT 4 –NITRATE AND GLUCOSE ADDITION

From the previous experiments it was apparent that oxidised nitrogen removal via denitrification might be restricted by two factors, both of which may have been artefacts of the experimental conditions:

- a lack of available organic carbon (not present in the artificial lake water solution nor in the sediments);
- DO within the water column remained aerobic throughout the batches (>25% saturation).

More organic carbon is likely to be available under and within a mature FTW system in a lake due to turn-over of plant and sediment derived organic matter and decomposition of algae transported from surrounding open water areas. There would also be a greater potential for lower DO levels to develop under field conditions due to the presence of sediments and associated benthos, and the longer residence times that may occur compared to the mesocosms where the water was renewed after each batch (every seven days).

Mesocosms with FTWs exhibited similar reductions in pH as seen in previous experiments. However, the Control mesocosms also showed a decrease in pH, in contrast with the pattern seen in the previous experiments. The initial DO was low suggesting that the heterotrophic bacteria inoculated into the mixing tank with addition of glucose as a supplementary organic carbon source consumed significant amounts of DO from the artificial lake water before the experiment began. The temporary increase in DO on Day 1 appears to have been due to unintended aeration while filling the mesocosms rather than a treatment effect. The addition of extra glucose on Day 2 ensured there was sufficient DOC to sustain denitrification as well as create anoxic conditions. The consumption of DOC throughout the experiment is thus attributable to heterotrophic organisms oxidising organic carbon inducing anoxic conditions, and subsequent anaerobic denitrifying organisms utilising the organic carbon as an electron donor under anaerobic conditions (Tiedje, 1988).

The rate of oxidised nitrogen attenuation was higher in Experiment 4 compared to the other experiments potentially indicating an enhanced denitrification rate. However, there was no significant difference in the oxidised nitrogen concentration after 7 days between the FTW Treatments and the Control mesocosms (p = 0.739). The reduction in oxidised nitrogen was also accompanied by a concurrent increase in organic nitrogen indicating that large amounts of nitrate were incorporated into microbial and/or algal biomass rather than being removed via denitrification. The lower rate of TN attenuation observed in this experiment was unexpected, and was possibly due to rapid uptake and conversion of oxidised nitrogen to organic nitrogen by the heterotrophic bacteria added to the mesocosms at the start of this trial. This made it difficult to determine the maximum potential denitrification rate of the in-situ biofilm associated with the FTW root mass and floating island matrix. The addition of glucose appeared to have further stimulated heterotrophic biomass production (and nitrate uptake) rather than denitrification. The maintenance of relatively stable TP concentrations within the mesocosms while DRP was rapidly removed provides some supporting evidence that there had been significant bacterial production in the mesocosms, with DRP being converted into organic biomass in the water column leading to the observed increase in organic phosphorus concentrations during the batch.

4.5 SUMMARY OF NITROGEN AND PHOSPHORUS MASS REMOVAL RATES

The mean TN, ammonium, oxidised nitrogen, TP and DRP areal mass removal rates of the mat area for the FTW Treatments and the equivalent shaded area of the Controls over the first three days of Experiment 1 – 3[1] are presented in Table 8. Removal rates for the first three days of the experiments were chosen because, after this, attenuation rates were generally low due to low nutrient availability.

The FTW Treatments achieved mean areal mass removal rates of 638 – 762 mg m^{-2} d^{-1} for TN. After subtracting the removal rate of the Controls, the FTWs removed an average of 339 mg m^{-2} d^{-1}, which may be considered a more appropriate value to use when predicting likely attenuation in an in-lake situation. This rate is equivalent to removing around a third to half the average mass of TN present in a cubic metre of water each day from the three major eutrophic lakes in the Rotorua region (CBER, 2010). Depending on the availability of the two dissolved forms of nitrogen supplied, this was expressed as a net attenuation rate for ammonium of 143 mg m^{-2} d^{-1} or for oxidised nitrogen of 331 mg m^{-2} d^{-1} (Table 8). While ammonium was preferentially removed when both forms of nitrogen were supplied in equal amounts (Experiments 1 and 2), removal within the Controls was also high, such that the net attenuation rate was less than half that of oxidised nitrogen. The TN attenuation rate is however more than three times higher than the plant uptake rates alone reported by Tanner and Headley (In Prep) for similar FTWs (same size, plant species and research facility) where minimum daily uptake rates of 36, 58, and 103 mg N m^{-2} d^{-1} for ST, JG and CU respectively (values are minima as plant biomass accumulated within the FTW matrix was not able to be sampled). This indicates that processes other than plant uptake are likely to have accounted for the majority of the observed N attenuation rates.

