Long-term changes in spring phytoplankton community composition in five south-central Ontario lakes and their relations with spring water chemistry and climate

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Spring is an ecologically important period for phytoplankton communities, as environmental stressors such as acid deposition and recovery, climate warming, and shoreline development may exert strong influence at this time of year. However, few studies have examined trends in spring phytoplankton community composition and biomass, and it is not known if changes in the spring phytoplankton are associated with trends in phytoplankton communities during the summer and fall periods. To determine long-term changes in phytoplankton community composition and biomass during the spring period, we examined spring phytoplankton samples, water chemistry samples, and meteorological data from the mid-1970s to 2011 at five lakes (Blue Chalk, Dickie, Harp, Plastic, and Red Chalk) in the Muskoka-Haliburton region of south-central Ontario, Canada. Trends in spring water chemistry and climate included significant increases in alkalinity, dissolved organic carbon concentration and fall mean air temperature, and significant decreases in concentrations of calcium, magnesium, and sulphate and the number of ice-on days. Significant increases in the relative and absolute biovolume of chrysophytes were observed at one lake (Blue Chalk), with coincident declines in the relative biovolume of diatoms and chlorophytes ($P < 0.05$). Significant increases in the absolute biovolume of chlorophytes, cryptophytes, and cyanophytes were observed at Dickie Lake ($P < 0.05$). Inter-annual variability of spring phytoplankton biovolume was high within each lake. Environmental variables that explained a significant portion of the spring phytoplankton variation differed for each lake, but generally included conductivity, nitrate/nitrite concentration, fall and/or winter mean air temperatures, and number of ice-on days. Variation partitioning analysis indicated that spring water chemistry variables, independent of climate, explained a significant proportion of the temporal variation in composition of spring phytoplankton communities at four of the five lakes (12%–28%, mean = 18.9%), while climate variables, independent of water chemistry, explained a significant proportion of the variation in one lake only ($P < 0.05$; 15%). High unexplained variation (55%–77%, mean = 68.7%) indicates that other factors play an important role in explaining the observed inter-annual variation in the spring phytoplankton community composition. A comparison of variation in spring phytoplankton with ice-free season composite phytoplankton revealed that chrysophytes, cryptophytes, and dinoflagellates generally have higher relative biovolumes in spring phytoplankton samples than in ice-free season composite phytoplankton samples. However, changes observed in the ice-free season composite phytoplankton in previous studies were not observed to the same extent in spring phytoplankton communities.

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Table of Contents

List of Figures vi
List of Tables vii
List of Appendices viii
1.0 Introduction 1
2.0 Materials and Methods 5
2.1 Study sites 5
2.2 Sample collection and analysis 7
2.3 Data analyses 9
3.0 Results 12
3.1 Water chemistry 12
3.2 Climate 13
3.3 Phytoplankton community composition 13
4.0 Discussion 22
4.1 Water chemistry and climate 22
4.2 Phytoplankton community composition 24
4.3 Drivers of variation in spring phytoplankton 25
4.4 Comparison with ice-free composite phytoplankton samples 26
5.0 Conclusions 28
6.0 References 29
Appendices 35

List of Figures

Figure 1. Map showing locations of the five Dorset Environmental Science Centre (DESC) long-term monitoring lakes studied in the research program. Grandview Lake, where ice-cover data were collected, is also shown. The location of the DESC office is indicated with a blue circle. The inset shows the location of the study area (indicated with a box) within Ontario, Canada.. 6

Figure 2. Temporal patterns of relative biovolume (%) for the major phytoplankton groups in spring samples from Blue Chalk, Red Chalk (Main Basin), Plastic, Dickie, and Harp lakes, Ontario, Canada from 1976 to 2011 (except for Blue Chalk: 1977 to 2011; Plastic: 1979 to 2011)..................................... 15

Figure 3. Principal components analysis (PCA) ordination plots showing the position of site years in relation to the relative biovolume of major phytoplankton groups. Lake codes: BC, Blue Chalk; RCM, Red Chalk (Main Basin); PC, Plastic; DE, Dickie; HP, Harp. Algal groups: Chry, chrysophytes; Cyan, cyanophytes; Diat, diatoms; Chlo, chlorophytes; Cryp, cryptophytes; Dino, dinoflagellates. Site years: red, 1970s; orange, 1980s; green, 1990s; blue, 2000s; purple, 2010s... 16

Figure 4. Results of two-category variance partitioning analysis (VPA) displaying the percentage of variation in the spring phytoplankton community composition data (relative biovolumes) explained by the unique and shared effects of water chemistry and climate variables at Blue Chalk (BC), Red Chalk (Main Basin; RCM), Plastic (PC), Dickie (DE), and Harp (HP) lakes, Ontario, Canada...................................... 19

Figure 5. Comparisons of the total biovolume ($mm^3 \cdot m^{-3}$) of spring phytoplankton samples and ice-free season composite phytoplankton samples from Blue Chalk (BC), Red Chalk (Main Basin; RCM), Plastic (PC), Dickie (DE), and Harp (HP) lakes, Ontario, Canada. Diagonal lines indicate 1:1 lines……………21

List of Tables

Table 1. Select morphological characteristics and water chemistry variables of Blue Chalk (BC), Red Chalk (Main Basin; RCM), Plastic (PC), Dickie (DE), and Harp (HP) lakes, Ontario, Canada. Morphological data adapted from Girard et al. (2007). Water chemistry variables are presented as mean values of samples collected during the ice-free seasons of 2007 to 2011, inclusive. 7

Table 2. Mann-Kendall monotonic trend test results of water chemistry variables for Blue Chalk (BC), Red Chalk (Main Basin; RCM), Plastic (PC), Dickie (DE), and Harp (HP) lakes during the spring seasons of 1976 to 2011 (except for Blue Chalk: 1977 to 2011; Plastic: 1979 to 2011). Arrows indicate directionality of significant trends after correction for the false discovery rate; dashes indicate no significant trend. 12

Table 3. Mann-Kendall monotonic trend test results of climate variables for Blue Chalk (BC), Red Chalk (Main Basin; RCM), Plastic (PC), Dickie (DE), and Harp (HP) lakes from 1976 to 2011. Arrows indicate directionality of significant trends; dashes indicate no significant trend. 13

Table 4. Sen's slopes and *p*-values from Mann-Kendall trend tests for the relative abundance of the six major phytoplankton groups for each study lake. 17

Table 5. Environmental variables selected to generate principal components analysis axes 1 and 2 scores used in the two-category variance partitioning analysis (VPA) of phytoplankton groups for Blue Chalk, Red Chalk (Main Basin), Plastic, Dickie, and Harp lakes. 18

List of Appendices

Appendix I: Spring phytoplankton and water chemistry sample collection dates 36
Appendix II: Spring water chemistry plots 39
Appendix III: Climate plots 57
Appendix IV: Bar charts of spring phytoplankton (absolute biovolume)... 67
Appendix V: Mann-Kendall trend tests for spring phytoplankton (absolute biovolume).......................... 69
Appendix VI: PCA biplots for spring phytoplankton (absolute biovolume).. 71
Appendix VII: Spring and ice-free phytoplankton comparisons (relative biovolume) 73
Appendix VIII: Spring and ice-free phytoplankton comparisons (absolute biovolume) 80
Appendix IX: Correlation matrices (spring water chemistry, climate, and phytoplankton)...................... 87

1.0 Introduction

Canada has an abundance of freshwater ecosystems, with over 3 million lakes covering 7.6% of the country's surface area (Palmer et al. 2011). These freshwater resources are necessary to sustain both terrestrial and aquatic biota and human life (Jackson et al. 2001; Baron et al. 2002; Smol 2010). However, freshwater ecosystems are among the most altered ecosystems globally by human activity (Millennium Ecosystem Assessment 2005). Multiple environmental stressors affect their water quality, water quantity, and ecological integrity (Smol 2010). Long-term monitoring programs are valuable in detecting and evaluating changes in freshwater ecosystems and understanding the cumulative effects of stressors on those ecosystems (Burt 1994; Lindenmayer and Likens 2009; Dodds et al. 2012).

Phytoplankton are sensitive indicators of environmental change and can assist aquatic scientists and natural resource managers to understand, predict, and manage freshwater ecosystems. Phytoplankton are ubiquitous, diverse, relatively easy to sample, and exhibit species-specific sensitivity to environmental conditions (Smol 2002; Stevenson and Smol 2003; Paterson et al. 2008). Community composition and biomass of phytoplankton typically shift in response to variations in nutrient levels, temperature, and light, and their responses are relatively rapid due to their short generation time (Wetzel 2001). These characteristics have made the measurement of phytoplankton communities an important component of long-term monitoring programs for freshwater lakes (Larson et al. 2007; Paterson et al. 2008; Fahnenstiel et al. 2010; Miller and McKnight 2015).

Phytoplankton are not only indicators of environmental change, but also play important roles in freshwater ecosystems. As primary producers of aquatic ecosystems, they provide a food source for zooplankton and other organisms. Thus, shifts in phytoplankton community composition and biomass may exert cascading effects to higher trophic levels (Jeppesen et al. 2005). Alterations to phytoplankton community composition and biomass may favour species known to cause water quality problems (e.g., algal blooms and taste and odour events), which can pose aesthetic and health concerns and impair key ecosystem services, including the recreational value of freshwater lakes, economically important sport fisheries, and the value of lakes as drinking water sources (Smith et al. 1999; Smith 2003; Smith and Schindler 2009).

The Muskoka-Haliburton region of south-central Ontario comprises a lake-rich landscape that is well known for recreation and tourism, due in part to the high water quality of many of its water bodies. However, lakes in the region have experienced decades of low to moderate intensity of environmental stressors (Paterson et al. 2008), and there are concerns that anthropogenic activities are causing deterioration of water quality and ecological integrity. Stressors including acid deposition and recovery, climate change, and shoreline development have led to detectable changes in the water quality of Precambrian Shield lakes in Ontario since the 1980s (Palmer et al. 2011). Large reductions in sulphur deposition have led to widespread decreases in lake sulphate concentrations, with corresponding (although limited) increases in alkalinity and pH (Dillon et al. 2003; Jeffries et al. 2003; Dillon et al. 2007; Watmough et al. 2016). Marked declines in lake calcium concentrations have been attributed to acid deposition (i.e., acidic leaching of catchment soil reserves) and forest harvesting and have profound implications for aquatic ecosystems (Watmough et al. 2003; Jeziorski et al. 2008; Jeziorski and Smol 2017). Increases in dissolved organic carbon (DOC) concentrations documented across the region may be due in part to decreased lake and soil acidity, which reduces photochemical loss of DOC and precipitation of DOC with metals (Keller et al. 2008), and increases DOC solubility in the watershed. Phosphorus concentrations have declined in many regional lakes due to reduced export from catchments undergoing reforestation (Hall and Smol 1996; Dillon and Molot 2005), while increases in sodium and chloride concentrations have occurred in lakes with more developed catchments due to salting of roads during winter (Molot and Dillon 2008). Some lakes in the Muskoka-Haliburton region have also seen the introduction of invasive aquatic species such as the spiny waterflea (*Bythotrephes longimanus*).

