Diatom assemblages and their associated environmental factors in upland peat forest rivers

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ABSTRACT

The acid-sensitive upland blanket peat catchments are important habitats for diatom assemblages. In this study, the distribution patterns of epilithic diatom assemblages in the streams of upland forested blanket peat in north-west of Ireland are presented and the associated environmental factors are discussed. A total of 43 sites in 16 rivers were sampled. Multivariate analysis highlighted alkalinity and conductivity as the main physicochemical drivers of riverine diatom assemblages. Contrary to expectations nutrients were not found to have a major influence on the diatoms. A major flood event had a significant impact on the diatom assemblage, and one year after the event, long stalked diatom taxa were still largely absent from the river, indicating that floods could be one of the important factors affecting diatom assemblages. However, the ecological status of the affected sites, as determined by the EQR, did not alter from before to after the flood. The results of this study could be applied to similar acid-sensitive upland peat forest catchments and used as the benchmark to assess the impact of forest operations and peat degradation on ecological status.

Keywords: Diatom assemblage; Blanket peat forest; Nutrients; Low alkalinity; Acid-sensitive; Flood; Water framework directive (WFD)

1. INTRODUCTIONS

The Water Framework Directive (WFD) requires EU Member States to achieve 'good ecological status' for all water bodies by 2015 (European Union, 2000). Assessing, maintaining and restoring good ecological status of aquatic ecosystems has become a priority for river basin management and water protection in Europe (Eloranta and Soininen, 2002; Kelly and Wilson, 2004; Leira and Sabater, 2005; Kelly et al., 2008; Urrea and Sabater, 2009). Diatoms have been used successfully as indicators of the ecological quality of aquatic ecosystems worldwide (Kelly et al., 1998; Leira and Sabater, 2005; Hering et al., 2006; Chen et al., 2008). This is due to their 1) being well established in the food web, 2) responding rapidly to the majority of physical, chemical and biological changes in water bodies and 3) having a one-stage life cycle and very short generation time (Stevenson and Yan, 1999). Many diatom indices such as the Trophic Diatom Index (TDI) in the UK (Kelly and Whitton, 1995) and Germany (Coring et al*.,* 1999); the Trophienindex (TI) in Austria (Rott et al*.,* 1999) and the Indice Biologique Diatomique (IBD) in France have been developed for the assessment of trophic conditions. However, to meet the requirements of the WFD, trophic indices must be compared to reference conditions. Ecological quality ratios (EQR's) have recently been derived for diatom indices, specifically the TDI, to allow the observed TDI to be compared with an expected reference index value (Kelly et al., 2006). For the EQR to be considered reliable and to meet WFD requirements, representative reference conditions need to be defined for a complete range of ecoregions and habitats. However, acid-sensitive and low alkalinity sites are underrepresented in the EQR (Kelly-Quinn et al., 2004; Kelly et al., 2006). The importance of characterising diatom assemblage in low alkalinity sites has been highlighted (Camburn and Charles, 2000; Tolotti, 2001; Cantonati and Lange-Bertalot, 2011).

Upland peat catchments in northwestern Europe are characterised as acid-sensitive areas. These areas contain the headwaters of rivers, many of which contain Red List species (e.g. salmonids and freshwater pearl mussels) which make them important biodiversity refuges. The main pressures to the rivers in these acid-sensitive areas include forestry operations and peat degradation. Since the 1950s, large areas of upland blanket peat have been afforested in northwestern European countries. Risk assessments on receiving waters have shown that forest operations result in increased phosphorus (P) release (Nisbet, 2001; Cummins and Farrell, 2003;

Nieminen, 2003; Rodgers et al., 2010). Acidification of surface waters draining forested catchments is also a concern (Jenkins et al., 1990; Ormerod et al., 1991; and Allott et al., 1997). Peat degradation and projected climate change lead to increased dissolved organic carbon (DOC) export, decreased pH in receiving waters and increased flood events (Fealy et al., 2010; Cantonati and Lange-Bertalot, 2011). In view of these multiple and increasing pressures, it is crucial to have a thorough understanding of the diatom assemblages which will be used in assessing ecological change in the rivers draining the acid-sensitive upland peat catchments. The main purpose of this study therefore is to characterise the diatom assemblages of these rivers and ascertain the environmental drivers of assemblage composition. To the best of our knowledge, there is no research focused on the diatom assemblages and their associated environmental factors in oligotrophic rivers draining upland forested blanket peat.

The rivers in upland blanket peat catchments are usually spate, prone to flash flooding and exhibit a quick response time to precipitation (Müller, 2000). The diatom assemblages are therefore likely to contain taxa well adapted to high flows and frequent changes in water level. It is unknown, however, how these assemblages respond to extreme flood events and the implications of flood events on the ecological status of sites. During the sampling period of this study, an extreme flood event occurred in one of our study rivers, where 52 mm of rain fell in two hours (Dalton et al., 2010). Such events are considered to occur once in 250 years (Fealy et al., 2010). This provided a fortuitous opportunity to assess the impact of an extreme flood on diatom assemblages.

2. MATERIALS AND METHODS

2.1 Study sites and characterisation

This study was based in three adjoining catchments, located in Mayo in the north west of Ireland (Figure 1). Most of the catchments are covered in blanket peat and overlie quartzite and schist bedrock. The catchment systems are described as acid oligotrophic and have a low buffering capacity (Byrne et al., 2004). The main land uses are forestry and sheep grazing and the catchments receive an average precipitation of over 2,000 mm per year (Dalton et al., 2010). Commercial coniferous plantations were planted in blocks or coupes starting in the 1950s

(O'Driscoll et al., 2011). A total of 43 sites in 16 rivers were selected for this study, 36 located in forested areas and the other 7 sites in unforested peatland.

Diatoms were sampled in June 2009. Water samples were taken at each sampling site and anaylsed on the same day for alkalinity and colour using standard procedures (APHA, 1989). Phosphorus, nitrate-nitrogen and ammonia were measured using a Konelab 20 Analyser (Konelab Ltd., Finland). Water temperature, pH and conductivity were recorded in the field, and altitude, catchment area, stream order (Strahler, 1957), and Shreve stream order (Shreve, 1966) were extracted from GIS maps of the areas. All the sites were sampled in baseflow conditions and so diatoms and environmental variables are representative of conditions at base flow. A subset of samples was taken the following year to examine the impact of an extreme flood event on diatom assemblages in one of the study rivers. 52 mm of rain falling in two hours, an event considered to occur once in 250 years (Fealy et al., 2010). Twelve samples were taken in the Srahrevagh and Glennamong rivers in summer 2010, one year after the flood event. The Glennamong is in a neighbouring sub-catchment and was un-impacted by the flood event and so is treated as a control.

2.2 Diatom sampling, preparation and identification

Diatoms were collected and prepared in accordance with Kelly et al. (1998). Taxa were identified to species level where possible and counted at x 1,000 magnification using an Olympus BX-51 microscope equipped with a x 100 phase contrast objective (numerical aperture: 1.25). At least 300 valves were identified and counted per slide (Krammer and Lange-Bertalot, 1986, 1997, 2000, and 2004). Certain taxa were difficult to identify and the approaches adopted for these species were as follows. *Achnanthidium minutissimum* varieties were split into types based on Potapova and Hamilton (2007). Three types were found in these samples: the 'capitate' morph which corresponds to 'type a' in these samples; 'linear' corresponds to 'type b' and 'narrow-linear' corresponding to 'type c'. These three *Achnanthidium* groups were largely present in girdle view and so were enumerated separately in girdle view and then divided between the three morphological groups based in proportion to their relative abundance. *Eunotia exigua*, also present in high numbers in girdle view, was difficult to distinguish from *Eunotia tenella* and *Eunotia meisteri* and so the three were combined and considered as *Eunotia exigua* complex. *Gomphonema parvulum* has been described with a number of varieties and attributed environmental preferences, however populations in these samples had high morphological variability, and so have been termed *Gomphonema parvulum* complex.