Limited nitrification may have occurred in those experiments where ammonium was added, as was seen in the similar study of Headley and Tanner (2006). However, in addition to wetland plant uptake, the key nitrogen attenuation mechanisms appeared to be a combination of algal uptake and settling, and denitrification.

Table 8: ***Combined mean TN, ammonium, oxidised nitrogen, TP and DRP areal mass removal rates over the first three days of Experiment 1 - 3 (± 1 standard deviation)***

Treatment	Nutrient removal rate (mg m^{-2} d^{-1})*									
	Total nitrogen		Ammonium		Oxidised nitrogen		Total phosphorus		Dissolved reactive phosphorus	
Control	379	± 442	516	± 156	170	± 312	39	± 28	44	± 32
Juncus edgariae (JE)	638	± 374	608	± 148	440	± 204	58	± 27	57	± 20
Schoenoplectus tabernaemontani (ST)	762	± 95	685	± 51	555	± 60	54	± 31	64	± 11
Cyperus ustulatus (CU)	754	± 146	683	± 42	509	± 161	56	± 25	59	± 25
Average Net Attenuation**	339		143		331		30		16	

[1] Experiment 4 was excluded due to the atypical conditions resulting from addition of glucose and bacterial biomass.

* Based on a FTW area of $0.36m^2$. Removal rates for Controls are also based on this area (which was shaded).

** Average FTW removal rate – removal rates of Controls.

The net attenuation rates measured were equivalent to those reported rates for conventional constructed wetland systems, where TN removal rates for mature systems vary between 270 and 330 mg m^{-2} d^{-1} (Kadlec & Knight, 1996; Tanner et al., 2005a; Tanner et al., 2005b; Tanner & Sukias, 2003; Tanner & Sukias, accepted pending minor revisions March 2010). In comparison, attenuation rates in natural seepage wetlands (Johnson & Gerbeaux, 2004) are commonly lower, with rates of 5-15 mg m^{-2} d^{-1} reported (Rutherford & Nguyen, 2004), however N loading rates also tend to be much lower in these systems. Care needs to be taken when considering the N removal rates observed in the current short-term mesocosm experiments or in applying them to field situations, as some of the observed attenuation is likely to represent assimilation into temporary storage compartments (rather than permanent removal). In addition, rates in small scale experiments are often higher than measured in the field due to a number of factors, particularly edge effects (e.g., the walls of the mesocosms may have provided a large attachment surface for algal growth) and temperature effects.

The background nitrogen attenuation rate, as seen in the Control mesocosms was substantial, at 379 mg m^{-2} d^{-1} of TN. This attenuation appeared to represent nitrogen assimilation via algae growth and subsequent settling. While it was not directly measured, there was a noticeable accumulation of algae in the bases of the mesocosm which was flushed out and cleaned after each experiment.

Mean TP and DRP areal attenuation rates for the FTWs were 30 mg m^{-2} d^{-1} and 16 mg m^{-2} d^{-1} respectively (Table 8). These rates were similar to those recorded by Headley and Tanner (10 – 20 mg m^{-2} d^{-1}, 2007) for similar FTWs, and do not differ greatly from phosphorus uptake rates by wetland plants recorded by Tanner (1996) in gravel bed wetland mesocosms treating wastewaters (5–21 mg P m^{-2} d^{-1}). All three wetland plant species selected for the batch experiments demonstrated similar rates of phosphorus attenuation.