Aquatic ecosystems of the Precambrian Shield are anticipated to experience changes in physical, chemical, and biological characteristics due to the direct and indirect effects of climate warming (Mortsch and Quinn 1996; Arnott et al. 2003; Keller 2007). Effects of climate warming are complex due to the regional heterogeneity of lake responses (Magnuson et al. 1997; Rühland et al. 2015). Climate change in the Precambrian Shield region is predicted to raise air temperature and precipitation, increase frequency and intensity of extreme weather events, and reduce snowfall and snowpack accumulation (Mortsch and Quinn 1996; Magnuson et al. 1997; Hengeveld 2000; Jentsch et al. 2007; Cheng et al. 2012), with most pronounced warming during the fall and winter seasons (Casson et al. 2012). The physical effects of climate warming on Precambrian Shield lakes are varied, but include increases in surface water temperature and thermal stability of the water column, earlier ice break-up dates, and longer ice-free seasons (Futter 2003; Duguay et al. 2006; Hadley et al. 2014; Palmer et al. 2014; O'Reilly et al. 2015). Changes in water balance (especially during the winter and spring seasons) and earlier spring runoff are also predicted to occur (Johnson and Stefan 2006; Yao et al. 2009). Climate warming may include alterations in chemical exports from catchments to Precambrian Shield lakes, changes in the concentrations of organic and inorganic compounds in lake water, and the delay or reversal of lake recovery from acidification (Schindler et al. 1996; Aherne et al. 2008). Climate warming may also interact with – and potentially magnify – other lake stressors (Schindler et al. 1996; Magnuson et al. 1997; Arnott et al. 2003; Keller 2007).

Phytoplankton communities of the Muskoka-Haliburton region have undergone changes in composition and biomass since pre-industrial times (Hall and Smol 1996; Paterson et al. 2004; Paterson et al. 2008). Widespread increases in the absolute and relative biovolumes of colonial chrysophytes have been observed, as well as declines in the relative biovolume of diatoms (Paterson et al. 2004; Paterson et al. 2008). Shifts in composition of diatom assemblages have also been documented (Hall and Smol 1996; Barrow et al. 2014). As the lakes of the Muskoka-Haliburton region are considered to be representative of thousands of lakes within the southern Precambrian Shield (Yan et al. 2008a; Palmer et al. 2011), these observed shifts in phytoplankton community composition and biomass could be occurring regionally (Paterson et al. 2008; Palmer et al. 2011). Drivers of observed changes in phytoplankton communities are hypothesized to consist of multiple anthropogenic stressors operating at a regional scale, including acid deposition and recovery, regional climate warming, and shoreline development (Hall and Smol 1996; Paterson et al. 2004; Paterson et al. 2008; Barrow et al. 2014). Specifically, Paterson et al. (2008) found that water chemistry variables, as well as the co-variation of water chemistry variables with physico-climatic variables, were the most important drivers of change in phytoplankton communities during the ice-free season.

Although phytoplankton communities of the Muskoka-Haliburton region are relatively well studied during the summer, few studies have examined trends in phytoplankton community composition and biomass during the ecologically important spring period. Environmental stressors such as acid deposition and recovery, climate warming, and shoreline development may exert greatest influence during the spring, when changes in snowpack accumulation and the timing and duration of snow melt and ice break-up can lead to alteration of water chemistry variables (e.g., DOC and phosphorus flux, lake-water pH, and salt concentrations). In particular, as climate warming is expected to alter physical processes important to the spring period (e.g., earlier ice break-up dates, earlier spring runoff), it is also likely to alter phytoplankton abundance and composition (Arnott et al. 2003; Keller 2007). For example, the decline in phosphorus concentrations that has been observed in many Precambrian Shield streams and lakes during the past several decades is likely driven by decreases in watershed delivery of phosphorus, particularly during the spring snow melt period (Quinlan et al. 2008; Eimers et al. 2009; Palmer et al. 2011). In forested catchments, such as many of those on the Precambrian Shield, the majority of phosphorus export occurs during episodes of high runoff, including spring snow melt and storm events (Meyer and Likens 1979). Due to the prominence of high discharge events (e.g., spring snow melt, comprising upwards of 50% of the annual runoff; Eimers et al. 2008), changes in the magnitude and timing of such events could affect phosphorus delivery to lakes (Eimers et al. 2009), and thereby cause the alteration of phytoplankton communities through shifts in biomass or composition (Watson et al. 1997).

Furthermore, studies examining shifts in phytoplankton communities have focused primarily on the late summer period, annual ice-free season composite samples (e.g., Paterson et al. 2008), or paleolimnological methods (e.g., Hall and Smol 1996; Paterson et al. 2004), and it is not known if changes in spring phytoplankton communities may affect later successional communities during the summer period. The spring phytoplankton bloom is a key annual event in aquatic ecosystems, the timing, duration, and magnitude of which may have implications for phytoplankton dynamics throughout the year (George et al. 2015; Lewandowska et al. 2015).

To determine the long-term changes in phytoplankton community composition and biomass during the critical spring period, we examined four decades of archived spring phytoplankton samples collected by the Ontario Ministry of the Environment, Conservation and Parks (MECP) at five lakes in the Muskoka-Haliburton region of south-central Ontario. The specific objectives of this study are to (*i*) identify which spring water chemistry and climate variables have changed since the mid- to late-1970s at the five study lakes, (*ii*) identify trends in spring phytoplankton community composition and biomass during the same time period, (*iii*) quantify the physical and chemical drivers explaining observed variation in the spring phytoplankton, and (*iv*) compare changes in spring phytoplankton communities with those in annual ice-free season composite phytoplankton samples from the same lakes.

2.0 Materials and Methods

2.1 Study sites

This study examines spring phytoplankton records from five lakes (Blue Chalk, Dickie, Harp, Plastic, and Red Chalk (Main Basin)) located in the Muskoka-Haliburton region of south-central Ontario, Canada (Figure 1). The lakes are part of the MECP Dorset Environmental Science Centre's (DESC) long-term monitoring program and have been studied intensively since the mid- to late-1970s (Ingram et al. 2006).

The Muskoka-Haliburton region consists of a predominantly forested landscape with numerous wetlands and inland lakes, and limited agricultural activity (Arnott et al. 2003; DeSellas et al. 2008; Palmer et al. 2011). Primary economic activities in the region are related to recreation and tourism (e.g., seasonal cottages and resorts; Dillon et al. 2007). The surficial geology of the study area is underlain by granitic bedrock of the Precambrian Shield, and the area is characterized by shallow, acidic soils which generate relatively low nutrient export (Chapman and Putnam 1984; Paterson et al. 2008). Mean air temperatures of the region are -10.3°C and 18.7°C for January and July, respectively, and mean total precipitation is 1105 $mm \cdot year^{-1}$ (Muskoka Airport weather station, 1981-2010; Environment Canada 2015).

Water chemistry trends during the past four decades have been well-documented in the DESC study lakes (e.g., Palmer et al. 2011). The trends include decreases in conductivity and concentrations of calcium, total phosphorus, sulphate, and metals, and increases in alkalinity, pH, and concentrations of chloride, dissolved organic carbon, nitrogen, and sodium (Dillon and Molot 2005; Keller et al. 2008; Watmough and Aherne 2008; Yan et al. 2008b; Palmer et al. 2011; Hadley et al. 2013). These changes are driven by regional stressors, including acid deposition and recovery, climate change, and residential development and associated road systems within watersheds (Palmer et al. 2011). Regional trends in ice phenology include earlier ice-off dates and longer ice-free season duration (Futter 2003), although not all lakes show the same trends (e.g., later ice-on dates have been observed at Dickie Lake, with no trend in ice-off date; Yao et al. 2013).

The five study lakes are small (<100 ha) headwater lakes, except for Red Chalk which is located immediately downstream of Blue Chalk. The lakes are typically oligotrophic and slightly acidic. Select morphological and water chemistry characteristics of the five study lakes are provided in Table 1. Watershed development ranges from moderate (Dickie: 143 residences in 2001; Harp: 110 residences in 2004) to minimal (Blue Chalk, Red Chalk) or absent (Plastic: no residential development; Dillon et al. 2007; Eimers et al. 2009). Harp Lake was invaded by the zooplankton species *Bythotrephes longimanus* in the early 1990s (Yan and Pawson 1998).

