Nutrient removal and plant biomass in a sub-surface flow constructed wetland in Brisbane, Australia.

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Abstract

Four native plant species (*Baumea articulata, Carex fascicularis, Philydrum lanuginosum* and *Schoenoplectus mucronatus*) are being investigated for their suitability in subsurface flow wetlands. The pilot scale Oxley Wetland, Brisbane, consists of 4 cells with different sized gravel (5 mm and 20 mm). The project aims to investigate nutrient removal rates and removal efficiency; nutrient storage in plant biomass; effect of cropping on plant regrowth, and the effect of gravel size on both water treatment and plant growth. Average daily mass removal rates ranged from 7.3 $Kgha^{-1}d^{-1}$ NH4-N in Cell D to 4.6 $Kgha^{-1}d^{-1}$ in Cell C i.e. 37%-22% removal efficiency respectively; 5.2 $Kgha^{-1}d^{-1}$ NOx-N in Cell C to 1.3 $Kgha^{-1}d^{-1}$ in Cell A (i.e. 75%-22% removal efficiency) and 0.8 $Kgha^{-1}d^{-1}$ PO_4-P in Cell A to 0.1 $Kgha^{-1}d^{-1}$ in Cell C (i.e. 10%-1% removal efficiency). Cell A was the youngest wetland with new 5 mm gravel. Plant biomass was highest for *Baumea* and *Carex*. Gravel size does not appear to have affected biomass and recovery following cropping. *Carex* consistently had the highest harvested above ground biomass with high re-growth following cropping. Cropping appears to have retarded growth of the other three species with *Schoenoplectus* consistently having slowest regrowth. Plant biomass and nutrient storage was highest in Cell A and accounted for 11% of nitrogen removal and 3% of phosphorus removal.

Keywords
biomass harvesting, macrophytes, nutrient removal, secondary effluent, sub-surface flow constructed wetland

Introduction

Constructed wetlands are an approved wastewater treatment system and have been used successfully worldwide to treat various types of wastewater including stormwater, industrial, domestic, agricultural, mine drainage and landfill leachate (Kadlec and Knight, 1996). Subsurface flow (SSF) constructed wetlands are most suitable for treating secondary effluent or in a treatment train after a settling pond or septic tank in which suspended solids have largely been removed. SSF wetlands have been widely used throughout Europe to provide secondary treatment after screening and primary settlement, for small communities and single households where conventional wastewater treatment can often be too expensive to construct and maintain (IWA, 2000).

A defining feature of a wetland is the presence of aquatic vegetation (macrophytes). Macrophytes play a wide range of roles in constructed wetlands for wastewater treatment. Roles include the physical effects of the plants themselves in sedimentation, erosion control and providing surface area for microbial growth (biofilms) thus increasing microbial assisted processes including nitrification and denitrification. Macrophytes also have a metabolic role in wastewater treatment with the potential to release oxygen into the rhizosphere aiding in nitrification and by the direct uptake of nutrients (Brix, 1997; Greenway and Woolley, 2001). *Phragmites australis* is the most commonly used emergent species in SSF wetlands particularly in temperate climates. In Queensland, Australia where the tropical/sub-tropical climate provides ideal growth conditions for macrophytes, numerous species of aquatic macrophytes have been successfully used in free water surface (FWS) wetlands (Greenway and Woolley, 1999; Greenway, 2003).

A research project in Brisbane, Australia is currently investigating the suitability of *Baumea articulata, Carex fascicularis, Philydrum lanuginosum* and *Schoenoplectus mucronatus* for use in SSF wetlands (Browning and Greenway, 2002). The aims of the research presented in this paper are to investigate nutrient removal rates and removal efficiency; nutrient storage in plant biomass; effect of cropping on plant regrowth and to determine whether gravel size effected water treatment and/or plant growth.

Methods

Wetland design

The pilot SSF constructed wetland is situated at the Oxley Wastewater Treatment Plant (WTP) in Brisbane. It is a horizontal SSF wetland, consisting of four equally sized cells (26m long, 4m wide and 0.5m deep). Each cell is lined with high-density polyethylene, and has three gravel sections (Section 1 to 3) separated by 1 m wide open water sections. The wetland receives secondary treated effluent at an average flow rate of 8L/min with a median hydraulic loading rate (HLR) of 0.12m/day. Flow rate was measured by tipping buckets located at the inlet and outlet of each cell. The experimental design involves four different substrate treatments: Cell A new 5mm gravel, Cells B and C old 20mm gravel and Cell D old 5mm gravel. Cells B, C and D have been operational since 1995 whereas Cell A has been in use since 2000. Cells B and D had previously been planted with *Phragmites australis* (Greenway, 2002).