2.3 Data analysis and statistics

Diatom species richness (***S***) was determined from the number of species counted on each slide. The Shannon-Weiner index (***H'***), which measures the proportional abundances of species in a community was calculated (Shannon and Weaver, 1963). In order to relate the diatom community to water quality, the revised Trophic Diatom Index (TDI), which quantifies the impact of nutrients on diatom assemblages, was calculated for each site (Kelly et al., 2008). The scores range from 0 (very low nutrients) to 100 (very high nutrients). The TDI was compared with reference assemblage characteristics and the EQR was calculated taking into account the relationship between nutrient gradients and diatom assemblages with season and alkalinity (Kelly et al., 2006). An EQR close to 1 indicates an un-impacted diatom assemblage, whereas a value close to 0 indicates a severe impact (Kelly et al., 2006).

2.4 Relationship of diatom assemblages with environmental variables

Diatom data were first analysed with detrended correspondence analysis (DCA) (Hill and Gauch, 1980) to determine the gradient length. The length of the gradient was greater than 2 standard deviation units (4.641), and so unimodal ordination techniques were chosen (ter Braak, 1987). Correspondence analysis (CA), was used to determine the major patterns of variation in species composition data following which canonical correspondence analysis (CCA), was used to relate diatom assemblages to all predictor environmental variables (ter Braak and Verdonschot, 1995). Data exploration highlighted significant correlation between pH and alkalinity and so pH was dropped from further analyses. To reduce further the environmental variables to those correlated significantly with the derived axes, step-wise forward selection and Monte Carlo permutation tests were used. Only those taxa that were observed in more than 5% of the samples were included in analyses of taxa abundances to minimize the influence of rare taxa. Taxa abundance was square root transformed in all analyses to reduce the effect of highly variable population densities on ordination scores. Environmental variables were appropriately transformed before analysis to reduce skewed distributions and all ordinations were performed using CANOCO version 4.1 (ter Braak and Šmilauer, 1998).

2.5 Impact of extreme flood event on diatom assemblages

To assess the impact of the extreme flood on diatom assemblages, similar analysis as that for determining the relationship of diatom assemblages with environmental variables was adapted. The Srahrevagh and Glennamong in 2009 and 2010 were used as environmental variables corresponding to before and after the flood respectively. Taxa abundance was square root transformed to reduce the effect of highly variable population densities on ordination scores.

3. RESULTS

3.1 Environmental characteristics of the sites

Nutrient concentrations in the study sites were very low, with the maximum PO_4-P, NH_4-N and NO_3-N concentrations of 6.27 µg L^{-1}, 122.12 µg L^{-1} and 97.02 µg L^{-1}, respectively (Table 1). Based on the nutrient concentrations all the study sites can be described as oligotrophic. Conductivities of the sites were between 67 µS cm^{-1} to 251 µS cm^{-1}(Table 1). pH values of the sites ranged from 3.55 to 8.49 (Table 1). Alkalinity in the study sites varied between -2.7 mg L^{-1} $CaCO_3$ and 68.8 mg L^{-1} $CaCO_3$ (Table 1).

3.2 Diatom species composition

Of the 57 taxa found, 52 taxa were observed in more than 5 % of the samples. The five most abundant taxa were *Achnanthes oblongella*, *Fragilaria capucina* var. *gracilis, Eunotia exigua, Tabellaria flocculosa,* and *Achnanthidium minutissimum* Type A, present in 77 %, 60 %, 65 %, 60 %, and 67 % of the sites, respectively. Species richness ranged from a minimum of 5 to a maximum of 25. The Shannon Weiner diversity index ranged from 0.40 to 2.79. TDI values ranged from 1.7 to 46.7. There was no correlation between TDI and P (PO_4 - P µg L^{-1}) of which all values are less than 10 µg L^{-1} (Spearman rho = -0.049, p = 0.75, d.f. = 41). There was a significant correlation between alkalinity and TDI (Spearman rho = 0.396, $p < 0.05$, d.f. = 41). EQR values ranged from 0.65 to 1.12, with a median value of 1.

CA ordination results showed that 20.2 % of diatom assemblage variance was explained on axis 1, with a further 12 % explained on axis 2 (Figure 2). There are two clear groupings from this graph, the first in the top left hand side quadrat and the second in the bottom right hand side quadrat which cluster along a gradient. Taxa situated on the left side of diagram included *Achnanthes oblongella*, *Fragilaria capucina* var. *gracilis* and *Gomphonema parvulum* complex. Taxa situated on the right side included the *Eunotia exigua* complex, *Pinnularia appendiculata*, *Eunotia paludosa* and *Tabellaria flocculosa*. Taxa with higher values on axis 2 included *Eunotia paludosa* and *Eunotia microcephala*. Taxa with maximum abundances and lowest values on axis 2 included the *Eunotia exigua* complex and *Tabellaria flocculosa*.

3.3 Important environmental variables

The first two axes explained a significant proportion of variance in the diatom taxa data ($P < 0.01$). CCA with forward selection identified all variables except colour to be significant ($P < 0.05$) accounting for significant portions (60 %) of the total variance in diatom species composition (Table 2). Alkalinity explained the largest portion (30 %) of the total unconstrained variance. CCA ordination plots identified three groupings of sites (Figure 3a, b). The first one comprised sites with high conductivity and alkalinity and featured *Reimeria sinuata*, *Gomphonema truncatum*, *Diatoma tenue*, *Cocconeis placentula* and *Ctenophora pulchella*. The second group comprised sites with high conductivity, low alkalinity, and first order streams with small upstream catchment area. These sites were dominated by *Eunotia paludosa*, *Pinnularia appendiculata* and *Eunotia microcephala*. The third group comprised sites with low conductivity, low alkalinity and higher stream order and upstream catchment area. *Brachysira neoexilis*, *Tabellaria flocculosa*, *Eunotia exigua* complex and *Eunotia implicata* were the common taxa observed at these sites.

3.4 Impact of extreme flood on diatom assemblages

Table 3 shows the representative diatom taxa in the Glennamong and Srahrevagh rivers a week before and one year after the extreme flood event. The flood altered the diatom assemblages in the Srahrevagh. The Glennamong, which was not affected by the flood, had five out of seven of the most common diatom species occurring in 2009 and 2010. Only one common species

Fragilaria capucina var. gracilis found in 2009 was replaced by *Eunotia incisa* and *Pinnularia appendiculata* in 2010. However, in Srahrevagh, 4 of the 6 common species found in 2009 were replaced in 2010 (Table 3). CCA ordination results showed that the environmental variables explain 29 % of the species data (Figure 4). Axis 1 separates the Glennamong and Srahrevagh rivers and explains 65.4 % of the variation. Axis 2 corresponds to the year 2009 and 2010 and a significantly larger variation can be seen in the impacted Srahrevagh river when compared to the Glennamong. This was owing to several species which were present in 2009 such as *Gomphonema truncatum*, *Gomphonema acuminatum*, *Epithemia adnata*, *Hannaea arcus* and *Ctenophora pulchella* and disappear entirely from the samples taken 12 months later in 2010. All sites in the impacted and non impacted rivers had an EQR between 0.8 and 1.0.

4. DISCUSSION

4.1 Low alkalinity gradient

Multivariate analysis indicated that variables driving the distribution of diatom assemblages in the study catchments were associated with physiography i.e., alkalinity, ionic concentration, stream order, upstream catchment area and Shreve stream order rather than nutrients. The geology of the western side of the study catchments is mostly comprised of quartzite and schist with the Glennamong, Altahoney and Maumaratta rivers being well represented by taxa with a preference for low pH such as the *Eunotia* genus. Representative diatoms include Red List species such as *Eunotia implicata*, *Eunotia bilunaris* var. *mucophila*, *Eunotia paludosa* and *Eunotia rhomboidea* (Lange-Bertalot, 1996). Cantonati and Lange-Bertalot (2011) highlight the importance of the Eunotia group and suggest in the threatened naturally-acidic and low-alkalinity waters, *Eunotia* species might be play a fundamental role as indicators of ecological status. Even when the dominant geology is granite/ schist, the presence of small veins of buffering geology (dolomite and wacke) (Fealy et al., 2010) can considerably raise the alkalinity of receiving waters and hence cause a shift to more circumneutral assemblages. For example, *Gomphonema olivaceoides*, abundant in the Srahrevagh is known to have an ecological preference for upland low nutrient streams with calcareous geology. In stream longitudinal alkalinity gradients are represented by a shift from upper sites abundant in *Achnanthes oblongella* to sites further down the catchment with a more diverse spread of species such as *Gomphonema truncatum*, *Reimeria* *sinuata* and *Cocconeis placentula*. Therefore in peatland catchments the underlying geology is crucial in determining diatom assemblages.

Low alkalinity in rivers is closely correlated with episodic acid pulses and the presence of many pH tolerant diatom species indicates that acidification may be a main driver of assemblage composition. Anthropogenic acidification has been known to occur due to afforestation (Battarbee et al., 2010) and peat degradation and associated DOC leaching and increased pH (Monteith and Evans, 2005; Jennings et al., 2010). It is also possible that these assemblages represent naturally acidic conditions. However, while many diatom metrics exist to measure acidity (Van Dam and Mertens, 1994; Kwandrans, 2007; Andren and Jarlman, 2008) none consider the expected value of sites as required by the WFD. Nevertheless, characterisations of diatom assemblages in these acid sensitive waters will prove crucial in the future in determining acidification impacts.

4.2 Low nutrient concentrations

The rivers included in this study can all be defined as oligotrophic, as the annual phosphorus concentrations were less than 20 µg PO_4-P L^{-1}. 44 of the 57 diatom taxa found in the study sites are known to be nutrient sensitive (sensitivity values of 1 and 2, Kelly et al., 2005). Although the range of TDI values measured in this study includes some moderately high values (e.g. 40, 42.2, 46.7), the EQR which corrects for alkalinity was found to be close to 1 for all the sites, indicating a 'good' or 'high' ecological status. While the felling of forest sub-catchments in the study areas has been shown to increase the phosphorus and sediment loads in receiving waters (Rodgers et al., 2010), it appears that the ecological quality of the diatom assemblages has not been impacted. We can therefore support the characterisation of riverine diatoms in this area as oligotrophic and lacking any sign of anthropogenic nutrient enrichment from forestry activities. These sites therefore represent reference conditions with respect to nutrient status. However, this result should be treated with a certain amount of caution as work is still ongoing on the use of EQR's in Ireland, particularly in low alkalinity sites (i.e. < 6.8 mg L^{-1} $CaCO_3$ (B. Kennedy, EPA Ireland, pers. comm.).

4.3 Spate nature of rivers

It is highly likely that the lack of impact due to nutrient enrichment on the diatom assemblages is due to the quick flushing of nutrients through these spate rivers. The diatom assemblages of first order streams that are liable to flash flooding and receive high annual precipitation (> 2000 mm) have high abundances of *Achnanthes oblongella*. *Achnanthes oblongella* attaches to the substrate by its valve face and mucilage which is likely to give it protection and resilience to floodwaters. *Achnanthes oblongella* showed resilience even to the major flood experienced in the Srahrevagh, having a maximum abundance both before and after the flood in 2009 at the upper first order sites. However the long stalked species such as *Gomphonema truncatum*, loosely attached taxa such as *Epithemia adnata* and *Fragilaria capucina* var. *gracilis* which were abundant at the lower sites before the flood disappeared from samples taken in 2010. They were replaced by r-strategists with small cell size, low biomass and fast growth such as the *Achnanthidium* types (Biggs et al., 1998), the *Gomphonema parvulum* complex and *Reimeria sinuata*, indicating that episodic flood events can be an important structuring factor for diatom assemblages. In their study, Cambra and Gomà (1997) noticed a shift from well structured diatom communities with a high diversity index to less well structured, low diversity communities dominated by r-strategist species after a perturbation. Despite the substantial shift in assemblages, no change in ecological status in terms of nutrients was evident the year after the flood. This highlights the sturdiness of the EQR in determining the ecological status of upland rivers draining forested blanket peat. However these results are based on a subset of samples taken the year after flood. Due to the highly dynamic nature of these rivers single sampling provides a snapshot overview of ecological status. Kelly et al. (2006) recommends six replicates of samples should be taken over two to three years to eliminate annual, seasonal and spatial variation. Further study should examine the influence of spatial and temporal variation on the diatom assemblages of acid-sensitive upland blanket peat catchments.

5. CONCLUSIONS

This study has provided a characterisation of diatom assemblages in upland peatland rivers characteristic of the west of Ireland and related alkalinity and conductivity as the main physicochemical drivers of the diatom assemblages. This highlights the importance of the underlying geology in determining diatom assemblage composition. Multivariate analysis indicated that nutrient enrichment from forestry activities did not stand out as having a major influence on the diatom assemblages. Therefore these upland peatland rivers represent reference conditions with respect to nutrient status. Further work needs to be carried out to determine if the acidic nature of the sites is a response to anthropogenic impacts or natural acidity. Spatial gradients highlighted an upstream-downstream trend and future work should concentrate on how the spatial and temporal variation impacts the diatom assemblages in these spate rivers. The results of this study could be applied to similar upland peat forest catchments and used as the benchmark to assess the impact of ongoing forest harvesting on ecological status. The impact of the flood on diatom assemblage structure is evident at the lower sites; however, this had no bearing on the EQR status. Future work needs to be carried out to determine how long (if at all) it takes for these species to return.

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Table 1
Physical and chemical characteristics of the sites.

	Conductivity ($\mu S\ cm^{-1}$)	Alkalinity (mg l^{-1} $CaCO_3$)	PO_4-P ($\mu g\ L^{-1}$)	NH_4-N ($\mu g\ L^{-1}$)	NO_3 -N ($\mu g\ L^{-1}$)	pH	Colour (PtCo)	Temperature (°C)	Altitude (m)	Stream Order	Upstream Catchment Area (ha)	Shreve Index
max	251	68.8	6.3	122.1	97.0	8.49	283	20.4	341	4	1549	33
min	67	-2.7	3.1	6.5	0	3.55	38	11.8	20	1	10	1
mean	120	12.1	4.1	50.6	20.3	4.43	121	16.1	128	2	474	8
median	98	8.1	3.7	42.8	7.9	6.22	86	16.2	91	2	238	4
std dev	50.6	17.09	0.9	32.5	27.8	4.08	78.8	2.5	94.4	1	516.9	10

Table 2

Weighted correlation matrix showing the relationship between species axes and environmental variables (Figure 3 a and b). The environmental variables listed exerted significant ($P < 0.05$) and independent influences on algal distributions.

Variables	Axis 1	Axis 2	Axis 3	Axis 4
Conductivity (µS cm-1)	-0.24	0.83	-0.04	-0.14
Alkalinity (mg l-1 CaCO3)	-0.89	0.28	0.00	0.00
$PO^{4}_{-3}P$	0.10	0.10	0.22	0.31
NH+4-N	0.42	0.07	-0.05	-0.14
NO-3 -N	0.13	-0.20	-0.41	0.14
Temperature (°C)	-0.49	0.13	-0.34	0.09
Altitude (m)	0.21	0.01	-0.32	0.57
Stream Order	-0.35	-0.30	0.13	-0.39
Upstream Catchment Area (ha)	-0.08	-0.52	0.08	-0.50
Shreve Order	-0.21	-0.45	-0.02	-0.46
Percentage variance of species-environment relationship	34.20	19.80	11.60	8.10
Eigenvalues :	0.60	0.34	0.20	0.14

Table 3. The main diatom taxa in the Glennamong and Srahrevagh rivers a week before and one year after the extreme flood event

	Glennamong		Srahrevagh	
		% of the total abundance		% of the total abundance
	Main diatom species		Main diatom species	
2009	*Achnanthes oblongella*	18.8	*Achnanthes oblongella*	23.7
	Fragilaria capucina var. *gracilis*	18.7	*Fragilaria capucina* var. *gracilis*	11.4
	Tabellaria flocculosa	17.2	*Fragilaria capucina* var. *rumpens*	9.2
	Achnanthidium minutissimum type A	13.2	*Diatoma tenue*	5.7
	Gomphonema parvulum	11	*Epithemia adnata*	5.5
	Eunotia rhomboidea	5.4	*Synedra ulna*	5.5
2010	*Eunotia rhomboidea*	21.9	*Achnanthes oblongella*	19.8
	Tabellaria flocculosa	16.7	*Achnanthidium minutissimum* Type A	16.5
	Achnanthes oblongella	10.7	*Fragilaria capucina* var. *gracilis*	9.6
	Eunotia incisa	7.1	*Gomphonema parvulum*	8.1
	Pinnularia appendiculata	6.7	*Reimeria sinuata*	6.9
	Gomphonema parvulum Complex	6.7	*Cocconeis placentula*	6.6
	Achnanthidium minutissimum Type A	6.3	*Planothidium lanceolatum*	5.4

Appendix A
Taxa Codes

Taxa	Label
Achnanthes oblongella Østrup	ACHOB
Achnanthidium minutissimum type 1 * sensu Potapova et Hamilton	ACHMNA
Achnanthidium minutissimum type 2 * sensu Potapova et Hamilton	ACHMNB
Achnanthidium minutissimum type 3 * sensu Potapova et Hamilton	ACHMNC
Asterionella formosa Hassall	ASTRION
Brachysira neoexilis Lange-Bertalot	BNEOEXILIS
Cocconeis placentula Ehrenberg	COCCPLA
Ctenophora pulchella (Ralfs ex Kützing) Williams & Round	CTENOPUL
Cyclotella radiosa Kützing ex. de Brébisson	CYCRADI
Cymbella affinis Kützing	CAFFIN
Diatoma mesodon (Ehrenberg) Kützing	DIAMESO
Diatoma tenue Agardh	DIATEN
Diploneis elliptica (Kützing) Cleve	DIPELLIP
Encyonema gracile Ehrenberg	ENCYGR
Encyonema silesiacum (Bleisch in Rabenhorst) Mann in Round, Crawford & Mann	ENCYSIL
Epithemia adnata (Kützing) Rabenhorst	EPITADNA
Eunotia bilunaris var. *mucophila* Lange-Bertalot and Norpel	EBILMUCO
Eunotia exigua complex	EEXIGUA
Eunotia exigua (de Brébisson ex Kützing) Rabenhorst	
Eunotia tenella (Grunow in Van Heurck) Cleve	
Eunotia meisteri (Hustedt)	
Eunotia implicata Norpel, Lange-Bertalot & Alles	EIMPLICT
Eunotia incisa Smith ex Gregory	EINCISA
Eunotia microcephala Krasske ex Hustedt	EMICRO
Eunotia minor (Kützing) Grunow in Van Heurck	EMINOR
Eunotia paludosa Grunow	EPALUD
Eunotia rhomboidea Hustedt	ERHOMBO
Eunotia subarcuatoides Alles, Norpel, Lange-Bertalot	ESUBARC
Fragilaria capucina var. *gracilis* (Østrup) Hustedt	FRAGGRAC
Fragilaria capucina var. *rumpens* (Kützing) Lange-Bertalot	FRAGRUM
Frustulia rhomboides (Ehrenberg) De Toni	FRUSRHOM
Gomphonema acuminatum Ehrenberg	GACUMIN
Gomphonema clavatum Ehrenberg	GCLAVAT
Gomphonema gracile Ehrenberg	GGRACIL
Gomphonema minutum (Agardh) Agardh	GMINUT
Gomphonema olivaceoides Hustedt	GOLIVAC
Gomphonema parvulum complex (Kützing) Kützing	GPARVUL
Gomphonema pumilum (Grunow) Reichardt & Lange-Bertalot	GPUMIL
Gomphonema sp.	GSPP
Gomphonema truncatum Ehrenberg	GTRUNCAT
Hannaea arcus (Ehrenberg) Patrick. in Patrick and Reimer	HANNARC
Meridion circulare (Greville) Agardh	MERIOCIR
Navicula lanceolata (Agardh) Kützing	NLANCEO
Nitzschia dissipata (Kützing) Grunow	NITDISSI
Nitzschia frustulum (Kützing) Grunow in Cleve & Grunow	NITFRUST
Nitzschia sp.	NITSPP
Pinnularia appendiculata (Agardh) Cleve	PAPPEND
Pinnularia rupestris Hantzsch in Rabenhorst	PRUPES
Pinnularia subcapitata Gregory	PSUBCAP
Planothidium lanceolatum (Brébisson ex Kützing) Lange-Bertalot	PLANOLAN
Reimeria sinuata (Gregory) Kociolek & Stoermer	REIMSIN
Sellaphora pupula (Kützing) Mereschkowsky	SELLAPH
Surirella sp.	SURIRELL
Synedra ulna (Nitzsch) Ehrenberg	SYNEDUL

Appendix B

Sample codes

Site	Label
Srahrevagh 1 (Upper)	SR1
Srahrevagh 2 (Upper)	SR2
Srahrevagh 3 (Upper)	SR3
Srahrevagh 4 (Mid-Upper)	SR4
Srahrevagh 5 (Mid-Upper)	SR5
Srahrevagh 6 (Mid-Upper)	SR6
Srahrevagh 7 (Middle)	SR7
Srahrevagh 8 (Middle)	SR8
Srahrevagh 9 (Middle)	SR9
Srahrevagh 10 (Lower)	SR10
Srahrevagh 11 (Lower)	SR11
Srahrevagh 12 (Lower)	SR12
Glennamong 1 (Upper)	GL1
Glennamong 2 (Upper)	GL2
Glennamong 3 (Upper)	GL3
Glennamong 4 (Mid-Upper)	GL4
Glennamong 5 (Mid-Upper)	GL5
Glennamong 6 (Mid-Upper)	GL6
Glennamong 7 (Middle)	GL7
Glennamong 8 (Middle)	GL8
Glennamong 9 (Middle)	GL9
Glennamong 10 (Lower)	GL10
Glennamong 11 (Lower)	GL11
Glennamong 12 (Lower)	GL12
Glendahurk	GH
Teevaloughan1	TV1
Teevaloughan2	TV2
Glennamong Control Stream	GCS
Glennamong Study Stream	GSS
Srahrevagh Study Stream	SSS
Srahrevagh Control Stream	SCS
Maumaratta Top	MT
Maumaratta Bottom	MB
Goulaun Top	GT
Goulaun Bottom	GB
Altahoney Top	AT
Altahoney Bottom	AB
Cottage Top	CT
Cottage Bottom	CB
Lodge Top	LT
Lodge Bottom	LB
Glendahurk	GHE
Glenthomas	GTE

Appendix C

Physical characteristics of the individual sites

	Sample Number	Temp (°C)	Altitude (m)	Stream Order	Upstream Catchment Area (ha)	Shreve Index
Srahrevagh Upper	3	18.0 (0.2)[a]	341.33 (18.0)	1	13	1
Srahrevagh mid-Upper	3	19.1 (0.1)	181.33 (1.2)	2	168	3
Srahrevagh Middle	3	20.4 (0.6)	130.0	2	266	4
Srahrevagh Lower	3	20.0 (0.2)	40.0	3	690	8
Glennamong Upper	3	14.2 (0.1)	230.0	2	191	2
Glennamong mid-Upper	3	16.3 (0.1)	107.3 (2.3)	2	605	14
Glennamong Middle	3	16.9 (0.1)	50.0	4	1145	29
Glennamong Lower	3	17.5 (0.1)	20.0	4	1549	33
Glendahurk	3	15.0	101.0	1	10	1
Teevaloughan1	3	14.0	280.0	1	20	1
Teevaloughan2	3	14.1 (0.10)	268.0	1	32	1
Glennamong Study	3	14.5	86.7	1	10	1
Glennamong Control	3	14.4 (0.1)	55.8	1	10	1
Srahrevagh Study	3	16.1	220.0	1	17	1
Srahrevagh Control	3	16.7	240.0	1	23	1
Maumaratta	3	14.0 (1.8)	95.0 (63.6)	2	473 (255)	3 (2)
Goulaun	3	18.1 (0.9)	85.00 (35.4)	3	754 (304)	6 (2)
Altahoney	3	12.8 (2.3)	80.00 (28.3)	3	1144 (181)	20 (3)
Cottage	3	11.8 (0.1)	60.00 (28.3)	3	210	6 (1)
Lodge	3	12.6 (0.1)	33.50 (5.0)	3	468	7 (1)
Glenthomas	3	18.37	50.0	3	1429	17
Glendahurk (main)	3	19.10	50.0	3	1211	25

[a]: () indicates standard deviation

Appendix D

Chemical characteristics of the individual sites

	Sample Number	Conductivity ($\mu S\ cm^{-1}$)	Alkalinity ($mg\ L^{-1}$ $CaCO_3$)	PO_4-P ($\mu g\ L^{-1}$)	NH_4-N ($\mu g\ L^{-1}$)	NO_3 -N ($\mu g\ L^{-1}$)	pH	Colour (PtCo)
Srahrevagh Upper	3	93 (3.5)[a]	13.5 (0.8)	3.2 (0.2)	27.5 (7.8)	12.2 (0.7)	7.4 (0.04)	38 (3.5)
Srahrevagh mid-Upper	3	141	37.0 (0.6)	4.7 (0.2)	26.1 (5.1)	7.1 (0.5)	7.7	49 (1.7)
Srahrevagh Middle	3	152 (12.0)	37.9 (5.2)	3.72 (0.4)	19.2 (5.9)	8.8(2.4)	7.3 (0.15)	41 (3.4)
Srahrevagh Lower	3	213 (0.7)	68.8 (0.3)	5.4 (0.6)	6.5 (2.1)	0.6 (0.1)	8.5 (0.01)	56 (0.6)
Glennamong Upper	3	67 (0.3)	0.1	4.8 (0.6)	36.6 (1.9)	97.0(33.2)	5.6 (0.07)	104 (5.8)
Glennamong mid-Upper	3	79 (0.6)	6.7 (0.4)	5.4 (0.5)	26.2 (3.4)	88.9 (37.6)	7.0 (0.05)	82 (3.7)
Glennamong Middle	3	93 (1.0)	10.7 (0.2)	4.5 (0.8)	29.1 (3.8)	28.4 (9.7)	7.3 (0.02)	81 (2.7)
Glennamong Lower	3	94	9.4 (0.2)	3.7 (0.3)	21.4 (7.5)	10.9 (1.0)	7.2 (0.02)	68 (1.2)
Glendahurk	3	89 (2.2)	2.8 (1.1)	3.6 (0.2)	54.4 (11.3)	49.5 (11.2)	5.6 (0.1)	74 (0.6)
Teevaloughan1	3	144 (0.6)	1.5 (0.1)	3.3 (0.1)	117.0 (3.5)	6.7 (1.7)	3.8 (0.01)	262 (0.3)
Teevaloughan2	3	122 (0.3)	1.7 (0.1)	3.5 (0.2)	77.7 (2.4)	34.1(2.3)	4.8 (0.01)	141 (1)
Glennamong Study	3	173 (0.3)	-1.7 (1.3)	4.0 (0.3)	73.9 (4.5)	39.0 (2.1)	3.9 (0.01)	256 (0.3)
Glennamong Control	3	251 (0.3)	-2.7 (0.3)	3.8 (0.3)	39.3 (3.8)	3.43 (0.8)	3.5 (0.01)	264 (0.3)
Srahrevagh Study	3	201 (0.9)	-2.4 (0.3)	6.3 (0.2)	110.7 (4.0)	2.0 (1.1)	3.6 (0.01)	283 (0.3)
Srahrevagh Control	3	115 (0.9)	9.9	4.6(0.2)	122.1(1.2)	49.9 (1.1)	5.8 (0.01)	168 (0.6)
Maumaratta	3	68 (3.5)	-0.5 (0.5)	4.9 (1.6)	43.4 (0.1)	0.0 (4.4)	5.8 (0.01)	138 (5.0)
Goulaun	3	102 (16.0)	17.0 (7.0)	3.7 (0.2)	59.4 (6.6)	0.0 (0.7)	7.1 (0.2)	66 (7.5)
Altahoney	3	75 (1.5)	-2.0 (1.0)	4.5 (0.6)	42.3 (5.0)	0.0 (0.53)	5.6	166 (3.0)
Cottage	3	98 (4.0)	18.0	3.3 (0.2)	43.4 (18.2)	9.8 (0.8)	7.3 (0.2)	72 (8.5)
Lodge	3	97 (1.0)	21.0	3.08 (0.1)	58.9 (2.3)	2.5 (3.7)	7.8	90 (2.0)
Glenthomas	3	82 (0.7)	6.0 (0.3)	3.2 (0.2)	21.5 (1.1)	5.1 (0.5)	6.2 (0.01)	110 (0.6)
Glendahurk (main)	3	87 (0.3)	11.4 (0.3)	3.5 (0.2)	65.1 (1.1)	2.1 (0.5)	6.3 (0.01)	64 (0.6)

[a]: () indicates standard deviation

Figure 1. The position of 43 sites where riverine diatom assemblages were sampled in 2009 in the North West of Ireland

Figure 2. Location in ordination space (correspondence analysis, CA) of the first and second axis of diatom taxa. Taxa shown in the diagram were found at least in 5% of all samples (taxa codes correspond to those in appendix A)

Figure 3. Canonical correspondence analysis (CCA) of diatom communities in streams of NW Ireland in the ordination space of first and second axis (ALK: alkalinity; ALT: altitude; COND: conductivity; TEMP: temperature; u/s AREA: upstream area); (a) ordination of diatom species, (b) ordination of sampling locations with significant and independent environmental variables (taxa and sample site codes correspond to those Appendix A and B)

Figure 4. Canonical correspondence analysis (CCA) of diatom assemblages after a major flood in the ordination space of first and second axis

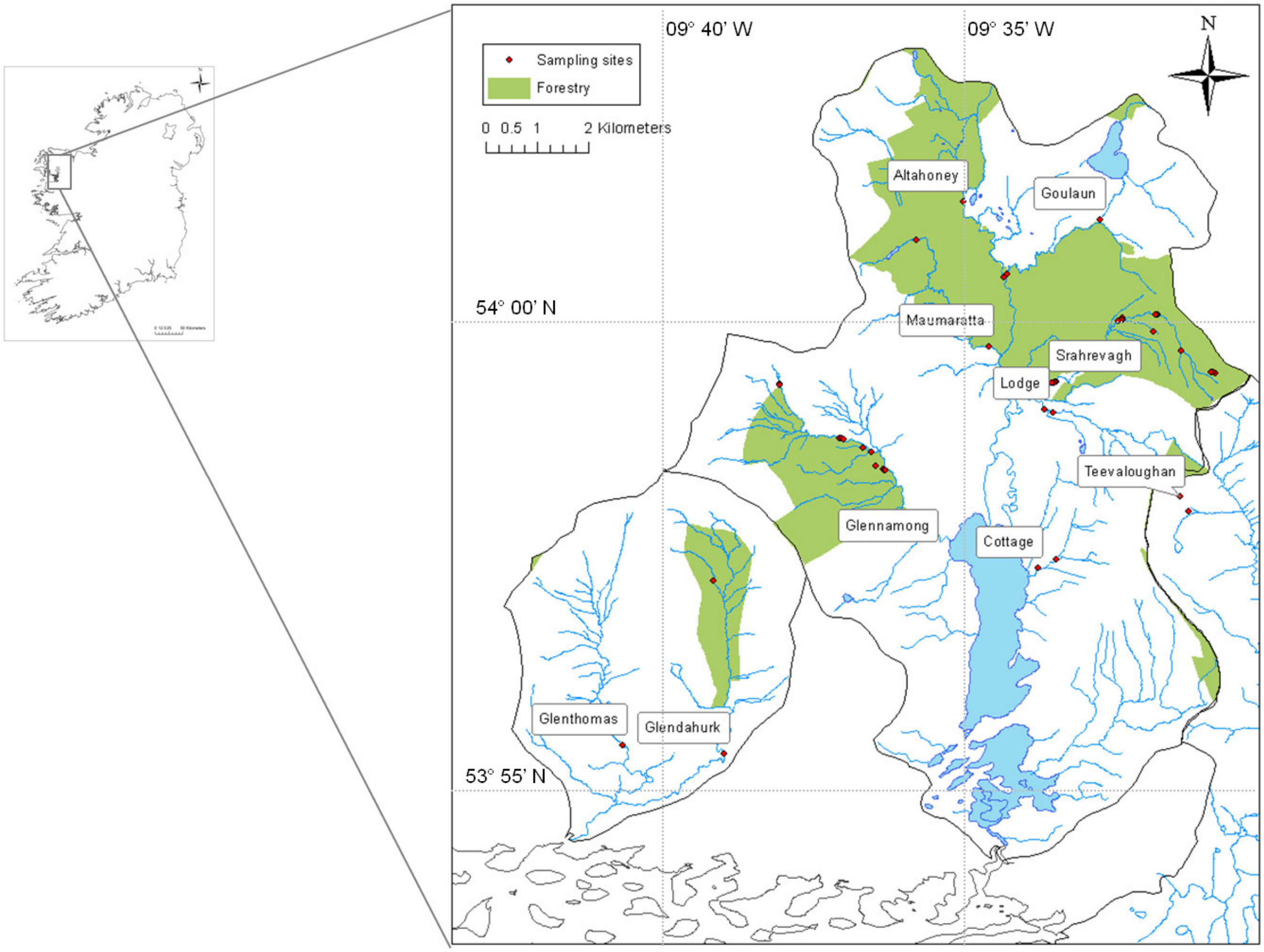
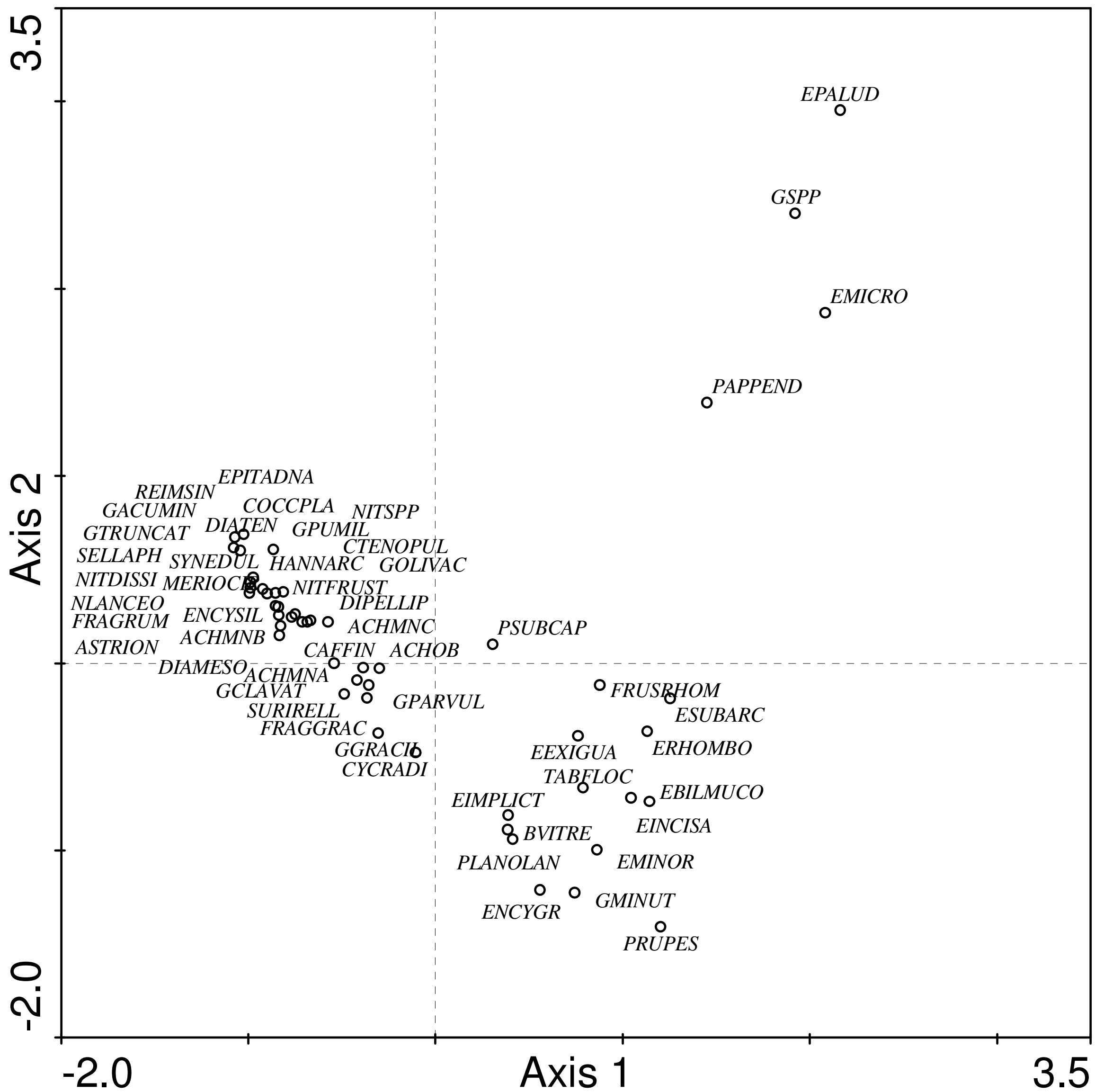
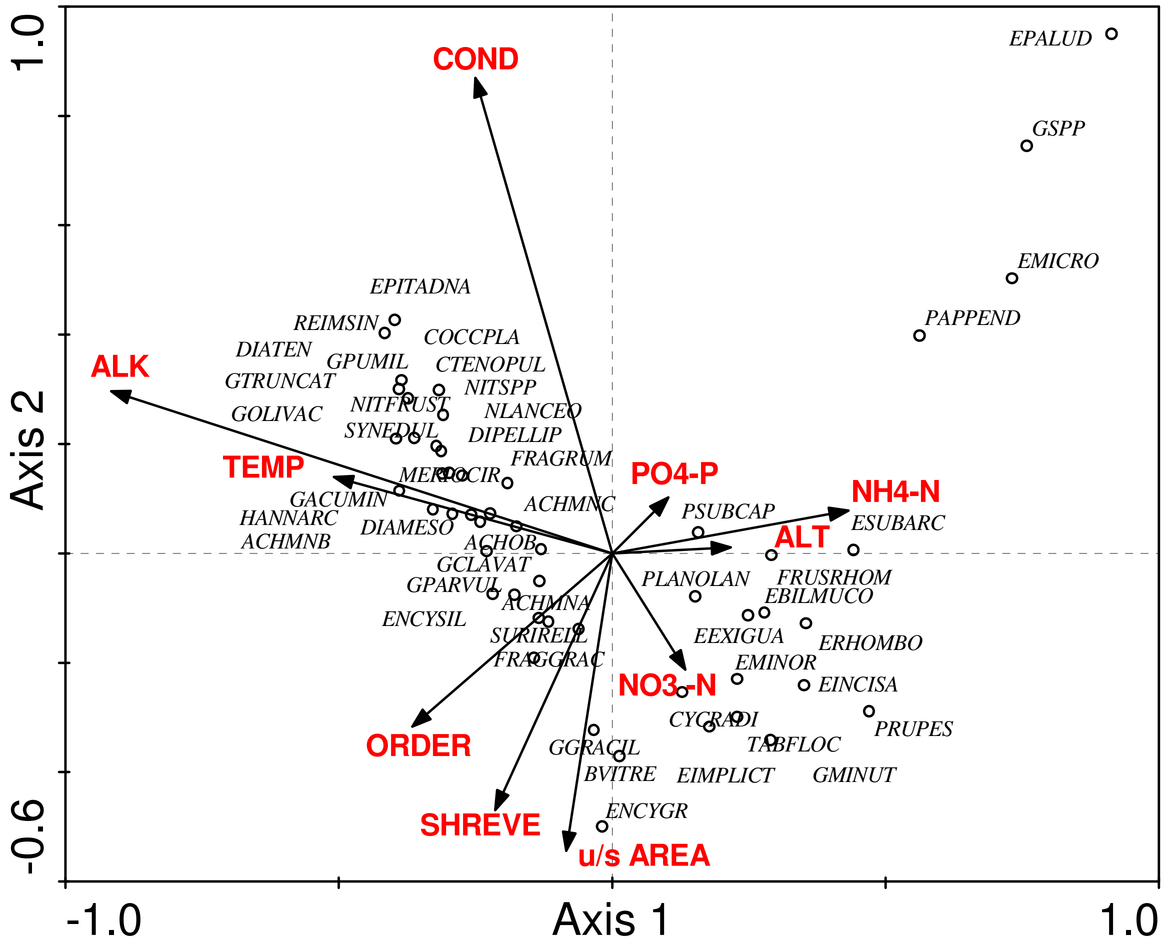

09° 40' W
09° 35' W
N
Sampling sites
Forestry
0 0.5 1 2 Kilometers
Altahoney
Goulaun
54° 00' N
Maumaratta
Srahrevagh
Lodge
Teevaloughan
Glennamong
Cottage
Glenthomas
Glendahurk
53° 55' N

Figure 1



3.5
-2.0
Axis 2
-2.0
Axis 1
3.5
EPALUD
GSPP
EMICRO
PAPPEND
EPITADNA
REIMSIN
COCCPLA
NITSPP
GACUMIN
DIATEN
GPUMIL
GTRUNCAT
CTENOPUL
SELLAPH
SYNEDUL
HANNARC
GOLIVAC
NITDISSI
MERIOCIR
NITFRUST
NLANCEO
DIPELLIP
ENCYSIL
FRAGRUM
ACHMNC
PSUBCAP
ACHMNB
ASTRION
CAFFIN
ACHOB
DIAMESO
ACHMNA
FRUSRHOM
GCLAVAT
GPARVUL
ESUBARC
SURIRELL
FRAGGRAC
ERHOMBO
GGRACIL
EEXIGUA
CYCRADI
TABFLOC
EBILMUCO
EIMPLICT
EINCISA
BVITRE
PLANOLAN
EMINOR
GMINUT
ENCYGR
PRUPES

Figure 2



Axis 1
Axis 2
-1.0
1.0
-0.6
1.0
COND
ALK
TEMP
PO4-P
NH4-N
ALT
NO3-N
ORDER
SHREVE
u/s AREA
EPALUD
GSPP
EMICRO
PAPPEND
EPITADNA
REIMSIN
COCCPLA
DIATEN
GPUMIL
CTENOPUL
GTRUNCAT
NITSPP
NITFRUST
NLANCEO
GOLIVAC
SYNEDUL
DIPELLIP
FRAGRUM
MERCOCIR
GACUMIN
ACHMNC
HANNARC
PSUBCAP
DIAMESO
ESUBARC
ACHMNB
ACHOB
GCLAVAT
PLANOLAN
FRUSRHOM
GPARVUL
EBILMUCO
ACHMNA
ENCYSIL
SURIRELL
EEXIGUA
ERHOMBO
FRAGGRAC
EMINOR
EINCISA
CYCRADI
PRUPES
GGRACIL
TABFLOC
BVITRE
EIMPLICT
GMINUT
ENCYGR

Figure 3a

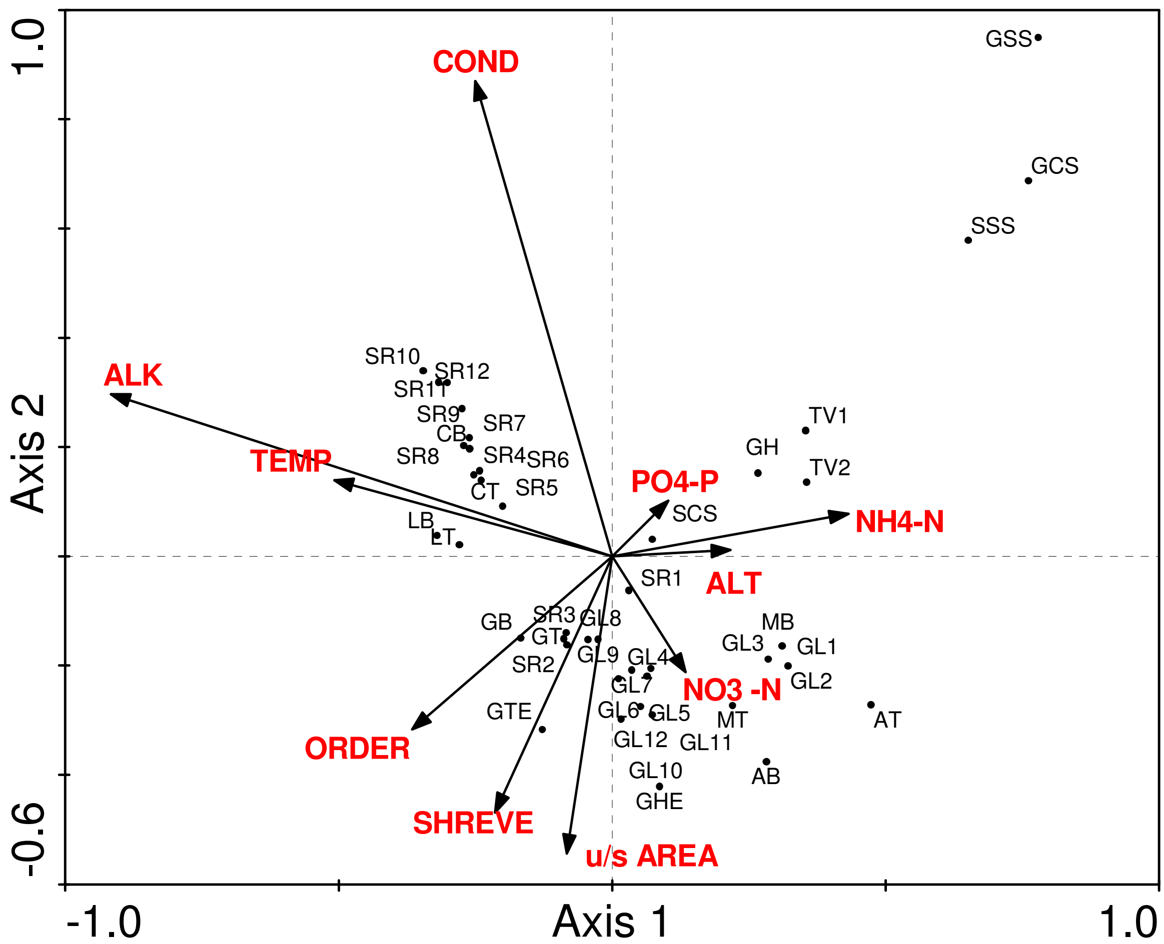
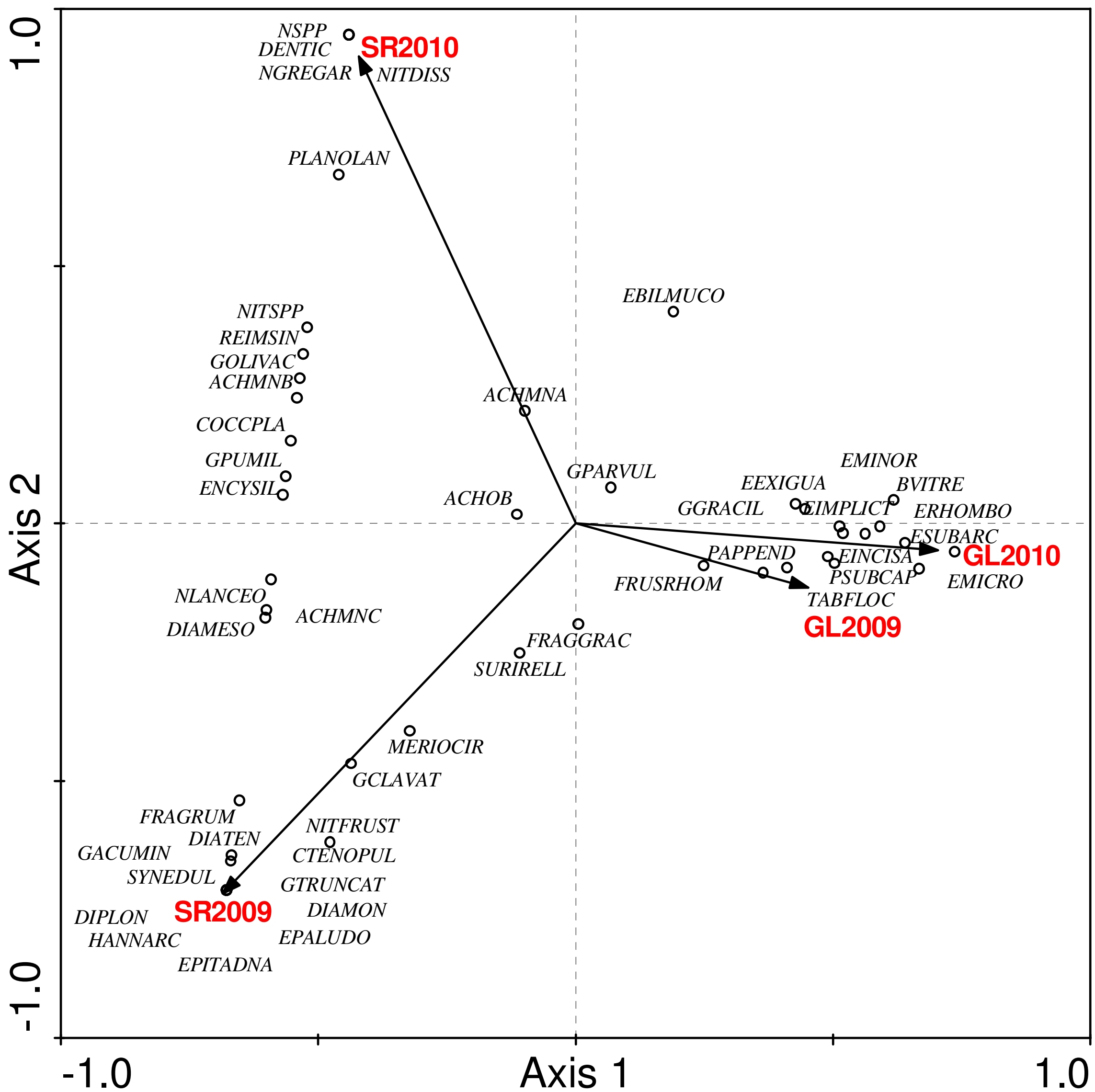

COND
ALK
TEMP
PO4-P
NH4-N
ALT
NO3 -N
ORDER
SHREVE
u/s AREA
GSS
GCS
SSS
SR10
SR12
SR11
SR9
SR7
CB
SR8
SR4
SR6
CT
SR5
LB
LT
GH
TV1
TV2
SCS
SR1
GB
SR3
GL8
GT
SR2
GL9
GL4
GL7
GTE
GL6
GL5
GL12
GL11
GL10
GHE
MB
GL3
GL1
GL2
MT
AT
AB
Axis 2
Axis 1
1.0
-0.6
-1.0
1.0

Figure 3b



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-1.0
Axis 2
-1.0
Axis 1
1.0
SR2010
SR2009
GL2010
GL2009
NSPP
DENTIC
NGREGAR
NITDISS
PLANOLAN
EBILMUCO
NITSPP
REIMSIN
GOLIVAC
ACHMNB
ACHMNA
COCCPLA
GPUMIL
ENCYSIL
ACHOB
GPARVUL
EEXIGUA
EMINOR
BVITRE
GGRACIL
EIMPLICT
ERHOMBO
ESUBARC
PAPPEND
EINCISA
PSUBCAP
EMICRO
FRUSRHOM
TABFLOC
NLANCEO
DIAMESO
ACHMNC
FRAGGRAC
SURIRELL
MERIOCIR
GCLAVAT
FRAGRUM
DIATEN
GACUMIN
SYNEDUL
NITFRUST
CTENOPUL
GTRUNCAT
DIAMON
DIPLON
HANNARC
EPALUDO
EPITADNA

Figure 4