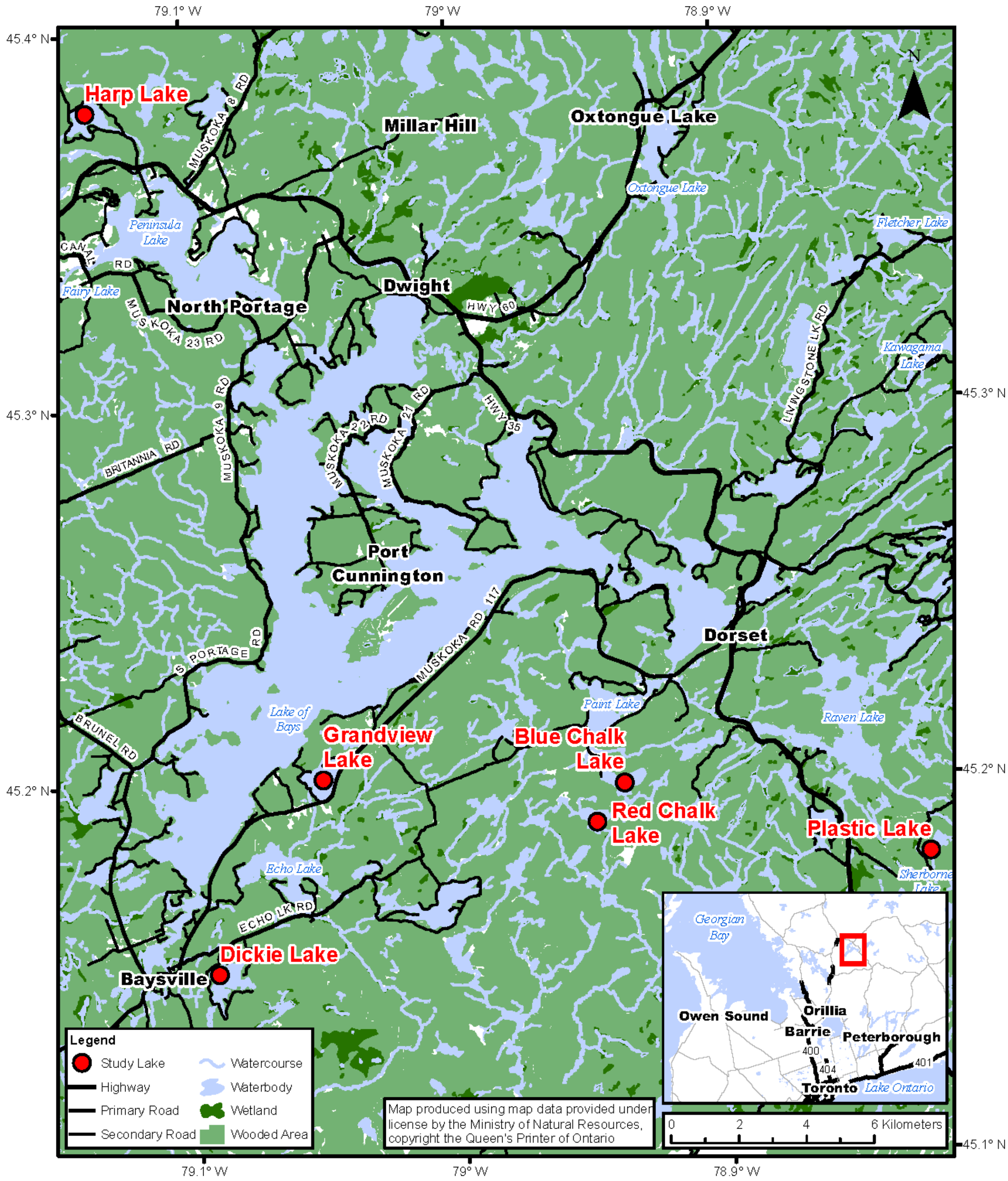


Figure 1. Map showing locations of the five Dorset Environmental Science Centre (DESC) long-term monitoring lakes studied in the research program. Grandview Lake, where ice-cover data were collected, is also shown. The location of the DESC office is indicated with a blue circle. The inset shows the location of the study area (indicated with a box) within Ontario, Canada.

Table 1. Select morphological characteristics and water chemistry variables of Blue Chalk (BC), Red Chalk (Main Basin; RCM), Plastic (PC), Dickie (DE), and Harp (HP) lakes, Ontario, Canada. Morphological data adapted from Girard et al. (2007). Water chemistry variables are presented as mean values of samples collected during the ice-free seasons of 2007 to 2011, inclusive.

Variable	BC	RCM	PC	DE	HP
Surface area (ha)	52.4	44.1	32.1	93.6	71.4
Lake volume ($10^5 \cdot m^3$)	44.7	73.5	25.2	46.7	95.1
Mean depth (m)	8.5	16.7	7.9	5.0	13.3
Maximum depth (m)	23.0	38.0	16.3	12.0	37.5
Watershed area[1] (ha)	105.9	532.3	95.5	406.4	470.6
Conductivity ($\mu S \cdot cm^{-1}$)	22.7	21.7	14.3	33.9	34.2
Dissolved organic carbon ($mg \cdot L^{-1}$)	2.2	2.9	2.6	6.5	4.3
pH	6.6	6.3	5.7	6.2	6.3
Total phosphorus ($\mu g \cdot L^{-1}$)	6.4	4.6	4.4	9.8	5.5

[1] Watershed area does not include lake surface area. The watershed area provided for Red Chalk (Main Basin; RCM) is that of the whole lake (sum of the Main and East basins).

2.2 Sample collection and analysis

Volume-weighted composite phytoplankton and water chemistry samples were collected by MECP staff at the central deep-water station of each of the five study lakes using a peristaltic pump and weighted polyvinyl chloride (PVC) hose. Sampling protocols followed standard methods described by Ingram et al. (2006) and Girard et al. (2007). The lakes were sampled from 1976 to 2011, inclusive, with the exception of Plastic Lake, which was sampled from 1979 to 2011. Each year, sampling began approximately one week to ten days following ice-off (Ingram et al. 2006).

Phytoplankton samples were collected as unfiltered composite samples, pumped from each odd metre throughout the euphotic zone (approximated as 2 x Secchi depth) and preserved with Lugol's iodine solution in the field. In the laboratory, samples were concentrated to 25 mL by sedimentation and preserved with two drops of 37% formalin as per standard MECP methods (Hopkins and Standke 1992). Phytoplankton samples were enumerated following standard MECP methods, as described in Paterson et al. (2008). Briefly, samples were analyzed using inverted microscopy and Utermöhl counting chambers by algal specialists to obtain estimates of biomass and community composition, and cell counts were expressed as biovolume (Hopkins and Standke 1992). The algal specialists were retained by the MECP and generally had over 20 years of experience in enumerating phytoplankton samples. All of the spring phytoplankton samples analyzed in this study were counted by a single algal specialist. Taxa were predominantly identified to species level (some were identified to genus level and some to a higher taxonomic level), and a minimum of 400 'pieces' (singly occurring cells or colonies) were enumerated, in accordance with previous studies conducted by the MECP (e.g., Paterson et al. 2008; Winter et al. 2008), to ensure accurate representation of the phytoplankton taxa in each sample. Taxa present at <0.5 μ^3·mL, which were noted as present but not expressed as an exact biovolume, were assigned a value of 0.25 μ^3·mL (as per Winter et al. 2008).

A spring phytoplankton data set was compiled for the first phytoplankton sample collected after the ice-off date for each monitoring year. Enumerated spring phytoplankton samples were not available for all years. Specifically, phytoplankton data were not available for the following years and lakes: Blue Chalk: 1976, 1984, 1986, 1989, 1994-1995, 2003-2004; Red Chalk (Main Basin): 1985, 1994-1995, 2003-2007; Plastic: 1984; Dickie: 1986; Harp: 1986, 1989-1990, 1994-1995, 2003-2004.

An ice-free season composite phytoplankton data set was also compiled for each of the study lakes using annual composite phytoplankton samples from each lake for each year. This data set was used to compare changes in the spring phytoplankton with those in the ice-free season composite phytoplankton samples. Lakes were sampled throughout the ice-free season at a sampling frequency of weekly, bi-weekly, or monthly and these sub-samples were combined into annual ice-free season composite samples. Enumerated ice-free season composite samples were available from 1981 to 2011 for each study lake, with the exception of 1983, when phytoplankton data were available for Plastic Lake only. Enumerated ice-free season composite phytoplankton samples were also available from 1979 to 1980 for Plastic Lake only.

Volume-weighted, whole-lake water chemistry samples were collected by pumping water from each odd metre from a depth of 0.1 m to the bottom of the lake. Water chemistry samples were filtered through 80-μm mesh in the field and analysed at the DESC laboratory following standard MECP analytical methods (Ontario Ministry of the Environment 1983). The following water chemistry parameters were measured for each lake: Gran alkalinity, pH, conductivity, and concentrations of calcium, chloride, dissolved inorganic carbon, dissolved organic carbon, iron, potassium, magnesium, sodium, ammonia/ammonium, nitrate/nitrite, total Kjeldahl nitrogen, total phosphorus, reactive silicate, and sulphate. Water chemistry data from the first sampling date after ice-off were used, matching the first spring phytoplankton sample date, when possible. The number of years when spring water chemistry data were not available for the same date as spring phytoplankton sample collection ranged from five to nine years per lake, and most (86%) occurred prior to 1993. When spring water chemistry data were not available for the spring phytoplankton sample collection date, data from the first available spring water chemistry sample collection date were used; this date was an average of 6.1 days after the phytoplankton sample collection date. Spring phytoplankton and water chemistry sample collection dates for each of the five study lakes are provided in Appendix I.

Meteorological data, including air temperature and precipitation, were collected from three to four stations run by the MECP that are located in proximity to the study lakes (one station near each of

Plastic (PCP2), Heney (HYP2), and Harp (HPP2) lakes; one station (DOR2/PT1P) near the DESC office in Dorset; Figure 1). Meteorological data are available from only one station (DOR2) prior to 1984. For years when data were unavailable (2009), data from the Muskoka Airport Environment Canada weather station were used for all lakes (http://climate.weather.gc.ca/historical_data/search_historic_data_e.html; 44.97°N latitude, 79.30°W longitude). Meteorological data were collected daily, but precipitation was summed to monthly totals and air temperature was averaged to monthly means. Ice data (including ice-on and ice-off dates, number of ice-on days, etc.) were estimated at one lake within the general study area (Grandview Lake; 45.20°N latitude, 79.05°W longitude; Figure 1) and were used for all five study lakes.

2.3 Data analyses

Spring water chemistry data were tested for normality using the Shapiro-Wilk normality test (*stats* package in R). Any spring water chemistry variable which was not normally distributed ($P < 0.05$) was log-transformed in an effort to increase its normality. Transformed water chemistry data were used if the normality improved after transformation (i.e., Shapiro-Wilk test statistic increased). The spring water chemistry data set was missing data for occasional years, for some variables. No more than 26 parameter-year gaps in the spring data set existed for each lake, with the percentage of missing data ranging from 1.78% to 4.25% for each lake. Gaps in the spring water chemistry data set were filled using linear regression (**lm** function in R) with a highly correlated variable ($r > 0.60$) from the same lake. Where there was no highly correlated variable ($r < 0.60$), the long-term average of the variable for all years available at the lake was used.

Meteorological data were tested for normality and log-transformed, where necessary, using the methods described above for spring water chemistry data. Pearson correlation analyses were also conducted on the meteorological data sets (using the **cor** function in R) to determine the correlations of variables among meteorological stations. Results of the correlation analyses, which indicated that the Pearson correlation coefficient between stations was typically 0.99 – 1.00 for temperature and 0.69 – 0.90 for precipitation, were used to inform methods used to fill in occasional missing values in the meteorological data sets. To fill data gaps ranging from one day to two weeks, direct substitution using data from the nearest station was implemented for temperature. For precipitation, weighted substitution from all stations was used, where the weight allocated to each station was determined by distance of the station (i.e., closer stations were allocated more weight). For longer data gaps (two weeks to multiple years), linear regression with the most highly correlated station was used. Meteorological data were analysed as seasonal variables: winter (December – February), spring (March – May), summer (June – August), and fall (September – November). As this study examines spring phytoplankton samples which were collected in April or May of each year, the previous year's summer and fall meteorological data were used to explore the influence of climate on spring phytoplankton. The same meteorological data set was used for both Blue Chalk and Red Chalk (Main Basin) lakes since they are adjacent to each other.

Mann-Kendall trend tests were conducted on the spring water chemistry and climate variables for each study lake (using the *wq* package in R) to determine whether or not monotonic temporal trends were present in the data. As the performance of multiple Mann-Kendall trend tests may increase the occurrence of false positives (i.e., increased Type I error), a correction for the false discovery rate (FDR) was applied to the Mann-Kendall trend test results, following methods outlined in Yan et al. (2008b).