Gravel Sections 2 and 3 were planted October 2000, with four Australian native macrophyte species: *Baumea articulata* (Jointed Twigrush), *Carex fascicularis* (Tassel sedge), *Philydrum lanuginosum* (Frogsmouth) and *Schoenoplectus mucronatus.* Section 1 remained unvegetated. Each section was divided into 4 compartments each $7m^2$ and planted with one of the four macrophyte species at a density of 9 per m^2. Thus, within every Cell each species covered a total of $14m^2$. Planting layout was the same for all Cells to allow comparison between Cells. Due to the decline of plant health and high plant mortality in Cell D following initial planting, this cell was replanted in February 2001.

Plant biomass and nutrient content

All Cells were harvested in August 2001 after 9 months growth (6 months growth for plants in Cell D) and again in February 2002 after 6 months regrowth. Plants were cropped approximately 10 cm from the gravel surface. All harvested plant material was weighed on site. Wet:dry weight ratios were used to estimate biomass. Plant components (leaves, stems, flowers, roots and rhizomes) were analysed for nitrogen and phosphorus using representative samples of all four species from each Cell. Prior to analysis dried samples were finely ground. Total nitrogen was determined using the automated combustion method, whereas total phosphorus involved a tri-acid digestion and the ascorbic acid reduction method for colourmetric determination (Kalra, 1998).

Water quality

Water quality was monitored in order to determine the effectiveness of the constructed wetland in the treatment of secondary effluent and to quantify the extent of nutrient removal by macrophytes. Water samples were collected fortnightly over 12 months from May 2001 to May 2002 from the inlet and outlet of each Cell. Samples were not collected in December 2001 as water to the wetland was temporarily offline due to maintenance to the WTP. Field parameters: pH, temperature and dissolved oxygen were measured *in situ* using a calibrated multiprobe. Parameters measured in the laboratory included: total suspended solids (TSS); chemical oxygen demand (COD); total nitrogen (TN); oxidised nitrogen (NO_x); ammonia (NH_4) and filterable reactive phosphorus (FRP). Samples were analysed in accordance with Standard Methods (1992).

Results and discussion

Water quality

Table 1. Water quality concentrations (mgL^{-1}) and loading rates ($Kgha^{-1}d^{-1}$) for Oxley Wetland Median values over 12 months (May 2001 – May 2002) (SD for means given to indicate range).

Parameter		Cell A	Cell B	Cell C	Cell D
Age of cell		1 yr	6 yr	6 yr	6 yr
Gravel size		5 mm	20 mm	20 mm	5 mm
Water temperature (C^0)		21.9 (2.7)	21.3 (2.8)	21.6 (2.7)	21.5 (2.7)
DO (mgL^{-1})	IN	2.5 (1.1)	2.4 (1.1)	2.0 (0.9)	1.6 (0.6)
DO (mgL^{-1})	OUT	0.7 (0.6)	0.4 (0.4)	0.4 (0.4)	0.5 (0.4)
COD (mgL^{-1})	IN	43 (17.3)	57 (18.1)	44 (18.0)	37 (10.2)
COD (mgL^{-1})	OUT	22 (9.5)	28 (6.9)	25 (8.0)	24 (6.9)
TSS (mgL^{-1})	IN	9.6 (8.1)	9.6 (5.8)	8.4 (7.2)	9.8 (6.3)
TSS (mgL^{-1})	OUT	1.3 (2.0)	1.6 (2.4)	1.1 (2.3)	1.4 (3.2)
Ammonia NH4 - N ($mgNL^{-1}$)	IN	12.5 (7.7)	12.9 (7.7)	12.3 (7.5)	12.9 (8.2)
Ammonia NH4 - N ($mgNL^{-1}$)	OUT	12.3 (3.6)	12.5 (5.3)	12.1 (5.3)	10.6 (4.4)
Ammonia NH4 - N $Kgha^{-1}d^{-1}$	Loading	13.8	14.3	13.6	14.3
Oxidised N ($mgNL^{-1}$)	IN	4.9 (4.9)	4.5 (5.3)	5.7 (5.2)	4.3 (5.5)
Oxidised N ($mgNL^{-1}$)	OUT	5.4 (4.7)	1.2 (3.4)	0.8 (2.7)	1.6 (3.6)
Oxidised N $Kgha^{-1}d^{-1}$	Loading	5.4	5.0	6.3	4.8
Total N ($mgNL^{-1}$)	IN	21.8 (5.1)	23.7 (5.3)	22.6 (5.2)	23.2 (5.1)
Total N ($mgNL^{-1}$)	OUT	19.0 (5.7)	17.3 (4.4)	17.3 (4.3)	15.3 (4.6)
Total N $Kgha^{-1}d^{-1}$	Loading	24.1	26.3	25.0	25.7
Filterable Reactive P	IN	6.2 (1.8)	6.5 (1.8)	6.3 (1.9)	6.5 (1.7)
FRP ($mgPL^{-1}$) *	OUT	6.4 (1.0)	6.8 (1.2)	7.0 (1.4)	7.1 (1.7)
FRP $Kgha^{-1}d^{-1}$	Loading	6.9	7.2	7.0	7.2

**NB. Outflow FRP was higher than inflow for 3 months.*

The Oxley Wetland was highly effective in reducing concentrations of TSS (a physical process) (<2mg/L) and COD (<30mg/L) but not ammonia or phosphorus (Table 1). NO_x concentrations were reduced except in Cell A (Table 1) Dissolved oxygen concentrations decreased once water entered the first gravel section and may have limited nitrification of ammonia, however macrophytes can potentially transport and release oxygen from roots to the surrounding rhizosphere providing aerobic conditions for nitrification to occur (Brix, 1997). Some studies of horizontal SSF wetland where oxygen levels are apparently low have shown low numbers of nitrifying bacteria in wastewater but quite high numbers on root and gravel surfaces (Ottova *et* al., 1997).

Mass loads of NH_4-N, NO_x-N and FRP over four 3 month periods is given in Table 2. Removal of FRP in all Cells was low. Average daily mass removal rates for FRP over the total 12 month period were 0.8 kg (10%), 0.4 kg (5%), 0.1 kg (1%) and 0.4 (5%) $kgha^{-1}d^{-1}$ in Cells A, B, C and D respectively. Cell A (5 mm new gravel) had the highest daily mass removal, whereas Cell C (20 mm old gravel) had the lowest FRP removal with export for 9 of the 12 months. From December 2001 to February 2002 all Cells exported FRP. For much of this period water supply to the wetland was disrupted with only 49 days of flow. Disruption to water supply may have facilitated the remobilisation of inorganic phosphate as found in a previous study by Greenway and Woolley (2001). Gravel size does not seem to have influenced FRP removal. Since Cell A has been in operation for less than 2 years it is possible that the phosphorus adsorption

capacity of substrate has not yet reached saturation unlike the older Cells. Long-term phosphorus removal is often difficult to achieve, in some cases phosphorus output may be higher than input with the release or de-sorption of phosphorus (Greenway and Woolley, 1999; Kadlec and Knight, 1996; Vymazal *et al.*, 1998).

Table 2: Removal of bioavailable nitrogen and phosphorus in each cell at Oxley Wetland over 12 months. Loading (kg), efficiency of removal (%) and daily removal rate ($kgha^{-1}d^{-1}$).

Days	Cell	NH4 – N				NOx – N				FRP			
		Load (kg)		Removal		Load (kg)		Removal		Load (kg)		Removal	
		In	Out	%	$kgha^{-1}d^{-1}$	In	Out	%	$kgha^{-1}d^{-1}$	In	Out	%	$kgha^{-1}d^{-1}$
90 Jun-Aug 2001	A	17.7	14.1	20	3.8	9.6	8.4	12	1.2	9.0	7.7	14	1.3
	B	18.7	16.3	13	2.5	9.9	3.9	60	6.4	9.5	9.1	4	0.4
	C	18.3	16.6	9	1.8	9.5	2.7	72	7.3	9.0	8.0	11	1.1
	D	18.9	13.3	30	6.0	10.6	5.0	53	5.9	9.8	9.7	1	0.1
88 Sep-Nov 2001	A	12.5	11.0	12	1.7	5.6	3.3	41	2.5	7.0	5.8	16	1.3
	B	13.6	13.1	4	0.6	4.9	0.9	82	4.9	7.7	6.8	12	1.0
	C	13.6	13.7	export	export	7.9	0.9	88	7.6	7.9	8.7	export	export
	D	12.4	8.6	31	4.2	5.2	1.1	79	4.5	7.4	5.3	28	2.3
49* Dec 01-Feb 02	A	15.7	8.1	48	14.8	0.6	1.4	export	export	2.7	4.1	export	export
	B	15.0	6.3	58	17.1	0.4	0.5	export	export	2.5	2.7	export	export
	C	21.0	12.1	42	17.4	0.6	0.8	export	export	3.3	3.3	export	export
	D	17.4	11.0	37	12.6	0.5	1.4	export	export	3.1	4.8	export	export
92 Mar-May 2002	A	9.4	4.3	55	5.4	1.5	0.4	73	1.1	3.1	1.9	39	1.3
	B	7.4	3.4	54	4.2	1.3	0.9	28	0.4	2.5	2.5	export	export
	C	7.0	4.5	35	2.6	1.3	0.4	70	1.0	2.5	2.6	export	export
	D	6.4	1.8	73	4.9	0.7	0.2	76	0.6	2.0	1.4	29	0.6
TOTAL													
270 Jun 01-May 02	A	55.3	37.5	32	6.3	17.2	13.5	22	1.3	21.7	19.5	10	0.8
	B	54.6	39.0	29	5.6	16.4	6.2	62	3.6	22.1	21.0	5	0.4
	C	59.8	46.9	22	4.6	19.3	4.8	75	5.2	22.7	22.6	1	0.1
	D	55.1	34.6	37	7.3	16.9	7.7	55	3.3	22.3	21.3	5	0.4

** Water supply to the wetland was disrupted for most of December 2001 and much of January 2002. Outflow rate and volume was estimated for Cell A (June to August 2001) and Cell B (December 2001 to February 2002) due to problems with tipping buckets.*

Average daily mass removal rates and removal efficiency for NH_4-N over 12 months were 6.3 kg (32%), 5.6 kg (29%), 4.6 kg (22%) and 7.3 $kgha^{-1}d^{-1}$ (37%) in Cells A, B, C and D respectively. Cell D consistently performed better than the other cells in the removal of ammonia. Low removal efficiencies for NH_4-N suggest that nitrification is limiting due to the lack of aerobic conditions. Average daily mass removal rates and removal efficiency for NO_x-N over the 12 months were 1.3 kg (22%); 3.6 kg (62%); 5.2 kg (75%) and 3.3 $kgha^{-1}d^{-1}$ (55%) in Cells A, B, C and D respectively. The lowest removal in Cell A suggests a more limited capacity for denitrification. Denitrification rates can be limited by organic carbon, as approximately 2.5g of organic carbon are required to denitrify 1g of nitrate (Kadlec and Knight, 1996). The decay of litter and microdetritus can provide an internal carbon supply for denitrification. A study by Gersberg *et al.* (1983) found that in a vegetated SSF wetland without additional organic carbon, nitrogen removal was relatively low (25%) but, after the addition of methanol, nitrogen removal

increased to 95%. Roots and rhizomes shed directly into the substrate may provide the organic carbon source within the substrate for denitrification rather than above ground plant litter (Tanner *et al.,* 1998).

As shown in Table 2 the removal of NH_4 and NO_x was variable both between Cells and sampling periods. From December 2001 to February 2002, NH_4 removal in all Cells was highest. Over this period all four cells experienced elevated NH_4 inflow concentrations. Several factors may be responsible for this improved performance including elevated nitrification rates and a possible increased nutrient demand by plants for flowering and rapid growth in February post cropping. During this period dissolved oxygen concentrations and water temperature within all four Cells were slightly elevated, median temperatures for all cells were close to 25C^{o} which is the optimal temperature for nitrification and denitrification (Hammer and Knight, 1994; Vymazal, 1995). Over the same period four Cells experienced NO_x export probably as a result of low inflow concentrations combined with effective conversion of NH_4 to NO_x through nitrification.

Plant biomass harvesting

Harvested above ground biomass showed considerable variability between species and Cells (Figure 1). The highest shoot biomass cropped in August 2001 after 9 months growth was 25.7kg (from 14m^2) for *Baumea* followed by *Carex* (24.8 kg from 14 m^2). Plant biomass for *Baumea* was lower than found in previous studies by Adcock and Ganf (1994) and Tanner (1996) in SSF wetlands where mean plant biomass was in the range of 8kg/m^2. As indicated in Figure 1 *Carex* is the only species that consistently had high regrowth following cropping and could achieve a harvestable above ground biomass in 6 months. Kim and Geary (2001) similarly found that regrowth of *B. articulata* and *S. mucronatus* was slow following harvesting. Greenway and Woolley (2001) showed that cropping invigorated growth in *Eleocharis sphacelata* but limited regrowth in *Schoenoplectus validus*. Gravel size does not appear to have affected biomass and recovery following cropping.

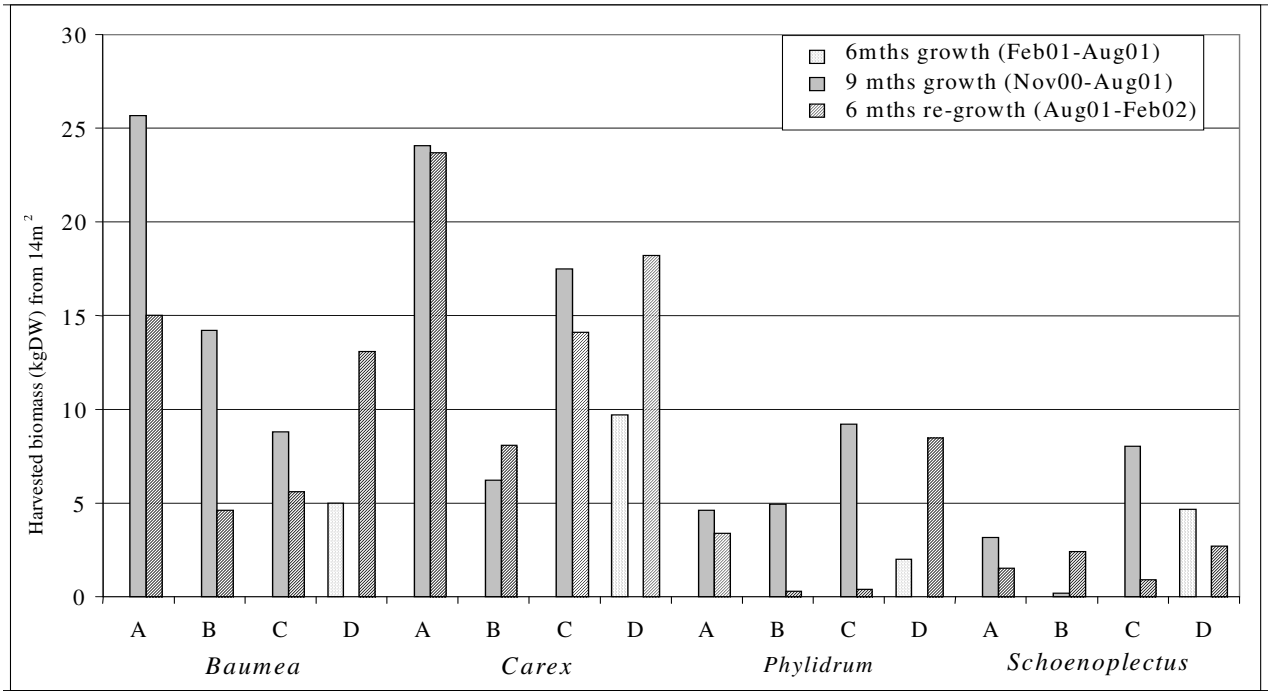

Figure 1. Total above ground biomass harvested for each species in each Cell (14m^2) in Aug 01–Feb 02. NB. Cell D was replanted in Feb 01 so harvesting in Aug 01 represents 6 months growth.

Nutrient content and storage

Nutrient content of the plant components is presented in Table 3 and nutrient storage as plant biomass is given in Table 4. Nutrient content is within the range of other macrophytes growing in treatment wetlands (Adcock and Ganf, 1994; Greenway, 1997; Greenway, 2002; Tanner, 1996). *Schoenoplectus* consistently had a higher phosphorus content. Kim and Geary (2001) found even higher P content especially in response to harvesting (6.5-8.5 mg/L). Biomass and nutrient storage for *Baumea* and *Carex* in Cell A was higher than a dense stand of *Typha* (Greenway and Woolley, 2001) indicating the potential of these 2 species for nutrient removal and storage.

Table 3. A comparison of nutrient content (mgP/g and mgN/g) in plant components (mean ± SD).

Species	P or N	Leaf (mg/g)	Stem (mg/g)	Root (mg/g)	Rhizome (mg/g)	Whole plant (mg/g)
Baumea articulata	P	1.9 ± 0.5		2.3 ± 1.6	3.5 ± 1.0	2.5 ± 1.3
	N	16.3 ± 3.8		11.2 ± 3.2	20.0 ± 4.2	15.7 ± 5.2
Carex fasicularis	P	2.7 ± 0.5		1.9 ± 0.7		2.3 ± 0.8
	N	16.9 ± 3.5		13.0 ± 3.0		15.2 ± 4.0
Philydrum languinosum	P	2.4 ± 0.9	2.6 ± 1.6	3.1 ± 1.8		2.6 ± 1.4
	N	17.8 ± 2.9	12.9 ± 5.1	14.7 ± 3.3		15.3 ± 4.3
Schoenoplectus mucronatus	P	3.9 ± 1.3		3.5 ± 1.9		3.3 ± 1.5
	N	18.2 ± 4.1		13.3 ± 2.3		14.9 ± 3.8

Table 4. Plant biomass (g DW/m^2) and nutrient storage (gP/m^2 and gN/m^2) in each cell by the four macrophyte species in August 2001 after 9 months plant growth (6 months for Cell D). NB. nutrient storage was calculated using mean nitrogen and phosphorus content of whole plant for each species.

	Cell A 9 months			Cell B 9 months			Cell C 9 months			Cell D 6 months		
	g/m^2	gP/m^2	gN/m^2	g/m^2	gP/m^2	gN/m^2	g/m^2	gP/m^2	gN/m^2	g/m^2	gP/m^2	gN/m^2
Baumea	2160	5.5	34	1195	3.0	18.8	740	1.9	11.6	419	1.1	6.6
Carex	1992	4.6	30	515	1.2	7.8	1448	3.4	22	803	1.9	12.2
Philydrum	347	0.9	5.3	371	1.0	5.7	692	1.8	10.6	149	0.4	2.3
Schoenoplectus	241	0.8	3.6	15	0.05	0.2	615	2.0	9.2	357	1.2	5.3

Nutrient removal by plants

Using total nitrogen and phosphorus removed from each Cell (between the planted Sections 2 and 3) and nutrient content and biomass for each species and Cell, an indication of nitrogen and phosphorus removal contained in plant biomass can be estimated as per Greenway and Woolley (2001). Estimates assumed a 6 month turnover of plant biomass for emergent species although as previously discussed this is only likely for *Carex*. There was considerable variability between Cells with biomass in August 2001 accounting for 11%, 3%, 2% and 1% nitrogen removal in Cells A, B, C and D; and 3%, 3%, 1%, 1% of phosphorus removal. These removal percentages are lower than those found in a previous study of a SSF system by Gersberg *et al.* (1986) but within the range found by Tanner *et al.* (1995), where over an annual period plant biomass accounted for 2-8% TN removal and 1.9-5.3% TP removal. In a tropical surface flow wetland in Cairns plants (including duckweed and submerged species) accounted for up to 47% for the nitrogen removal and 65% of the phosphorus removal (Greenway and Woolley, 2001). However, nutrient loading in the Cairns wetlands was low 3.6 kg TN and 3.3 kg TP $ha^{-1}d^{-1}$ compared to Oxley wetland with loading of 24 kg N and 6.7 kg FRP $ha^{-1}d^{-1}$.

Conclusion

Nutrient concentrations and loading rates were high at the Oxley wetland. Average daily mass removal rates over 12 months ranged from 7.3-4.6 $kgha^{-1}d^{-1}NH_4$-N , 5.2-1.3 $kgha^{-1}d^{-1}$ NO_x-N and 0.8-0.05 $kgha^{-1}d^{-1}$ PO_4-P . Removal efficiencies ranged between 37-22% for NH_4-N, 75-22% NO_x-N and 10-1% PO_4-P. Removal of FRP was highest in Cell A where gravel was relatively new and capacity for phosphorus adsorption was higher than for older Cells B, C and D. This field trial has shown that *Carex fascicularis* is the most suitable species of the four trialed for use in SSF constructed wetlands as re-growth was high following cropping with above ground biomass achieved in 6 months. Estimates of nutrient uptake by plants was highest in Cell A which had the highest plant biomass, and accounted for 11% of the nitrogen removed and 3% of the phosphorus removed.

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