The FTW matrix covered only 30% of the mesocosm water surface area. Within a eutrophic lake context, providing this degree of shading (30% coverage) over most lakes is unlikely to be economically viable, but could be achieved for eutrophic ponds. However there is anecdotal evidence given to FTW manufacturers that FTWs have induced clear-water conditions at very low levels of lake or pond surface area (Floating Island International, 2010). It is possible that the dense root-mass hanging beneath the FTW provides a refuge for zooplankton, in a similar way to that provided by emergent and submerged macrophytes within the littoral zone (Stansfield et al., 1997). In addition, it is possible that the hanging root-mass causes an allelopathic response in phytoplankton by releasing compounds that are antagonistic to algal metabolism. Such compounds have been isolated from characean species (Wium-Andersen et al., 1982), and are believed to be associated with clear-water areas above charophyte beds (Scheffer et al., 1994). While enhancement of zooplankton densities was not a mechanism within our mesocosm studies as none are likely to have had time to establish within the short time frame of the experiments, the potential for an allelopathic mechanism cannot be excluded.

The batch experiments conducted using FTWs provide strong evidence that the plants played a critical role in enhancing attenuation of nitrogen and phosphorus from artificial eutrophic lake water. The long term sustainability of the measured attenuation rates has not been determined, as nutrients taken up into algal biomass and then removed by settling are likely to be recycled from the sediments back into the overlying water via mineralisation. Denitrification rates however are likely to be sustained or even increase as litter production within the FTW increases over time, providing available carbon as a microbial energy source.

5 CONCLUSIONS

Experimental studies were conducted under various nutrient conditions to assess the potential of floating treatment wetlands (FTWs) for nutrient attenuation from eutrophic lakes. Four 1-week batch mesocosm studies using replicated buoyant fibrous polyester floating mats planted with one of three wetland sedge species (*Cyperus ustulatus*, *Juncus edgariae* and *Schoenoplectus tabernaemontani*) were conducted over summer at the Ruakura Research Centre in Hamilton, New Zealand. The study found that the FTWs were capable of nitrogen and phosphorus removal rates equivalent to gravel bed wetlands (mean TN 339 mg m^{-2} d^{-1}; NH_4-N 143 mg m^{-2} d^{-1}; NO_X-N 331 mg m^{-2} d^{-1}; TP 30 mg m^{-2} d^{-1}; DRP 16 mg m^{-2} d^{-1}) from waters with N and P concentrations in the upper range found in eutrophic lakes around the Bay of Plenty.

Various nutrient attenuation mechanisms appeared to be in operation, with uptake into algae and subsequent settling appearing to be important. Denitrification within the FTW matrix was apparent when N was supplied as nitrate, but was limited by a lack of available organic carbon. Plant uptake of N and P also appeared likely. All three of the plant species used in the trials showed similar nitrogen and phosphorus attenuation rates, and can be generally recommended for use in FTWs employed for nutrient attenuation in eutrophic lake waters.

The daily areal nutrient removal rates recorded for the FTWs (over and above the substantial attenuation seen simply by shading the water surface) are equivalent to between a third and a half of median levels of nutrients present in a cubic metre of water in eutrophic Bay of Plenty lakes.

The results of this study indicate the potential of this technology for eutrophic lake water remediation. Realistically even covering 10% of the surface of anything but a very small lake is likely to be impractical, and probably also unacceptable to the lake users. However coverage in this order may be acceptable in targeted bays where high nutrient inputs have been identified, which may represent an effective application of this technology in combination with other remediation tools. In addition, if planted FTWs can significantly reduce algal biomass and other sources of turbidity within underlying waters and buffer wave action, there may be potential for using this technology to help re-establish submerged and emergent macrophytes in adjacent areas of shallow algal-dominated eutrophic lakes.

While nutrient removal rates were equivalent to other passive, natural technologies, the experiments undertaken in the present study were all small-scale, of short duration and undertaken during summer. As a portion of the attenuation appeared to be incorporation of nutrients within finite or temporary storage pools (algal sedimentation and plant uptake), it is unclear whether the measured attenuation rates would be sustained in the longer-term. Removal rates during colder winter months are likely to be lower, due to reduced microbial activity and plant growth. Larger-scale, longer-term studies would be necessary to evaluate the practical efficacy of FTWs for localised control of lake eutrophication in the field.

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