Spring and ice-free season phytoplankton data were analysed at the class level (i.e., diatoms, chlorophytes, chrysophytes, cryptophytes, cyanophytes, and dinoflagellates). Euglenoids were excluded from analyses, as they never exceeded 4% of the relative biovolume in a given spring or ice-free season phytoplankton sample and averaged less than 0.2% of the relative biovolume for each study lake over the time period examined. Both absolute ($mm^3 \cdot m^{-3}$) and relative (%) spring and ice-free season phytoplankton biovolumes were analysed. However, the majority of data analyses were conducted on the relative spring and ice-free season phytoplankton biovolumes in order to be consistent with previous analyses conducted on the DESC ice-free season composite phytoplankton samples (i.e., Paterson et al. 2008).

Mann-Kendall trend tests were conducted on the spring phytoplankton data using the *wq* package in R to determine if monotonic temporal trends occur in the relative and absolute phytoplankton data, and results were corrected for the FDR as described above. Detrended correspondence analyses (DCA; *vegan* package in R, **decorana** function) indicated primary axes lengths for the biological data of less than two standard deviations and so linear ordination methods (principal components analysis, PCA and redundancy analysis, RDA) were used to explore temporal patterns of variation in abundance and composition of the spring phytoplankton communities. Spring phytoplankton data were square-root transformed to normalize the variables and equalize variances prior to data analyses. Exploratory PCAs were conducted using the *vegan* package in R for both relative and absolute phytoplankton biovolumes. The R function **rda** was used to perform PCAs, with species scaled to unit variance (scale=TRUE), species scores scaled by eigenvalues, and site scores unscaled (scaling=2).

Variance partitioning analysis (VPA) was conducted on the spring phytoplankton relative biovolume data following methods outlined in Paterson et al. (2008) and Leavitt et al. (1999) to determine the proportion of variation in the phytoplankton community composition explained by unique effects of spring water chemistry and meteorological variables, and their covariation. First, constrained ordinations with permutation tests were conducted in order to select the water chemistry and climate variables to be included in the VPA. Here, RDAs were conducted one environmental variable at a time using the *vegan* package (**rda** function) in R. Permutation tests were conducted using the **permutest** function in R (with 999 permutations) to assess the significance of the constraining variables. Environmental variables that explained a significant portion of the phytoplankton variation ($P < 0.1$) were selected for the VPA. This reduced the number of explanatory variables to one to eight variables per category (water chemistry and climate; Table 5). This variable selection process followed methods used by Paterson et al. (2008). In the one instance where only one significant variable was selected (Plastic Lake climate), a second variable which was not significant ($P = 0.11$) was included. As the number of variables selected for each category can influence the percent variance explained by the category, PCAs were conducted for each lake and each category. The first two axes of the PCAs were used as environmental input variables for the VPA (i.e., water chemistry PCA axes 1 and 2; climate PCA axes 1 and 2). Next, a series of RDAs was run for each lake, as follows: (1) one RDA was run with all four variables (i.e., two water chemistry PCA axes and two climate PCA axes) in order to measure the total amount of variation in the relative phytoplankton biovolume that could be explained by the water chemistry and climate variables; (2) two partial RDAs were run, with one category (i.e., water chemistry or climate) as explanatory variables and the other category partialled out as co-variables, in order to determine the amount of variation explained uniquely by each category; (3) the percent shared variance was calculated by subtracting the variation unique to each category measured in the second step from the total variation measured in the first step; (4) the unexplained variance was calculated by subtracting the total explained variation measured in the first step from 100%.

An exploratory comparison of the spring phytoplankton biovolume data and ice-free season phytoplankton biovolume data was conducted by plotting the spring phytoplankton biovolume against the ice-free season phytoplankton biovolume. For each major phytoplankton group, spring and ice-free season biovolumes (absolute and relative) were plotted by lake. This comparison was undertaken in order to determine the extent to which the ice-free season phytoplankton signal was driven by higher spring phytoplankton abundances, as opposed to summer or fall phytoplankton abundances.

3.0 Results

3.1 Water chemistry

Significant temporal monotonic trends were observed in one or more lakes for 16 of the 17 spring water chemistry variables examined (Table 2; Appendix II). Plotted z-scores for each lake illustrate that similar trends have been observed across lakes for many of the spring water chemistry variables examined. Significant increasing trends were observed in spring alkalinity and dissolved organic carbon concentration across most lakes (*P* < 0.05), while significant decreases occurred for concentrations of calcium, magnesium, and sulphate (*P* < 0.001). Significant decreases in spring concentrations of iron (Plastic and Harp lakes), potassium (Red Chalk (Main Basin), Plastic, and Harp lakes), and nitrate and nitrite (Red Chalk (Main Basin) and Plastic lakes; *P* < 0.05) were also observed in some lakes. Significant declines in spring total phosphorus concentrations occurred at Red Chalk (Main Basin) and Harp lakes (*P* < 0.01).

Table 2. Mann-Kendall monotonic trend test results of water chemistry variables for Blue Chalk (BC), Red Chalk (Main Basin; RCM), Plastic (PC), Dickie (DE), and Harp (HP) lakes during the spring seasons of 1976 to 2011 (except for Blue Chalk: 1977 to 2011; Plastic: 1979 to 2011). Arrows indicate directionality of significant trends after correction for the false discovery rate; dashes indicate no significant trend.

Variable	BC	RCM	PC	DE	HP
Alkalinity	**↑**	—	—	**↑**	↑
Ca^{2+}	**↓**	**↓**	**↓**	**↑**	**↓**
Cl^{-}	—	**↓**	—	**↑**	**↑**
Conductivity	**↓**	**↓**	**↓**	**↑**	—
DIC	↑	—	—	—	—
DOC	**↑**	**↑**	—	↑	**↑**
Fe	—	—	↓	—	**↓**
K^{+}	—	↓	**↓**	—	**↓**
Mg^{2+}	**↓**	**↓**	**↓**	—	**↓**
Na^{+}	—	—	—	**↑**	**↑**
$NH_3 + NH_4^{+}$	↑	—	↓	—	—
$NO_2^{-} + NO_3^{-}$	—	↓	↓	—	—
TKN	—	—	—	—	—
pH	—	—	—	**↑**	↑
TP	—	↓	—	—	**↓**
SiO_3^{2-}	—	—	**↓**	—	**↑**
SO_4^{2-}	**↓**	**↓**	**↓**	**↓**	**↓**

Note: Arrows indicate significance at *P* < 0.05 after correcting for the false discovery rate; bold arrows indicate significance at *P* < 0.001.

For some variables, temporal trends were different between lakes with more developed watersheds (i.e., Dickie, Harp) compared to those with less developed watersheds (i.e., Blue Chalk, Red

Chalk (Main Basin), Plastic). For example, significant increases in spring chloride and sodium concentrations ($P < 0.001$) occurred at Dickie and Harp lakes, but not at the lakes with less developed watersheds. Significant increases in pH ($P < 0.05$) occurred at Dickie and Harp lakes, while no trends in spring pH were documented at Blue Chalk, Red Chalk (Main Basin), or Plastic lakes. Conductivity decreased significantly ($P < 0.001$) in the three lakes with less developed watersheds.

3.2 Climate

A significant increase in fall mean air temperature occurred at four of the five study lakes (i.e., three of the four meteorological stations; $P < 0.01$) after correction for the false discovery rate (Table 3; Appendix III). A significant increase in fall mean air temperature was not observed at Harp Lake after correction for the false discovery rate. No significant temporal monotonic trends were observed in seasonal precipitation at any of the study lakes. A significant decrease in the number of ice-on days occurred during the study period (Sen's slope: -0.56 days·year^{-1}; $P < 0.01$), but no significant monotonic trend was observed in the ice-off date.

Table 3. Mann-Kendall monotonic trend test results of climate variables for Blue Chalk (BC), Red Chalk (Main Basin; RCM), Plastic (PC), Dickie (DE), and Harp (HP) lakes from 1976 to 2011. Arrows indicate directionality of significant trends; dashes indicate no significant trend.

Variable	BC/RCM	PC	DE	HP
Winter Temperature	—	—	—	—
Spring Temperature	—	—	—	—
Summer Temperature	—	—	—	—
Fall Temperature	↑	**↑**	↑	—
Winter Precipitation	—	—	—	—
Spring Precipitation	—	—	—	—
Summer Precipitation	—	—	—	—
Fall Precipitation	—	—	—	—
Ice-off Date[1]		—		
Ice-on Days[1]		↓		

Note: Arrows indicate significance at $P < 0.05$ after correcting for the false discovery rate; bold arrows indicate significance at $P < 0.001$. Temperature values are presented as mean air temperature.
[1] Variable was estimated at one lake within the general study area and used for all five study lakes.

3.3 Phytoplankton community composition

Spring phytoplankton communities at each of the study lakes were composed mainly of chrysophytes, cryptophytes, diatoms, dinoflagellates, chlorophytes, and cyanophytes. Communities at all five study lakes were dominated by chrysophytes during the spring period, with the mean relative spring chrysophyte biovolume ranging from 35% (Plastic Lake) to 58% (Dickie Lake) during the study period (Figure 2). Cryptophytes were the second most abundant phytoplankton class at Red Chalk (Main Basin), Dickie, and Harp lakes, with the mean relative spring biovolume ranging from 13% (Dickie Lake) to 22% (Harp Lake). Diatoms were the second most abundant spring phytoplankton class at Blue Chalk Lake (mean relative spring biovolume: 21%), while dinoflagellates were the second most abundant spring phytoplankton class at Plastic Lake (mean relative spring biovolume: 31%). The least prevalent spring phytoplankton class across the study lakes was cyanophytes, with the mean relative spring cyanophyte biovolume ranging from 0.3% (Dickie Lake) to 4.5% (Harp Lake).

Inter-annual variability of total spring phytoplankton biovolume was high within each study lake, but varied across lakes (Appendix IV). The coefficient of variation for total spring phytoplankton biovolume was lowest at Harp Lake (56%), moderate at Plastic and Blue Chalk lakes (79% and 80%, respectively), and highest at Red Chalk (Main Basin; 118%) and Dickie (133%) lakes. Absolute phytoplankton biovolume data indicate the magnitude of chrysophyte blooms during certain years, with absolute chrysophyte biovolume reaching over 5,400 $mm^3 \cdot m^{-3}$ in one bloom (Dickie Lake, 2002).

PCA biplots of spring phytoplankton data show the temporal patterns of change in spring phytoplankton community composition within each study lake (Figure 3; Appendix VI). The first PCA axis explained 35%–49% of the variation in the relative phytoplankton biovolume (absolute biovolume = 32 to 41%), while the second PCA axis explained 22%–27% of the variation in the relative phytoplankton biovolume (absolute biovolume = 20 to 26%). At Blue Chalk Lake, the progression of sample scores along PCA axis 1 identifies an increase in relative biovolume of chrysophytes during the 2000s and early 2010s. Higher relative biovolumes of chrysophytes present in spring 1982, 1990, and 1998 position those years with the 2000s and 2010s along PCA axis 1. At Dickie Lake, the shift of sample scores along PCA axis 1 indicates an increase in relative biovolume of chlorophytes, cryptophytes, and cyanophytes in the 2000s. The lack of distinct temporal patterns in the PCA biplots for Harp, Plastic, and Red Chalk (Main Basin) lakes demonstrate a lack of temporal trend and substantial inter-annual variation within the spring phytoplankton communities.

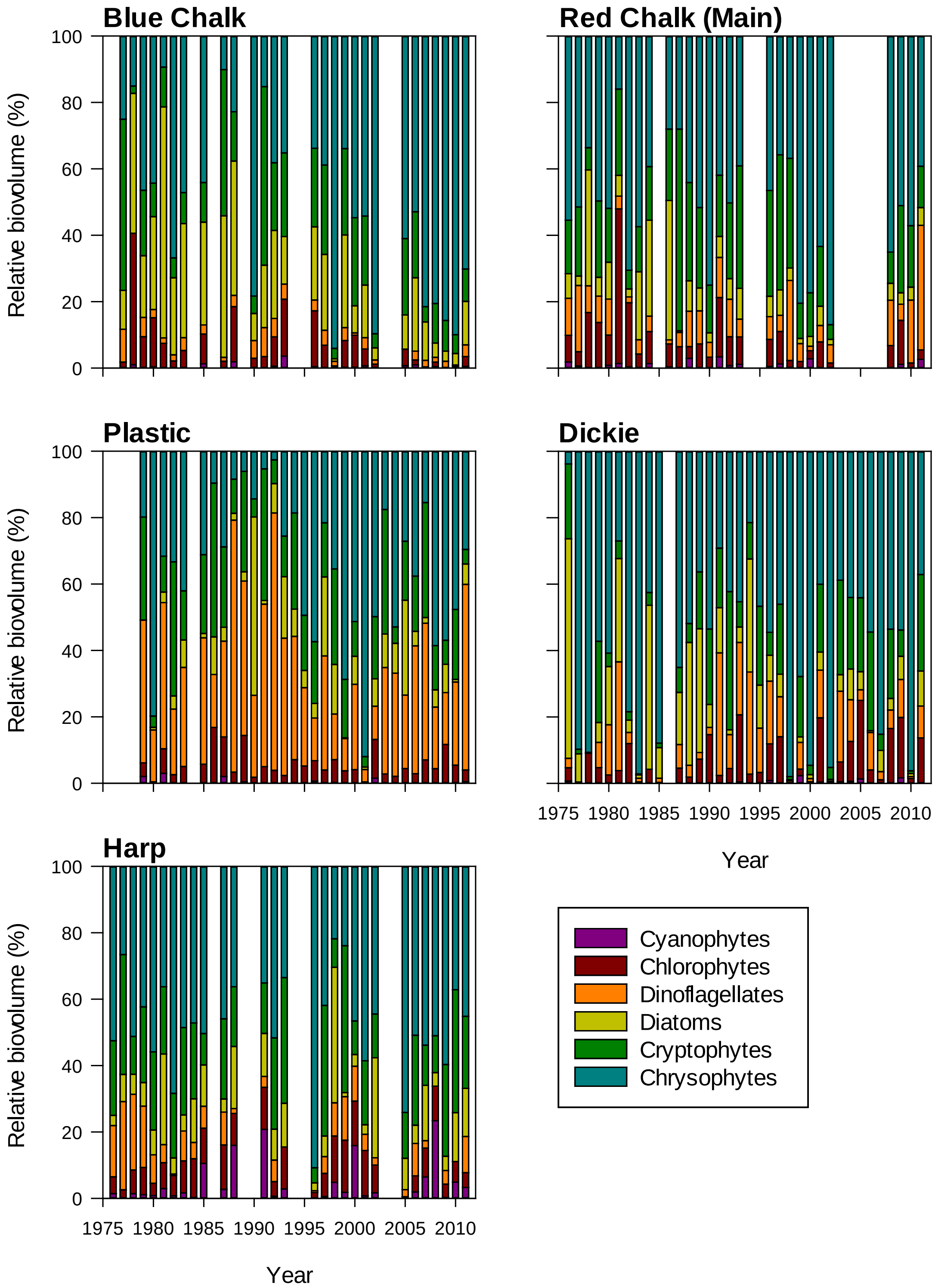


Figure 2. Temporal patterns of relative biovolume (%) for the major phytoplankton groups in spring samples from Blue Chalk, Red Chalk (Main Basin), Plastic, Dickie, and Harp lakes, Ontario, Canada from 1976 to 2011 (except for Blue Chalk: 1977 to 2011; Plastic: 1979 to 2011).

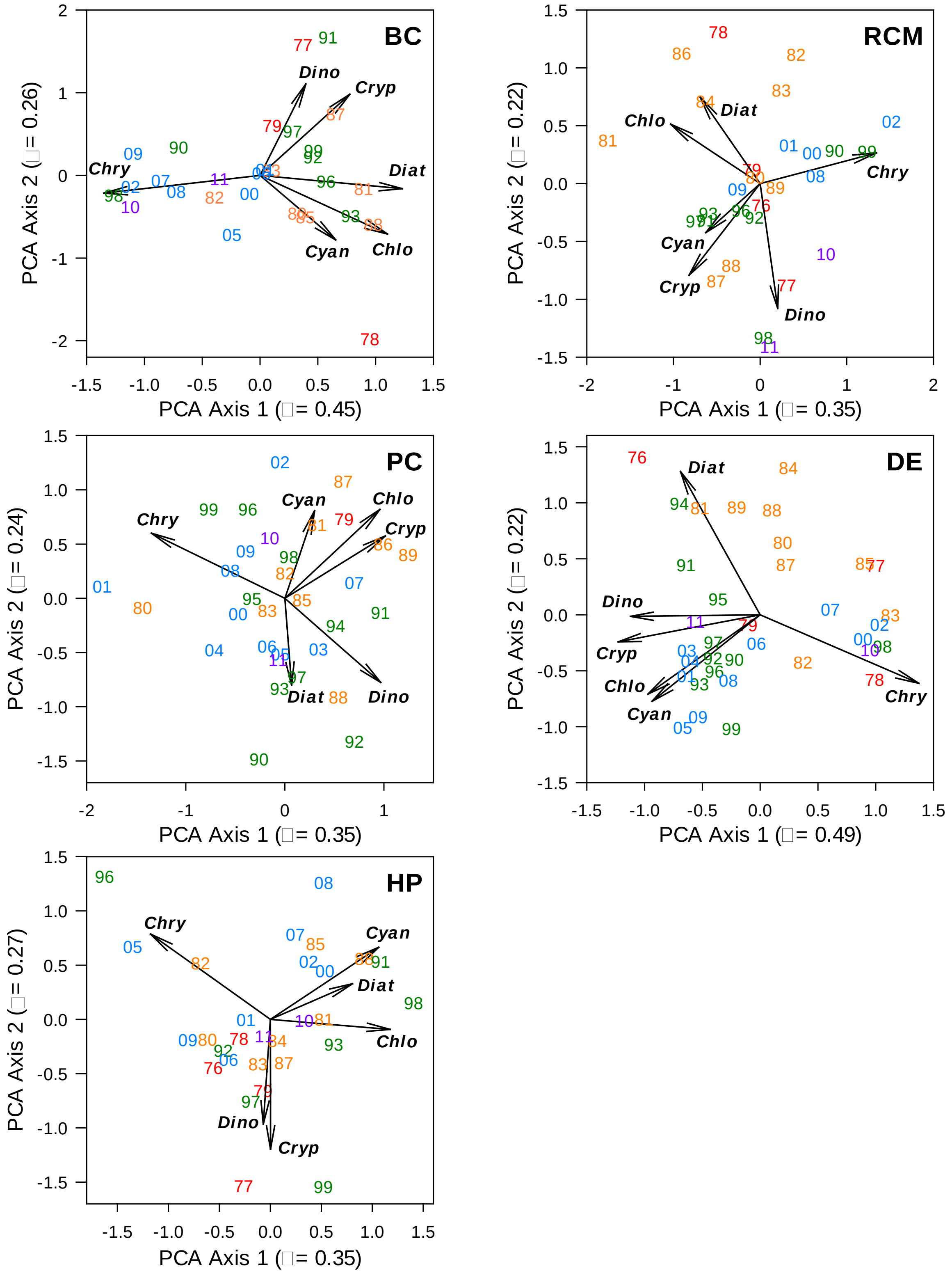


Figure 3. Principal components analysis (PCA) ordination plots showing the position of site years in relation to the relative biovolume of major phytoplankton groups. Lake codes: BC, Blue Chalk; RCM, Red Chalk (Main Basin); PC, Plastic; DE, Dickie; HP, Harp. Algal groups: Chry, chrysophytes; Cyan, cyanophytes; Diat, diatoms; Chlo, chlorophytes; Cryp, cryptophytes; Dino, dinoflagellates. Site years: red, 1970s; orange, 1980s; green, 1990s; blue, 2000s; purple, 2010s.

Significant monotonic trends in the relative biovolume of spring phytoplankton classes were documented at Blue Chalk Lake during the study period, but not at the other four study lakes (Table 4). At Blue Chalk Lake, the relative biovolume of diatoms and chlorophytes decreased ($P < 0.01$), while the relative biovolume of chrysophytes increased ($P < 0.01$).

Significant monotonic trends in the absolute biovolume of spring phytoplankton classes were observed at Blue Chalk and Dickie lakes (Appendix V). The absolute biovolume of chrysophytes increased at Blue Chalk Lake (Sen's slope 14.4 $mm^3 \cdot m^{-3} \cdot year^{-1}$; $P < 0.01$), as did the total phytoplankton biovolume (17.7 $mm^3 \cdot m^{-3} \cdot year^{-1}$; $P < 0.01$). At Dickie Lake, significant increases were observed in the absolute biovolume of chlorophytes (0.8 $mm^3 \cdot m^{-3} \cdot year^{-1}$; $P < 0.05$), cryptophytes (1.8 $mm^3 \cdot m^{-3} \cdot year^{-1}$; $P < 0.01$), and cyanophytes (0.04 $mm^3 \cdot m^{-3} \cdot year^{-1}$; $P < 0.01$). No significant temporal monotonic trends were observed in absolute phytoplankton biovolume at Harp, Plastic, or Red Chalk (Main Basin) lakes after correction for the false discovery rate.

Table 4. Sen's slopes and *p*-values from Mann-Kendall trend tests for the relative abundance of the six major phytoplankton groups for each study lake.

	Statistics	BC	DE	HP	PC	RCM
Chlorophytes	Sen's slope (%·$year^{-1}$)	**-0.21**	0.12	0.04	-0.01	-0.15
	p value	**<0.01**	0.20	0.60	0.85	*0.01
Chrysophytes	Sen's slope (%·$year^{-1}$)	**1.69**	0.02	0.06	0.67	0.37
	p value	**<0.01**	0.99	0.79	0.15	0.26
Cryptophytes	Sen's slope (%·$year^{-1}$)	-0.10	0.30	-0.03	-0.26	0.00
	p value	0.55	*0.05	0.93	0.31	1.00
Cyanophytes	Sen's slope (%·$year^{-1}$)	0.00	0.01	0.04	0.00	0.00
	p value	0.89	*0.01	0.21	0.91	0.77
Diatoms	Sen's slope (%·$year^{-1}$)	**-0.83**	-0.29	0.05	0.09	-0.16
	p value	**<0.01**	*0.04	0.68	0.22	*0.04
Dinoflagellates	Sen's slope (%·$year^{-1}$)	-0.07	0.07	-0.26	-0.35	0.05
	p value	0.10	0.47	*0.02	0.30	0.38

Note: Lake codes: BC, Blue Chalk; DE, Dickie; HP, Harp; PC, Plastic; RCM, Red Chalk Main. Bold values indicate significance at $P < 0.05$ after correcting for the false discovery rate. An asterisk indicates significance at $P < 0.05$ only before correction for the false discovery rate.

Two-category variation partitioning analysis (VPA) was conducted on the spring phytoplankton relative biovolume data to determine the proportion of variation in the phytoplankton community composition explained by the unique effects of spring water chemistry and climate variables and their covariation. The subsets of significant environmental variables selected for the VPAs differed for each study lake (Table 5). The number of spring water chemistry variables selected for each lake ranged from two (Harp Lake) to eight variables (Blue Chalk and Plastic lakes). Conductivity was a significant explanatory variable for Blue Chalk, Red Chalk (Main Basin), Plastic, and Dickie lakes. Nitrate/nitrite was selected for Blue Chalk, Dickie, and Harp lakes. The remaining spring water chemistry variables were selected for one to two study lakes. The number of climate variables selected for each study lake ranged from two (Dickie and Plastic lakes) to four variables (Harp and Red Chalk (Main Basin) lakes). Temperature was selected for all lakes. Winter and/or fall mean air temperatures were selected at each study lake, while spring and/or summer mean air temperatures were also selected for Red Chalk (Main Basin), Dickie, and Harp lakes. Precipitation (summer) was selected only for Red Chalk (Main Basin) Lake. The number of ice-on days was selected for three lakes (Blue Chalk, Plastic, and Harp lakes), and ice-off date was selected for one lake (Harp Lake).

Table 5. Environmental variables selected to generate principal components analysis axes 1 and 2 scores used in the two-category variance partitioning analysis (VPA) of phytoplankton groups for Blue Chalk, Red Chalk (Main Basin), Plastic, Dickie, and Harp lakes.

	Blue Chalk	Red Chalk	Plastic	Dickie	Harp
Water chemistry	Alkalinity	Ca	Alkalinity	Conductivity	NO_2-NO_3
	Cl	Conductivity	Ca	Na	TN
	Conductivity	DOC	Conductivity	NH_3-NH_4	
	DOC		DIC	NO_2-NO_3	
	Mg		Mg	TP	
	NO_2-NO_3		Na	TN/TP	
	pH		SiO_3		
	SO_4		SO_4		
Climate	Fall T	Summer T	Fall T	Winter T	Winter T
	Winter T	Fall T	Ice-on days*	Spring T	Spring T
	Ice-on days	Winter T			Ice-off date
		Summer P			Ice-on days

Note: Air temperature, in °C; precipitation, in mm; T, temperature; P, precipitation. Asterisk indicates variable was not significant ($P > 0.1$); however, variable was included in VPA in order to include two variables in each category.

Spring water chemistry and climate variables explained a significant proportion of the temporal variation observed in spring class-level phytoplankton community composition at each of the five study lakes ($P < 0.05$), with total explained variation ranging from 23.3% (Plastic Lake) to 45.4% (Blue Chalk Lake; mean = 31.3%; Figure 4). Spring water chemistry variables explained a significant proportion of the variation in all study lakes with the exception of Red Chalk (Main Basin) Lake ($P < 0.05$; 11.6%–28.2%, mean = 18.9%), and explained the highest proportion of unique variation in the spring phytoplankton at Blue Chalk (28.2%), Plastic (13.6%), and Dickie (22.2%) lakes. Climate variables explained the highest proportion of unique variation at Red Chalk (Main Basin; 12.0%) and Harp (14.8%) lakes, but explained a significant proportion of the variation in Harp Lake only ($P < 0.05$). The covariation of spring water chemistry and climate variables explained 1.3%–13.2% (mean = 6.7%) of the total variation in the spring phytoplankton. The amount of unexplained variation ranged from 54.6%–76.7% (mean = 68.7%).

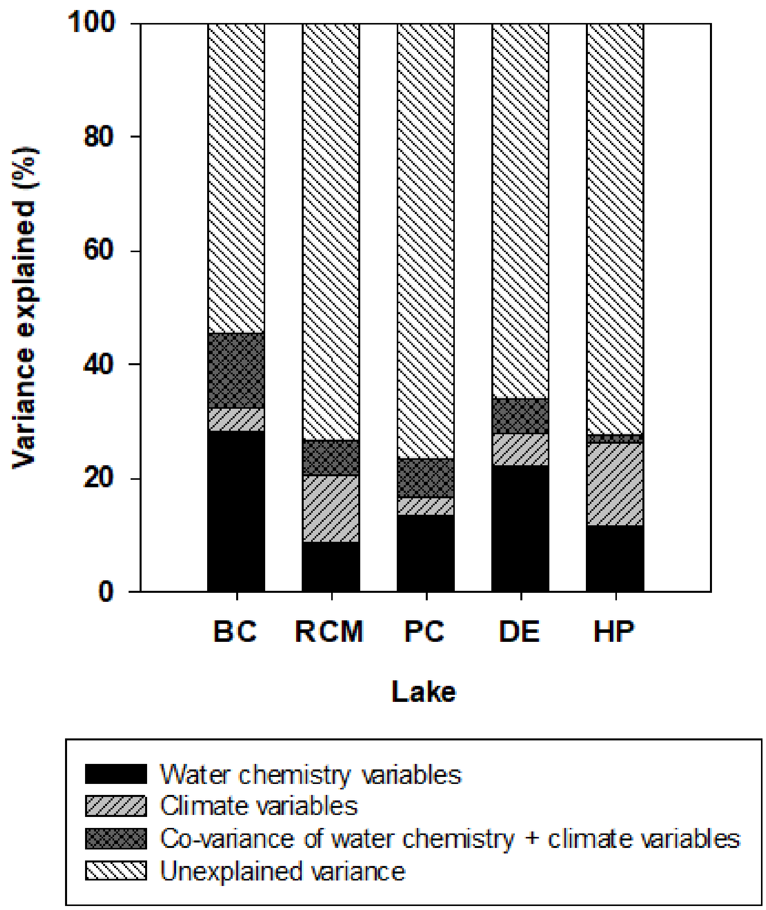


Figure 4. Results of two-category variance partitioning analysis (VPA) displaying the percentage of variation in the spring phytoplankton community composition data (relative biovolumes) explained by the unique and shared effects of water chemistry and climate variables at Blue Chalk (BC), Red Chalk (Main Basin; RCM), Plastic (PC), Dickie (DE), and Harp (HP) lakes, Ontario, Canada.

Spring phytoplankton biovolume was plotted against ice-free composite phytoplankton biovolume in order to compare the relative and absolute abundance of major phytoplankton groups during the spring sampling period and the ice-free season (Figure 5; Appendix VII; Appendix VIII). The comparative plots indicate interesting patterns with respect to the seasonal timing of variations in phytoplankton biovolumes in the study lakes. High spring biovolumes do not appear to translate to correspondingly high ice-free season biovolumes. Cryptophytes and dinoflagellates compose a higher proportion of the spring phytoplankton samples, in comparison to the ice-free season composite samples, at all study lakes. A similar pattern was observed for chrysophytes, whereby the spring phytoplankton samples generally contain a higher proportion of chrysophytes than the ice-free season composite phytoplankton samples; this is especially the case at Red Chalk (Main Basin) and Blue Chalk lakes. However, the proportion of chrysophytes is higher in the ice-free season composite samples than in the spring phytoplankton samples at Plastic Lake. Chlorophytes, cyanophytes, and diatoms generally compose a higher proportion of the ice-free season composite phytoplankton samples, in comparison with the spring phytoplankton samples, at all five study lakes.

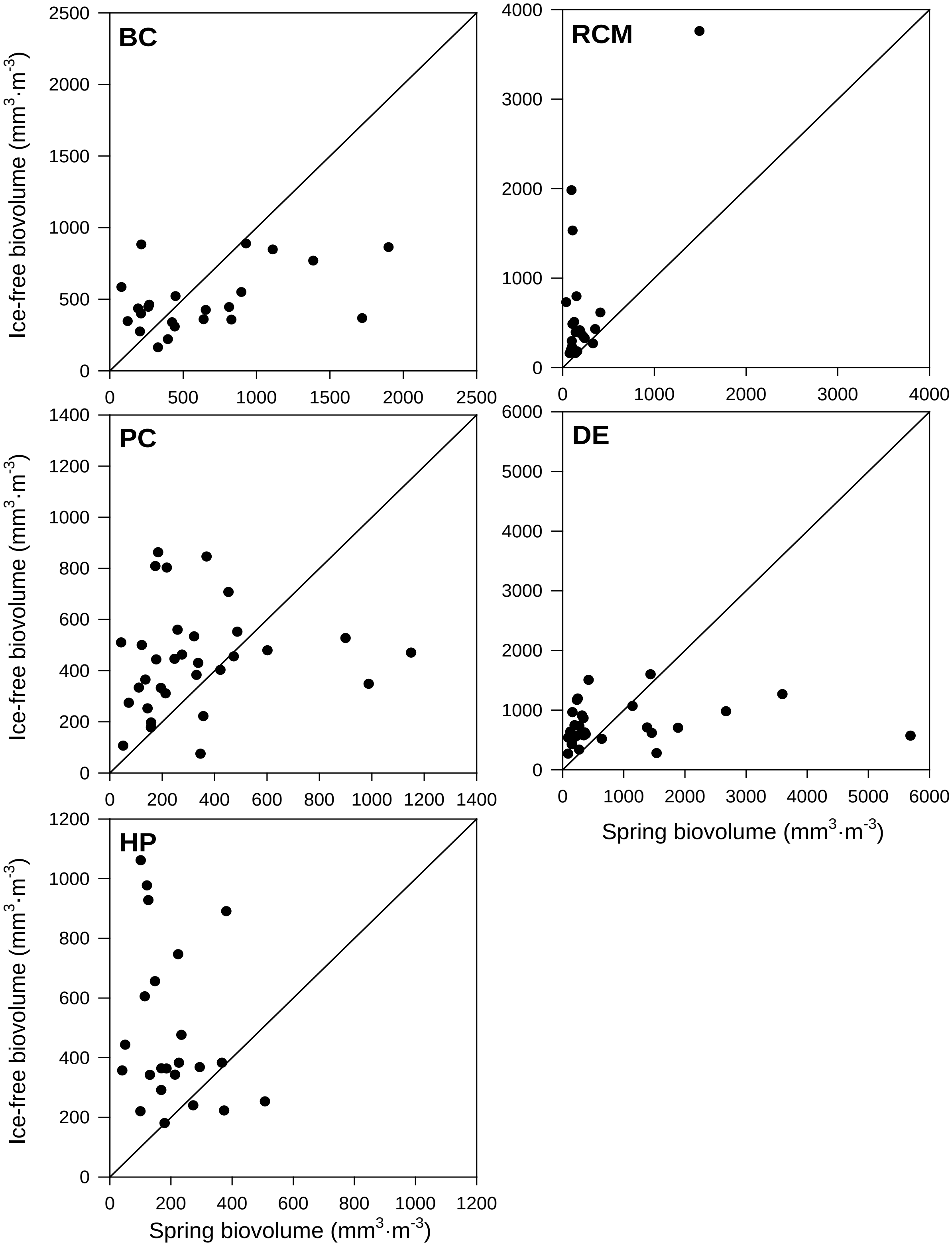


Figure 5. Comparisons of the total biovolume ($mm^3 \cdot m^{-3}$) of spring phytoplankton samples and ice-free season composite phytoplankton samples from Blue Chalk (BC), Red Chalk (Main Basin; RCM), Plastic (PC), Dickie (DE), and Harp (HP) lakes, Ontario, Canada. Diagonal lines indicate 1:1 lines.

4.0 Discussion

The spring period is important to phytoplankton communities. Spring is when processes such as snow melt, ice break-up, and water column mixing have the potential to influence the timing, magnitude, and composition of spring phytoplankton communities. Spring conditions and the spring phytoplankton bloom may affect lake conditions during the summer and fall seasons, as well as subsequent phytoplankton communities. For example, a shortened spring mixing period and earlier onset of stratification associated with climate warming can result in the incomplete replenishment of hypolimnetic oxygen concentrations in smaller lakes, which may lead to more frequent summer anoxic events and, consequently, enhanced internal nutrient loading (Beutel et al. 2008; Crossman et al. 2016a). Despite this importance, few studies have examined changes to the spring phytoplankton or the drivers behind those changes. Examination of only ice-free season composite phytoplankton samples may challenge our ability to understand important ecological signals that originate during the spring period. The purpose of this study is to determine the long-term changes in phytoplankton community composition and biomass during the spring period through an examination of spring phytoplankton samples from five lakes in the Muskoka-Haliburton region. Specifically, this study identifies which spring water chemistry and climate variables have changed since the mid- to late-1970s at the study lakes, identifies trends in spring phytoplankton community composition and biomass, quantifies the physical and chemical drivers explaining observed variation in the spring phytoplankton, and compares changes in spring phytoplankton communities with those in annual ice-free season composite phytoplankton samples from the same lakes.

4.1 Water chemistry and climate

Trends observed in spring water chemistry and climate variables at the five study lakes are consistent with those reported in other studies of south-central Ontario lakes (e.g., Palmer et al. 2011). The changes are also consistent with the observed effects of sulphur deposition and recovery, climate warming, and shoreline development on water quality parameters (e.g., Dillon et al. 2003; Watmough and Dillon 2003; Keller et al. 2008).

Effects of acid deposition and recovery in the Muskoka-Haliburton region were noticeable in the long-term spring water chemistry records at the five study lakes. Significant decreases in spring lake sulphate concentrations occurred at all five study lakes ($P < 0.001$), and corresponding significant increases in spring lake alkalinity and pH at a subset of the lakes ($P < 0.05$) can be attributed to large reductions in sulphur deposition within the region (Dillon et al. 2003; Jeffries et al. 2003; Dillon et al. 2007; Watmough et al. 2016). Similarly, the significant increases in spring DOC concentrations observed at four of the five study lakes ($P < 0.05$) may be attributed to decreases in lake acidity, which reduces photochemical loss of DOC and precipitation of DOC with metals (Keller et al. 2008). Increases in spring DOC concentrations may also be caused by declining calcium concentrations associated with reductions in acid deposition, as declines in calcium concentrations have been shown to reduce DOC adsorption in mineral soils, thereby increasing DOC export from lake catchments (Kerr and Eimers 2012). The significant declines in spring concentrations of base cations observed at several of the study lakes (calcium, magnesium, and potassium; $P < 0.05$) are likely due to a combination of decades of acid deposition (i.e., acidic leaching of catchment soil reserves) and forest harvesting (Watmough and Dillon 2004; Jeziorski and Smol 2017).

Effects of climate warming and its influence on spring water chemistry variables are evident in meteorological and lake monitoring data sets within the Muskoka-Haliburton region. Significant increase in fall mean air temperature at four of the five study lakes ($P < 0.05$) and decline in the number of ice-on days ($P < 0.05$) are consistent with a warming climate (Mortsch and Quinn 1996; Magnuson et al. 1997; Futter 2003). However, ice data collected at Grandview Lake (located centrally within the study area) indicate that the duration of the ice-on season has decreased due to a significantly later ice-on date (Sen's slope: 0.56 days·year^{-1}; P-value < 0.001), with no significant trend observed in the ice-off date. This is contrary to trends documented in the literature, in which shorter ice-on seasons are often attributed to earlier ice break-up dates (e.g., Futter 2003; Duguay et al. 2006). Significant increases in spring DOC concentrations observed at four of the five study lakes ($P < 0.05$) may be due in part to climate change, as rates of terrestrial decomposition and DOC export from lake watershed are expected to increase with a warming climate (Keller et al. 2008). Conversely, the significant decreases in spring total phosphorus concentrations observed at two of the five study lakes ($P < 0.01$) may be attributed, in part, to reduced export from lake watersheds associated with climate warming.

As documented in Palmer et al. (2011)'s examination of regional water quality changes, the effects of lakeshore development and road proximity were noticeable on spring water chemistry trends. Significant increases in spring chloride and sodium concentrations occurred at Dickie and Harp Lakes ($P < 0.001$), but did not occur at the study lakes with less developed watersheds (i.e., Plastic, Blue Chalk, and Red Chalk (Main Basin) lakes), which is to be expected due to road salt application (Dugan et al. 2017; MacDougall et al. 2017). Palmer et al. (2011) found that lakeshore development and proximity to roads were associated with increases in concentrations of sodium and chloride, as well as smaller conductivity decreases; this is consistent with changes observed in spring water chemistry at the five study lakes. The declines in spring total phosphorus concentrations observed at two of the five study lakes ($P < 0.01$) may also be attributed to catchment reforestation which reduces phosphorus export to lakes, as the establishment of new vegetation increases phosphorus uptake within the watershed (Hall and Smol 1996; Dillon and Molot 2005; Crossman et al. 2016b).

4.2 Phytoplankton community composition

Chrysophytes were the dominant phytoplankton class at all five study lakes during the spring period (mean relative spring biovolume: 35-58%). Chrysophytes are typically associated with low to moderate nutrient concentrations, low alkalinity and conductivity, and neutral to slightly acidic pH (Sheath and Wehr 2015), conditions which are representative of the study lakes. Chrysophytes are able to compete for low levels of dissolved phosphorus and other nutrients, often allowing them to dominate in water bodies with these conditions (Sheath and Wehr 2015), such as lakes in the Muskoka-Haliburton region of Ontario. Scaled chrysophytes (e.g., *Chrysosphaerella*, *Dinobryon*, *Synura*, *Uroglena*) also require large quantities of silica (Sheath and Wehr 2015), which may cause competition for silica uptake with diatoms. Cyanophytes, which are often associated with high nutrient concentrations, were the least abundant phytoplankton class at all five study lakes (mean relative spring biovolume: 0.3-4.5%).

Trends in spring phytoplankton community composition and biomass at the study lakes varied from those described in studies that examine phytoplankton composition during summer months, or across annual to multi-annual time periods. In general, few monotonic temporal trends were documented in the spring phytoplankton. For example, although increases in the biovolumes of chrysophytes have been widely observed in ice-free season composite samples, as well as declines in the biovolumes of diatoms (Paterson et al. 2004; Paterson et al. 2008), these changes were documented in only one of the study lakes (Blue Chalk) when examining spring phytoplankton assemblages. Similarly, total biovolume was observed to increase in only one lake (Blue Chalk), with no significant trend in total biovolume at four of the five study lakes. This is contrary to findings of Palmer et al. (2011), who observed a decline in ice-free season chlorophyll *a* concentration at 70% of lakes in south-central Ontario, when comparing changes from the 1980s to 2004-2005. Interestingly, although Blue Chalk and Red Chalk (Main Basin) lakes are hydrologically connected, very different trends in the spring phytoplankton were observed at each lake. This may indicate the heterogeneity of lake responses to environmental stressors, with respect to spring phytoplankton community composition and biomass, in the Muskoka-Haliburton region.

The strong monotonic temporal trends observed in spring water chemistry variables, and to some extent climate variables, have largely not translated into monotonic trends in spring phytoplankton biovolume at the study lakes. This may indicate that other explanatory factors are at play. It is also possible that the high inter-annual variation observed in the spring phytoplankton may obstruct the detection of temporal trends. In addition, enumerated spring phytoplankton samples were not available for each monitoring year during the period examined, and these gaps in the data sets differed across study lakes. This made comparisons between study lakes difficult. For example, it is difficult to say if the lack of temporal trends in spring phytoplankton communities across lakes is a true pattern or is an artifact of the difference in years examined.

4.3 Drivers of variation in spring phytoplankton

Spring water chemistry variables, independent of climate, explained a significant proportion of temporal variation in the composition of spring phytoplankton communities at four of the five study lakes, and explained the highest proportion of unique variation in the spring phytoplankton at three lakes (Blue Chalk, Plastic, and Dickie). This indicates that spring phytoplankton community composition is strongly affected by water chemistry variables not associated with patterns of climate change. Instead, variation in the spring phytoplankton may be primarily explained by water chemistry variables associated with other environmental stressors, such as shoreline development and acid deposition and recovery. At these three lakes (Blue Chalk, Plastic, and Dickie), the co-variance of water chemistry and climate variables explained the next highest proportion of the variation. This indicates that water chemistry variables associated with climate warming, such as DOC and TP, may also influence the composition of spring phytoplankton communities. For example, increases in terrestrial DOC inputs to lakes observed with climate warming are hypothesized to lead to declines in primary productivity and the nutritional content of lake food webs (Creed et al. 2018).

Climate variables, independent of water chemistry, explained a significant proportion of the variation in one of the five study lakes (Harp Lake), and explained the highest proportion of unique variation in the spring phytoplankton at two lakes (Red Chalk (Main Basin) and Harp). Interestingly, Red Chalk (Main Basin) and Harp lakes are the deepest of the study lakes with the largest volumes. Large lakes are sensitive to physical processes associated with lake cooling (i.e., fall turnover and ice-on), as their large volumes of water take longer to cool during the fall and winter seasons (Crossman et al. 2016a). A delay in fall turnover associated with climate warming may lead to increased hypolimnetic depletion of oxygen concentrations and increased internal nutrient loading (Jankowski et al. 2006), thereby affecting phytoplankton communities. This is consistent with the significant increases in fall mean air temperature ($P < 0.05$) and significantly later ice-on date ($P < 0.001$) observed at the study lakes, and indicates that lake physical processes occurring during the fall may influence spring phytoplankton communities in the following year. Ice-off date and the number of ice-on days were significant explanatory variables at Harp Lake, in addition to winter and spring mean air temperatures. Grazing variables explained a significant portion of the ice-free season phytoplankton variance in Paterson et al. (2008)'s study, likely due to the invasion of the lake by *Bythotrephes* in the early 1990s, and it is hypothesized that the duration of the ice-on season, in combination with winter and spring mean air temperatures, may affect grazing pressure on spring phytoplankton by overwintering zooplankton (Lewandowska and Sommer 2010; Yang et al. 2016). Thus, the significance of the climate variables in explaining variation in the spring phytoplankton at Harp Lake may be an indirect effect of biological drivers (i.e., grazing pressure by overwintering zooplankton affected by changes in climate).

A relatively high proportion of variance was not explained by spring water chemistry variables, climate variables, or the co-variance of the two, indicating that other drivers play an important role in explaining the observed inter-annual variation in the spring phytoplankton community composition. Other variables which could explain variation in the phytoplankton include biological drivers (e.g., zooplankton), other climate factors not analyzed in this study (e.g., effects of time lags between climate and biotic responses), and light levels. Additionally, it is possible that winter phytoplankton blooms develop in the study lakes under ice cover (e.g., Twiss et al. 2012), which could affect the magnitude and composition of the spring phytoplankton bloom by depleting available nutrients.

Although we may expect to see a grouping of developed lakes (Harp and Dickie) and undeveloped lakes (Blue Chalk, Red Chalk, Plastic), the VPA indicates that differences in the relative influence of climate and water chemistry are larger within each category than between them. For example, Blue Chalk and Red Chalk (Main Basin) are hydrologically connected to each other but show very different VPA results.

4.4 Comparison with ice-free composite phytoplankton samples

Changes in spring phytoplankton communities were compared with those previously detected in ice-free season phytoplankton communities from the same lakes (i.e., Paterson et al. 2008) to determine whether changes observed in the ice-free season composite samples are driven by the spring season. Paterson et al. (2008) examined ice-free season composite phytoplankton samples for seven lakes in the Muskoka-Haliburton region (Blue Chalk, Chub, Crosson, Dickie, Harp, Plastic, and Red Chalk (Main Basin)) from 1981 to 2003.

Changes in the spring phytoplankton correspond to a limited extent with changes observed in the ice-free composite phytoplankton samples by Paterson et al. (2008). Significant increases in the relative biovolume of chrysophytes were documented at six of the seven study lakes (Blue Chalk, Chub, Crosson, Dickie, Harp, and Red Chalk (Main Basin)) during the ice-free season, while significant declines in the relative biovolume of diatoms at were also observed at several lakes (Blue Chalk, Harp, and Red Chalk (Main Basin); Paterson et al. 2008). Considering the increase in chrysophytes during the ice-free season at many of the study lakes, along with the observation that chrysophytes are a dominant component in the spring (Appendix VII; Appendix VIII), we would expect to see a similar increasing trend in the spring phytoplankton. However, this was observed in only one lake during the spring period (Blue Chalk). This may indicate that chrysophytes are no longer increasing in biovolume (i.e., the eight additional years examined in the spring phytoplankton dampen the trends seen in the ice-free composites analyzed by Paterson et al. (2008)) or that the inter-annual variability in spring phytoplankton biovolumes may obscure a clear trend. Following similar logic, we may not be surprised that the declines in diatoms observed by Paterson et al. (2008) are largely not observed in the spring data, as diatoms in the study lakes appear to be more prevalent in the summer and fall seasons (Appendix VII; Appendix VIII). Significant declines in spring diatoms were observed at Blue Chalk Lake.

Paterson et al. (2008) also observed significant declines in cyanophytes in Crosson Lake, as well as declines in dinoflagellates in Dickie and Plastic Lakes. Although we would expect to see these declines in dinoflagellates apparent in the spring period, since dinoflagellates are more abundant during the spring period (Appendix VII; Appendix VIII), no significant monotonic trends in dinoflagellates were observed in the spring data. The large inter-annual variation at all study lakes observed by Paterson et al. (2008) was present in the spring phytoplankton data, which may be influenced by the presence or absence of bloom events at the time of sampling (Paterson et al. 2008). It is difficult to fully determine if changes observed in phytoplankton communities between the spring period and the ice-free season composite are due to differences in the sampling season or due to differences in the study period examined (i.e., study years).

As the spring phytoplankton data set relies on a single spring phytoplankton sample, in contrast with the ice-free season phytoplankton data set which are means of several samples obtained throughout the ice-free seasons, it is possible that more variability may be present in the spring phytoplankton data set, since it relies on a ‘snapshot’ of lake and phytoplankton conditions. Following this logic, we may expect to observe fewer monotonic temporal trends in the spring phytoplankton due to this increased interannual variability.

For each lake, years when spring phytoplankton samples were available did not always match years when enumerated ice-free composite phytoplankton samples were available. Because of this, it is difficult to determine if observed differences in the spring phytoplankton samples as compared with the ice-free season composite phytoplankton samples are due to the additional sampling period (i.e., additional study years) or due to spring versus ice-free seasonality.

5.0 Conclusions

Phytoplankton communities are relatively well-studied during the late summer period. In this study, we examined changes in phytoplankton community composition and biomass during the ecologically important – and rarely analyzed – spring period. Notable changes in spring water chemistry and climate were observed at five lakes in the Muskoka-Haliburton region of south-central Ontario from the mid-1970s to 2011. Inter-annual variability of spring phytoplankton biovolume was high within each lake, and limited monotonic temporal trends in the relative and absolute spring phytoplankton biovolumes were observed. Spring water chemistry variables explained a significant proportion of the temporal variation in spring phytoplankton community composition at four of the five lakes, while climate variables explained a significant proportion of the variation in one lake only. However, high unexplained variation suggests that other factors are important in explaining the observed inter-annual variation in spring phytoplankton community composition. Future studies are suggested to examine the influence of biological drivers of change in spring phytoplankton communities (i.e., zooplankton), especially as higher temperatures associated with climate warming may enhance grazing pressure on phytoplankton by overwintering zooplankton (Lewandowska and Sommer 2010; Yang et al. 2016). The inclusion of additional physical and chemical variables in future assessments of change in the spring phytoplankton is also recommended. In addition, an analysis of changes in spring phytoplankton community composition at the species level may yield interesting insights. Future studies could also examine multiple spring phytoplankton samples each year, so that a single spring sample (or ‘snapshot’) is not relied upon to characterize the spring conditions.

6.0 References

Arnott, S.E., Keller, B., Dillon, P.J., Yan, N., Paterson, M., and Findlay, D. 2003. Using temporal coherence to determine the response to climate change in Boreal Shield lakes. Environmental Monitoring and Assessment, **88**: 365-388.

Baron, J.S., Poff, N.L., Angermeier, P.L., Dahm, C.N., Gleick, P.H., Hairston, N.G., Jackson, R.B., Johnston, C.A., Richter, B.D., and Steinman, A.D. 2002. Meeting ecological and societal needs for freshwater. Ecological Applications, **12**: 1247-1260.

Barrow, J.L., Jeziorski, A., Ruhland, K.M., Hadley, K.R., and Smol, J.P. 2014. Diatoms indicate that calcium decline, not acidification, explains recent cladoceran assemblage changes in south-central Ontario softwater lakes. Journal of Paleolimnology, **52**: 61-75.

Beutel, M.W., Horne, A.J., Taylor, W.D., Losee, R.F., and Whitney, R.D. 2008. Effects of oxygen and nitrate on nutrient release from profundal sediments of a large, oligo-mesotrophic reservoir, Lake Mathews, California. Lake and Reservoir Management, **24**: 18-29.

Burt, T.P. 1994. Long-term study of the natural environment – perceptive science or mindless monitoring? Progress in Physical Geography, **18**: 475-496.

Chapman, L.J., and Putnam, D.F. 1984. The physiography of southern Ontario. Special volume 2, Ontario Geological Survey, Toronto, Ontario.

Creed, I.F., Bergstrom, A.K., Trick, C.G., Grimm, N.B., Hessen, D.O., Karlsson, J., Kidd, K.A., Kritzberg, E., McKnight, D.M., Freeman, E.C., Senar, O.E., Andersson, A., Ask, J., Berggren, M., Cherif, M., Giesler, R., Hotchkiss, E.R., Kortelainen, P., Palta, M.M., Vrede, T., and Weyhenmeyer, G.A. 2018. Global change-driven effects on dissolved organic matter composition: implications for food webs of northern lakes. Global Change Biology, **24**: 3692-3714.

Crossman, J., Eimers, M.C., Kerr, J.G., and Yao, H. 2016a. Sensitivity of physical lake processes to climate change within a large Precambrian Shield catchment. Hydrological Processes, **30**: 4353-4366.

Crossman, J., Eimers, M.C., Watmough, S.A., Futter, M.N., Kerr, J., Baker, S.R., and Dillon, P.J. 2016b. Can recovery from disturbance explain observed declines in total phosphorus in Precambrian Shield catchments? Canadian Journal of Fisheries and Aquatic Sciences, **73**: 1202-1212.

DeSellas, A.M., Paterson, A.M., Sweetman, J.N., and Smol, J.P. 2008. Cladocera assemblages from the surface sediments of south-central Ontario (Canada) lakes and their relationships to measured environmental variables. Hydrobiologia, **600**: 105-119.

Dillon, P.J., and Molot, L.A. 2005. Long-term trends in catchment export and lake retention of dissolved organic carbon, dissolved organic nitrogen, total iron, and total phosphorus: the Dorset, Ontario, study, 1978-1998. Journal of Geophysical Research, **110**: G01002, doi: 10.1029/2004JG000003.

Dillon, P.J., Watmough, S.A., Eimers, M.C., and Aherne, J. 2007. