PHYTOPLANKTON ASSEMBLAGES IN FOUR WETLANDS CREATED ON CUTAWAY PEATLANDS IN IRELAND

Heather Lally, Mike Gormally, Tara Higgins, Martin Gammell and Emer Colleran

Heather Lally (corresponding author; e-mail: heatherlally@gmail.com) and Mike Gormally, Applied Ecology Unit, Centre for Environmental Science, School of Natural Sciences, National University of Ireland, Galway; Tara Higgins, Environmental Microbiology Research Unit, Department of Microbiology, School of Natural Sciences, National University of Ireland, Galway and Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford; Martin Gammell, Department of Life and Physical Sciences, Galway–Mayo Institute of Technology, Dublin Road, Galway; and Emer Colleran, 33 Beech Grove, Oranmore, Co. Galway.

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ABSTRACT

The deliberate flooding of cutaway peatlands has resulted in the creation of 3700ha of new wetlands in the Irish Midlands. None of Ireland's cutaway wetlands have been designated as artificial water bodies for the purposes of the Water Framework Directive (2000/60/EC) (WFD). Nevertheless, ensuring that the created wetlands do not adversely affect downstream water quality or the potential of neighbouring designated rivers to achieve their environmental objectives under the WFD is of primary concern to environmental managers and regulators. Phytoplankton communities in four created wetlands were monitored over a 33-month period. The study aimed to assess whether phytoplankton communities in the created wetlands have the potential to be reliable indicators of chemical water quality. Longer term changes in the phytoplankton communities in two of the wetlands were also assessed. Indicator species analysis identified the presence of a number of algal species regarded as reliable indicators of eutrophic and mesotrophic water quality. Longer term trends indicated that the created wetlands have a propensity to develop phytoplankton blooms in the early years following flooding, in response to high ambient phosphorus concentrations. The data indicate a trend of improving water quality as the created wetlands mature and stabilise.

INTRODUCTION

Phytoplankton are of key ecological importance because of the major role they play in aquatic food web interactions. Phytoplankton communities are extremely dynamic and respond to changes in light, nutrients and sediment loads, rapidly changing in biomass distribution and species composition, thereby making phytoplankton good indicators of aquatic health and water quality. The presence of blue-green algae (Cyanophyta) such as *Anabaena*, *Oscillatoria*, *Lyngbya* and *Microcystis*, for example, may indicate freshwater nutrient enrichment as these genera commonly respond to increases in nutrients, as do certain green algae (Chlorophyta) from the genera *Chlorella*, *Chlamydomonas*, *Spirogyra*, and *Tetraedron* (Bowling 2009). Other green algae from the genera *Merismopedia*, *Staurastrum*, and *Ankistrodesmu*s are found mainly in clean, oligotrophic freshwaters, as are the diatoms (Bacillariophyta) *Cyclotella* and *Pinnularia*. Phytoplankton have been used as indicators of changing environmental conditions and water quality in both acidic and mineral influenced peatland pools (Borics *et al.* 2003; Nováková 2007). Acidic peatland habitats typically contain phytoplankton communities characterised by diatoms (Bacillariophyta), dinoflagellates (Pyrrophyta) (in particular *Gymnodinium* and *Peridinium* species) and Chrysophytes (Hehmann *et al.* 2001; Krivograd and Vrhovŝek 2003), while fen peatland systems influenced by mineral groundwater or sediments are characterised by green algae (Chlorophyta) and, where nutrients are abundant, blue-green algae (Cyanophyta) and Euglenophytes (Nováková 2007). There has been limited study of the phytoplankton of wetlands created on former industrial peatlands, where green algae (Chlorophyta), mostly coenobial taxa such as *Scenedesmus* species, were reported prominent (Muylaert *et al.* 2003).

In the Irish Midlands, large areas of abandoned cutaway peatlands have been reflooded to create wetlands. The approaches used to create the wetlands are selected by peatland managers on a site-specific basis and vary greatly in complexity and cost, involving different degrees of peat removal, hydrological manipulation and post-flooding management (Egan 1998; Higgins and Colleran 2006). Article 4(3) of the Water Framework Directive (WFD Ireland 2004) (2000/60/EC) recognises the ecological effects of anthropogenic alterations on water bodies and provides a legal framework in which artificial water bodies (AWB) must achieve the standard of good ecological potential (GEP). GEP recognises the maximum quality achievable by an AWB's aquatic ecosystem taking into account its artificial characteristics (UKTAG 2008). None of Ireland's artificial cutaway peatland wetlands have

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been designated as AWB for the purposes of the WFD and therefore are not subjected to the environmental objective of GEP. Nevertheless, it is imperative to environmental managers and regulators that the newly created wetlands do not adversely affect water quality downstream in existing rivers, which are subject to the WFD target of achieving good status by 2015. Since three local rivers (Boora River, River Brosna and Silver River) have been categorised at risk of not achieving good status (ShIRB 2005), improving the water quality of these rivers and ensuring their protection from any further deterioration is a priority. The rivers are locally important water courses for salmon and wild brown trout and they in turn discharge into the River Shannon, an internationally acclaimed salmon and trout fishery.

The primary objective of this study was to characterise the phytoplankton communities of four wetlands created on cutaway peatland and to assess whether phytoplankton have the potential to be reliable indicators of chemical water quality. In addition, longer term changes in the phytoplankton communities of two of the wetlands were examined. It is anticipated that the data will provide useful information on the water quality, phytoplankton and trophic status of the selected wetlands and assist in developing management practices aimed at ensuring the creation of wetlands of GEP in the long term.

METHODS AND MATERIALS

WETLAND CREATION APPROACHES

The wetlands studied were created using two different wetland construction approaches, referred to here as partial peat removal (PPR) and simple rewetting (SR). PPR involves excavating some of the residual peat layer of the cutaway peatland to create a shallow lake basin, in the process partially exposing the underlying glacial mineral sediments. The wetland is allowed to flood to an average depth of about 1m from a combination of precipitation and, depending on the site, either groundwater spring discharges or else a supplemental piped riverine inflow diverted from a nearby stream (McNally 1999). Natural recolonisation of some PPR wetlands is promoted by planting wild grass seed mixtures and *Betula* spp saplings. SR is the common European approach to shallow wetland creation on abandoned/degraded peatlands (Meade 1992; Vasander *et al.* 2003; Sallantaus 2004; Kieckbusch and Schrautzer 2007; Lundin *et al.* 2008). This approach involves blocking up the network of drainage channels and ditches constructed to drain the peat field for harvesting by infilling them with peat. The area then floods naturally from a combination of precipitation and associated surface runoff to form a shallow wetland (0.5–1m depth). Little on-site disturbance occurs, making this a highly cost-effective wetland creation approach (Table 1).

SITE SELECTION

Four created wetlands, three created using PPR (PPR 2, PPR 3 and PPR 4) and one created using SR (SR 1) were selected from the Bord na Móna estate in County Offaly, Ireland. PPR 2 and SR 1 had been previously studied (Higgins and Colleran 2006; Higgins *et al.* 2006; 2007) thereby providing a longer term (64 month) dataset. PPR 2 and SR 1 represent the oldest and youngest, respectively, of the cutaway wetlands created in Ireland while PPR 3 and PPR 4, which were previously unstudied, are the two largest wetlands created to date. The four wetlands were studied between April 2006 and September 2008. PPR 2 and SR 1 were sampled monthly (total of 30 sampling dates) and PPR 3 and PPR 4 were sampled fortnightly for the first year and monthly thereafter (total of 39 sampling dates). The principal characteristics of the four created wetlands are presented in Table 1.

WATER CHEMISTRY VARIABLES

Following recommended water sampling techniques and procedures from Higgins and Colleran (2006) and Higgins *et al.* (2007) near-surface (0.3m) water samples were taken at the overflow channel of each created wetland. Samples were collected in six-litre opaque, acid washed polyethylene containers and returned to the laboratory within six hours of collection. On site analysis of pH, conductivity, dissolved oxygen (DO) and water temperature was conducted using a WTW P4 Multiline field kit. Turbidity was measured on unfiltered samples by the nephelometric method using a HANNA HI93703 (APHA 1998). Total Phosphorus (TP) and soluble reactive phosphorus (SRP) were analyzed according to the CLS 57 and Konelab CLS 35 (precision $\pm 0.04 \mu g\ PO_4\ L^{-1}$) specification, respectively. Nitrate was analyzed using Konelab CLS 39 (precision $\pm 2 \mu g\ NO_3^- - N\ L^{-1}$) specifications. All nutrient analyses were carried out by Complete Laboratory Solutions in Rosmuc, Co. Galway, Ireland. Chlorophyll-a, with correction for pheophytin, was measured spectrophotometrically using 90% acetone extraction (Lorenzen 1967).

PHYTOPLANKTON ANALYSIS

Phytoplankton samples were collected in 75ml culture bottles within 0.3m of the surface water and preserved with Lugol's iodine solution (Wetzel and Likens 2000; John *et al.* 2002). Phytoplankton

Table 1—Principal characteristics of the four created wetlands (PPR 2, PPR 3, PPR 4 and SR 1) studied in mid-county Offaly, Ireland.

	PPR 2	*PPR 3*	*PPR 4*	*SR 1*
Local names	Turraun	Drinagh	Tumduff Mór	Clongawny
Location	7°44'10W 53°15'34N	7°49'59W 53°12'15N	7°42'0W 53°12'34N	7°52'55W 53°10'3N
Peat production ceased	mid-1970s	mid-1980s	1988	1993/1994
Year wetland created	1991	1999	1997	2001
Age of wetland (in years) in 2008	17	9	11	7
Construction approach	PPR	PPR	PPR	SR
Construction costs (€ per ha)	500	500	500	200
Wetland area (ha)	70	186	40	12
Water depth range (m)	0.5–1.5	1–9	2–5	0.5–1
Water Supply	Piped riverine inflow, Spring discharge, Precipitation	Spring discharge, Precipitation & surface runoff	Piped riverine inflow, Precipitation & surface runoff	Groundwater seepage, Precipitation & surface runoff
Post-flooding management	Area around the wetland landscaped & reseeded	None	None	None
Wetland outputs	Overflow channel discharges into the Boora River which joins the River Brosna (poor status) approx. 1.5km downstream	Overflow channel discharges into the Silver River (moderate status) which joins the River Brosna (poor status) approx. 6km downstream	Overflow channel discharges into Tumduff Brook which joins the Boora River (poor status) before discharging into the River Brosna (poor status) approx. 8km downstream	Overflow channel discharges into the Little River which joins the River Brosna (poor status) approx. 12km downstream
Surrounding wetland land uses	Natural recolonisation (56%) Abandoned cutaway peatland (22%), Agricultural grassland (15%), Conifer plantations (6%)	Natural recolonisation (38%), Active industrial peat fields (33%), Agricultural grasslands (19%), Conifer plantations (10%)	Reclaimed agricultural grasslands (33%), Natural recolonisation (28%) Commercial conifer plantation (23%), Active industrial peat fields (13%)	Abandoned & Active industrial peat fields (32%), Natural recolonisation (26%) Agricultural grasslands (24%) Commercial conifer plantation (19%)

PPR, Partial peat removal; SR, Simple rewetting.

identification and enumeration were carried out using an Olympus CK 40 inverted microscope (Lund *et al.* 1958) to facilitate viewing of all parts of the counting chamber. Standard bench references and more specialised keys were used to identify the algal taxa (Lind and Brook 1980; Popovský and Pfiester 1990; Kelly 2000; John *et al.* 2002; Pliński and Wolowski 2008). Organisms were identified to species level where possible, with the genus otherwise recorded. Cell enumeration was carried out on preserved samples. A count at magnification ×200 was performed until at least 100 algae units per species were recorded to yield a precision of ±20% (Lund *et al.* 1958).

STATISTICAL ANALYSIS

To determine whether phytoplankton species within the four created wetlands were preferential indicator species, indicator species analysis (ISA) was undertaken. ISA considers the relative frequency and abundance of the species in the four created wetlands and uses the Monte Carlo randomisation procedure to evaluate significances (McCune and Grace 2002). To investigate changes in the phytoplankton communities of PPR 2 and SR 1 over 64 months (2002–2008), Non-metric multidimensional scaling (NMS) was used. NMS is an ordination technique which minimises stress between the ordination and the multidimensional dissimilarity matrices. The technique is based on rank distances which has many advantages over ordination techniques based on eigen values, since the latter typically assumes multivariate normality which is often not the case with ecological data (McCune and Grace 2002). NMS was used with an overlay of factor 'Wetland age' with trophic status vectors (TP and chlorophyll-a) to investigate dissimilarity between phytoplankton community compositions and water quality in the two created wetlands over the 64 month period. The trophic status vectors allow for correlations with the ordination axes to be identified. All multivariate analyses were performed using PC-ORD (version 5).

RESULTS

WATER CHEMISTRY VARIABLES

Water chemistry data for April 2006-September 2008 presented in Table 2 shows that PPR 2, PPR 4 and SR 1 were alkaline wetlands while PPR 3 was mildly acidic. All four wetlands were oxygenated (mean $DO > 8mg\ L^{-1}$). Mean water temperatures ranged from 12.1°C to 13.3°C. PPR 3 and SR 1 recorded the highest mean turbidities, while PPR 4 was the least turbid. Comparing the mean TP concentrations in the created wetlands with the OECD (1982) lake classification scheme, PPR 2 was eutrophic ($> 35\mu g\ l^{-1}$) while the other three wetlands were mesotrophic ($10–35\mu g\ l^{-1}$) (Table 2 and Fig. 1). Mean SRP concentrations were broadly similar for all four wetlands, ranging from $10.53\mu g\ l^{-1}$ in SR 1 to $11.47\mu g\ l^{-1}$ in PPR 2. Nitrate was highest in PPR 4 (Table 2).

PHYTOPLANKTON COMMUNITY CHANGES

Mean phytoplankton biomass, measured as chlorophyll-a, was highest in PPR 2 ($9.07 \pm 6.43ug\ l^{-1}$) and lowest in PPR 4 ($5.02 \pm 5.61ug\ l^{-1}$) (Fig. 2) between April 2006 and September 2008. Referring to the OECD (1982) lake classification scheme, PPR 2 and PPR 3 were eutrophic while PPR 4 and SR 1 were mesotrophic on the basis of these chlorophyll-a levels (Figs 1 and 2). Species richness (total counts of algal taxa) was higher in the PPR wetlands (PPR 2–4) than in the SR 1 wetland. The group with the highest number of species in all four wetlands were the green algae (Chlorophyta), with 28, 27, 22 and 21 species recorded within PPR 2, PPR 3, PPR 4 and SR 1, respectively. The green algae were followed by diatoms (Bacillariophyta), blue-green algae (Cyanophyta) and Euglenophytes in the PPR wetlands (PPR 2, 3 and 4) and by dinoflagellates (Pyrrophyta) and Euglenophytes in SR 1. Total abundance (total counts of algal taxa) was also higher in the PPR wetlands, in particular PPR 3, compared to the simple rewetted wetland. Green algae were the most abundant group within all three PPR wetlands followed by blue-green algae, Euglenophytes and dinoflagellates in PPR 2 and Euglenophytes and blue-green algae in PPR 3 and PPR 4. In contrast blue-green algae, dinoflagellates and Euglenophytes were the most abundant groups in SR 1.

PHYTOPLANKTON SPECIES AS INDICATORS OF WATER QUALITY AND TROPHIC STATUS

The trophic status of the created wetlands was assessed using the OECD (1982) lake classification scheme. PPR 2, PPR 3, PPR 4 and SR 1 were classified as eutrophic, mesotrophic-eutrophic, mesotrophic and mesotrophic-eutrophic, respectively (Fig. 1). Eutrophic indicates high levels of enrichment (TP: $35–100\mu g\ l^{-1}$, Chl-a: $8-25\mu g\ l^{-1}$), mesotrophic indicates a medium level of enrichment (TP: $10–35\mu g\ l^{-1}$, Chl-a: $3–8\mu g\ l^{-1}$) and mesotrophic-eutrophic indicates an intermediate stage where the wetlands are moderately enriched (Vollenweider and Kerekes 1982). ISA assessed the preferential phytoplankton species within wetlands PPR 2, PPR 3, PPR 4 and SR 1. Overall, seven, nine, ten and three phytoplankton species were significantly preferential to PPR 2, PPR 3, PPR 4 and SR 1, respectively (Table 3). For PPR 2, three

Table 2—Chemical variables (mean and standard deviation) recorded for PPR 2, PPR 3, PPR 4 and SR 1 between April 2006–September 2008. Chemical ranges for all variables are given in brackets.

	PPR 2	*PPR 3*	*PPR 4*	*SR 1*
PH	7.8 ± 0.7 (6.2–9.6)	6.8 ± 1.9 (2.3–9.3)	8.0 ± 0.7 (5.0–9.2)	7.1 ± 0.8 (5.2–9.3)
Dissolved Oxygen mg L^{-1}	8.80 ± 5.68 (3.12–19.17)	9.64 ± 6.50 (2.37–39.60)	11.12 ± 3.88 (4.46–21.30)	9.30 ± 2.52 (5.24–16.30)
Temperature °C	13.3 ± 5.6 (5.5–21.6)	12.2 ± 5.3 (4.5–21.8)	12.1 ± 5.4 (3.8–22.6)	12.6 ± 5.6 (4.2–23.8)
Turbidity NTU	2.4 ± 1.8 (0.1–10.2)	4.3 ± 2.6 (1.2–13.9)	1.7 ± 1.1 (0.1–5.6)	4.9 ± 4.7 (0.3–24.6)
Total phosphorus µg L^{-1}	38.63 ± 25.29 (10–130)	33.94 ± 16.65 (10–76)	25.95 ± 12.62 (10–64)	34.21 ± 51.55 (10–296)
Soluble reactive phosphorus µg L^{-1}	11.47 ± 4.15 (10–27)	11.03 ± 2.9 (10–25)	10.97 ± 3.04 (10–28)	10.53 ± 1.36 (10–16)
Nitrate µg L^{-1}	1610 ± 3850 (440–16540)	640 ± 640 (440–3950)	8510 ± 10240 (440–38360)	480 ± 110 (440–940)

PPR, Partial peat removal; SR, Simple rewetting.

of the seven preferential phytoplankton species *Ankistrodesmus spiralis*, *Chlamydomonas* spp (both Chlorophytes) and *Navicula gregaria* (Bacillariophyta) are indicative of eutrophic water quality. PPR 3, which was mesotrophic-eutrophic in water quality, recorded two mesotrophic species *Chlorella* spp. and *Pediastrum tetras* (both Chlorophytes) and three eutrophic species *Aphanocapsa holsatica* (Cyanophyta), *Euglena acus* (Euglenophyta) and *Monoraphidium* spp (Chlorophyta). For PPR 4, five of the ten preferential phytoplankton species *Euglena proxima*, *Phacus caudatus*, *P. longicauda* (all Euglenophytes), *Fragilaria vaucheriae* (Bacillariophyta) and *Spirogyra* spp (Chlorophyta) were indicative of mesotrophic-eutrophic water quality. For SR 1, two of the three preferential species *Cosmarium depressum* and *Staurodesmus indentatus* (both Chlorophytes) were indicative of mesotrophic-eutrophic water quality (Table 3).

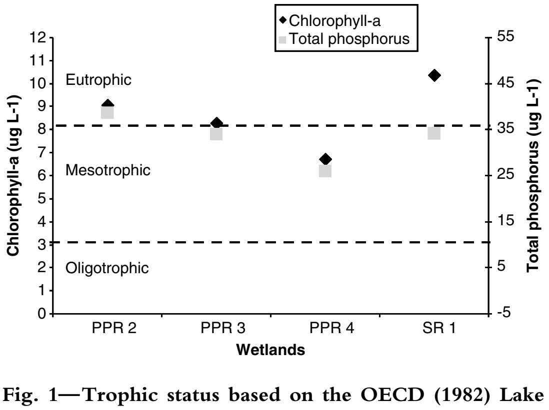

Fig. 1—Trophic status based on the OECD (1982) Lake Classification Scheme of the four created wetlands (PPR 2, PPR 3, PPR 4 and SR 1) between April 2006 and September 2008.

LONG TERM CHANGES FOR PPR 2 AND SR 1

The NMS ordination revealed a 2-dimensional solution for the 64 month dataset (Fig. 3) with axis 1 accounting for 15.2% of the variation in species matrix and axis 2 accounting for 21.5%. Together the ordination accounts for 36.6% of the variation in the original species dissimilarity matrix with an orthogonality of 99.8%. The ordination revealed that PPR 2 (11–13 years post-wetland creation) was grouped on the top left of axis 2 while 4 years later, it was grouped on the bottom left and right of axis 2. A similar trend can be seen for SR 1 which 1–3 years post-wetland creation was grouped predominantly on the top right of axis 2 and 4 years later was grouped on the bottom left and right of axis 2. Total abundance data (total

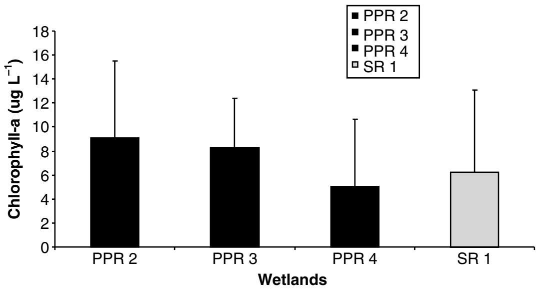

Fig. 2—Chlorophyll-a in the four created wetlands between April 2006 and September 2008. Values shown are mean, with error bars showing the standard deviation.

Table 3—Indicator species analysis (ISA) for the four created wetlands (PPR 2, PPR 3, PPR 4 and SR 1) investigated under grouping variable "Wetland". *IV* = Indicator value with *P* = significant *P*-value. The following letters denote their corresponding taxonomic groups: C = Chlorophyta, Cy = Cyanophyta, E = Euglenophyta and B = Bacillariophyta.

	Wetland					
	Maximum group	*Total abundance in maximum group*	*Proportion of total abundance in maximum group (%)*	*IV*	*P*	*Trophic status*
Ankistrodesmus spiralis (C)	PPR 2	249,519	26	60.5	0.0004	Eutrophic[a,b]
Chlamydomonas spp. (C)	PPR 2	23,107	2	33.3	0.0108	Eutrophic[c,d]
Coelosphaerium kuetzingianum (Cy)	PPR 2	44,510	5	59.2	0.0010	Mesotrophic[d]
Cymbella kappii (C)	PPR 2	8	0	21.5	0.0028	–
Merismopedia glauca (Cy)	PPR 2	2,790	0	63.1	0.0028	Mesotrophic[c,d,e]
Navicula gregaria (B)	PPR 2	5	0	15.4	0.0126	Eutrophic[f]
Sphaerobotrys fluviatilis (C)	PPR 2	18,278	2	51.8	0.0002	–
Aphanocapsa holsatica (Cy)	PPR 3	36,010	2	40.7	0.0040	Eutrophic[e]
Chlorella spp. (C)	PPR 3	383,802	19	54.0	0.0002	Mesotrophic[a,c,e]
Chroococcus minutus (Cy)	PPR 3	215,187	11	40.5	0.0334	–
Crucigenia tetrapedia (C)	PPR 3	131,581	7	92.6	0.0002	–
Euglena acus (E)	PPR 3	5,769	0	37.0	0.0034	Eutrophic[c,d,e]
Monoraphidium spp. (C)	PPR 3	404,285	20	57.2	0.0128	Eutrophic[a,e]
Pediastrum tetras (C)	PPR 3	10,066	0	93.4	0.0002	Mesotrophic[a,d,e]
Staurastrum cingulum (C)	PPR 3	12	0	23.2	0.0042	–
Tetraedron muticum (C)	PPR 3	1	0	82.9	0.0002	–
Carteria spp. (C)	PPR 4	7	0	14.0	0.0402	–
Coelastrum microporum (C)	PPR 4	1,810	0	62.0	0.0148	–
Euglena proxima (E)	PPR 4	2	0	14.8	0.0138	Meso-eu trophic[d,e]
Fragilaria vaucheriae (B)	PPR 4	6	0	13.2	0.0410	Meso-eu trophic[f]
Golenkinia radiate (C)	PPR 4	611	0	22.0	0.0176	–
Phacus caudatus (E)	PPR 4	239,790	34	45.2	0.0462	Meso-eu trophic[c,d]
P. longicauda (E)	PPR 4	4,893	1	65.1	0.0002	Meso-eu trophic[c,d]
Spirogyra spp. (C)	PPR 4	4	0	14.8	0.0150	Meso-eu trophic[a,c,d]
Staurastrum cingulum var. obesum (C)	PPR 4	816	0	38.0	0.0086	–
Staurastrum gracile (C)	PPR 4	12	0	28.1	0.0004	–
Cosmarium depressum (C)	SR 1	9,092	8	43.1	0.0068	Meso-eu trophic[d]
Staurodesmus indentatus (C)	SR 1	5	0	18.5	0.0020	Meso-eu trophic[d]
Xanthidium octocorne (C)	SR 1	13	0	38.1	0.0002	–

[a] Bellinger (1992)
[b] Biggs & Kilny (2000)
[c] APHA (1998)
[d] John et al. (2002)
[e] Reynolds et al. (2002)
[f] Kelly (2000)

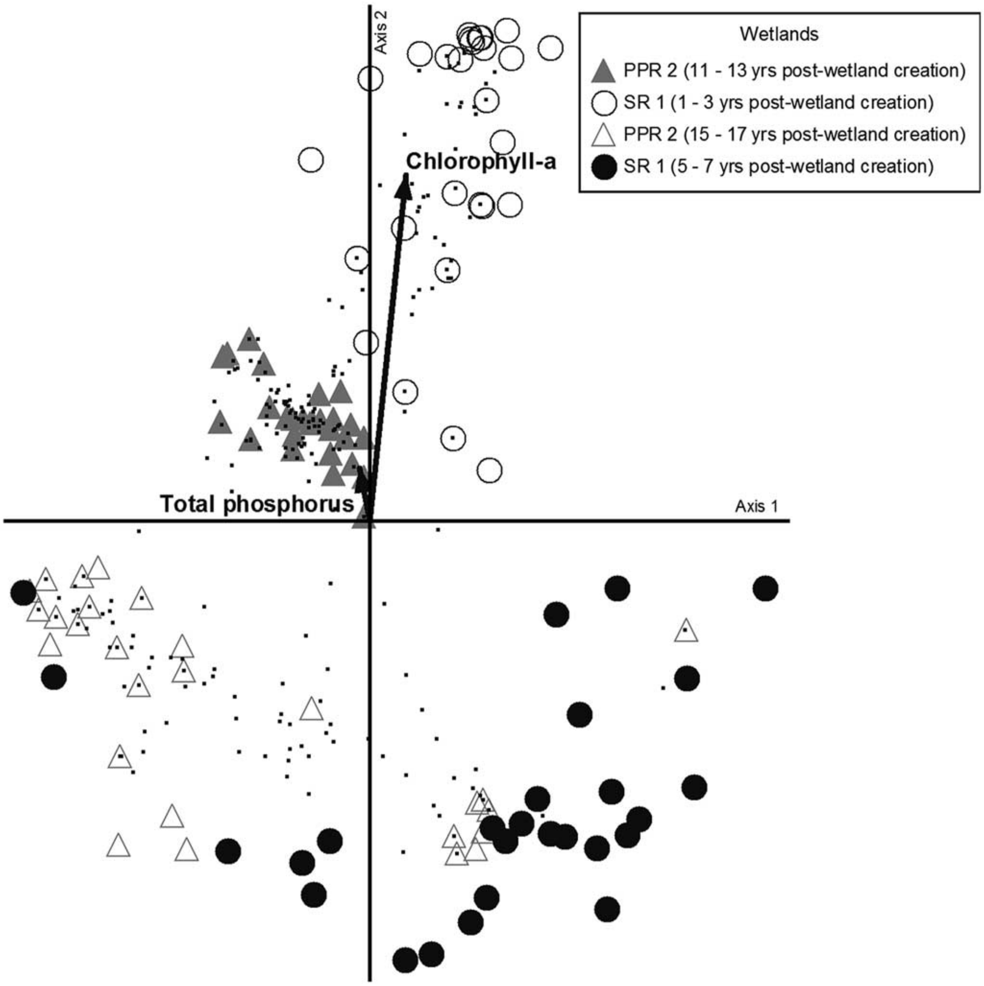

Fig. 3—Non-metric multidimensional scaling ordination for PPR 2 and SR 1 during sampling periods 2002–2004 (11–13 years and 1–3 years post-wetland creation, respectively) and 2006–2008 (15–17 years and 5–7 years post-wetland creation, respectively) in species-space. Small black squares represent the phytoplankton species.

counts of algal taxa) from the 64 month dataset revealed a successional shift in the phytoplankton composition of both PPR 2 and SR 1 between April 2002 and September 2008 (Fig. 4). For PPR 2 green algae (Chlorophyta) were prominent in the phytoplankton community throughout the 64 months with blue-green algae (Cyanophyta), dinoflagellates (Pyrrophyta) and Euglenophytes becoming more abundant between 2006 and 2008 (Fig. 4). For SR 1 green algae were the dominant group between 2002 and 2004. However, between 2006 and 2008 green algae abundance reduced dramatically, with lower numbers of blue-green algae and Euglenophytes also recorded (Fig. 4).

DISCUSSION

Phytoplankton community analysis and ISA indicated the influence that elevated phosphorus levels had in shaping the phytoplankton community composition in the four created wetlands. The two wetland types, PPR and SR, exhibited differences in algal species composition and species richness and abundance. The low species richness and total abundances within SR 1, in addition to a subdominance of dinoflagellates (Pyrrophyta) and the identification through ISA of preferential desmid species (Chlorophyta) *Cosmarium depressum*, *Staurodesmus indentatus* and *Xanthidium octocorne*, likely reflects the presence of ombrotrophic peats which underlie SR 1, as desmids have a well-documented affinity to peaty humic waters (Lind and Brook 1980; Hehmann *et al.* 2001; John *et al.* 2002). The high species richness and abundances recorded in the PPR wetlands and dominance of green algae (Chlorophyta) probably reflects the presence of minerotrophic influences (Nováková 2007), resulting from the partial exposure of the subpeat mineral subsoils consisting of blue-silty

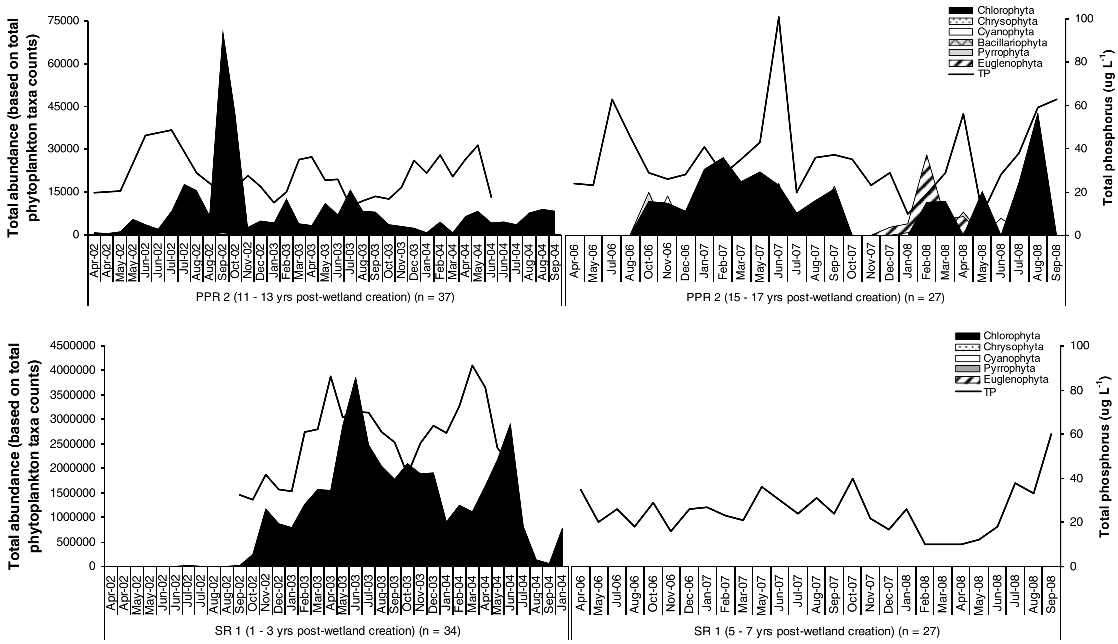

Fig. 4—Changes in phytoplankton abundance and total phosphorus in PPR 2 and SR 1 between 2002–2004 (11–13 years and 1–3 years post-wetland creation, respectively) and 2006–2008 (15–17 years and 5–7 years post-wetland creation, respectively). A minimum of two samples per month were taken throughout the 64 month sampling period. These monthly samples were averaged to allow for comparison between the two datasets 2001–2004 and 2006–2008.

clay, gravel and marl. Overall, the high abundances of blue-green algae (Cyanophyta) (notably *Aphanocapsa holsatica*) and Euglenophytes (*Euglena acus*, *E. proxima*, *Phacus caudatus*, *P. longicauda*) in the four created wetlands can be considered as indicative of high ambient phosphorus concentrations (Findley *et al.* 1999; Reynolds *et al.* 2002). High phosphorus in surface waters is a problem throughout the River Brosna catchment, attributed mainly to diffuse agricultural runoff (ShIRB 2005). High TP and chlorophyll-*a* in PPR 2, PPR 3 and SR 1 corresponded with these wetlands being eutrophic, meso-eutrophic and meso-eutrophic, respectively. TP and chlorophyll-a were much lower in PPR 4, corresponding to its mesotrophic status waters. In addition to catchment landuses, internal nutrient release caused by the rewetting of dried peat deposits may have contributed to some degree to the high phosphorus levels within the created wetlands. Studies by Sallantaus (2004) and Kieckbusch and Schrautzer (2007) found that the rewetting of well-drained peat deposits can result in diffusion and suspension of nutrients due to increased aeration and higher pH levels (compared to those of the original peatland), which allows more aerobic and nitrifying bacteria to grow and/or more organic nutrients to be mineralised. Furthermore, phosphorus may be indirectly released due to the biological mobilisation of phosphorus via lower redox conditions. The seasonal die-back and decomposition of littoral vegetation, particularly *Phragmites australis* and *Typha latifolia* within the PPR wetlands, may also have increased phosphorus levels through internal nutrient cycling (Landers 1982; Stephen *et al.* 1997).

Changes in phytoplankton biomass and composition in PPR 2 and SR 1 between 2002 and 2008 suggest that maturity will be a major factor influencing the phytoplankton communities in the created wetlands. NMS and total abundance analysis for both PPR 2 and SR 1 revealed that significant changes in their phytoplankton communities occurred between 2002–2004 and 2006–2008. PPR 2 showed an increase in subdominant taxa such as blue-green algae (Cyanophyta), dinoflagellates (Pyrrophyta) and Euglenophytes between 2006 and 2008. The increased abundance of blue-green algae and Euglenophytes in particular corresponded with an increase in TP between 2006 and 2008 and consequentially led to a deterioration in trophic status from mesotrophic in 2002–2004 (Higgins and Colleran 2006) to eutrophic in 2006–2008. The observed changes in phytoplankton community composition are consistent with the findings of Findley *et al.* (1999) for other freshwaters with elevated phosphorus. The findings for PPR 2 indicate that phosphorus is a key factor in determining the phytoplankton community composition and biomass in that wetland, even 15–17 years post-flooding. For future wetlands created using the PPR approach, estimating the potential for internal phosphorus release due to peat rewetting would be beneficial prior to flooding. In contrast to PPR 2, the longer term phytoplankton community analysis for SR 1 revealed a complete community shift in dominance from green algae (Chlorophyta) (2002–2004) to blue-green algae (Cyanophyta) and dinoflagellates (Pyrrophyta) (2006–2008). In the early years following the creation of SR 1 (2002–2004), blooms of *Chlorella* spp and *Cosmarium pygmaeum* (both small unicellular Chlorophytes) were observed in the wetland, indicating hyper-eutrophic conditions (Higgins and Colleran 2006). Blooms were associated with high phosphorus concentrations ($> 35\text{ug l}^{-1}$), with phosphate fertiliser runoff from nearby conifer plantations being the most likely source (Higgins *et al.* 2006). It is equally possible that the initial rewetting of the peat deposits may have led to large quantities of phosphorus being released, as has been recorded elsewhere (Sallantaus 2004; Kieckbusch and Schrautzer 2007). Although phosphorus remained high in SR 1, no blooms were recorded between 2006 and 2008. The longer term data suggest that the SR wetlands are most at risk of developing poor water quality and phytoplankton blooms in the early years following flooding, with phytoplankton biomass subsequently stabilising. Sallantaus (2004) reported a decline in nutrient availability in created wetlands on cutaway peatlands after 8 years. Current findings for SR 1 suggest that, as the SR wetland matures (> 10years), the release of nutrients from the rewetted peat deposits appears to decline, in turn resulting in improved water quality in the SR wetland and the development of a favourable and diverse phytoplankton flora.

CONCLUSION

The phytoplankton communities in the three PPR wetlands were dominated by green algae (Chlorophyta), indicative of peatland habitats influenced by mineral groundwater or sediments (Nováková 2007). In contrast dinoflagellates (Pyrrophyta) were the subdominant group in SR 1, similar to the phytoplankton flora of other rewetted cutaway peatlands elsewhere (Hehmann *et al.* 2001; Krivograd and Vrhovsek 2003; Muylaert *et al.* 2003). The high abundances of blue-green algae (Cyanophyta) and Euglenophytes were characteristic of phosphorus rich wetlands. High phosphorus appears to be the main pressure threatening the development of created wetlands of high water quality and GEP. Longer term data indicate that the created wetlands have a propensity to develop phytoplankton blooms in the early years following flooding, in response to elevated phosphorus concentrations. Improvements in water quality are likely to occur as the created wetlands mature.

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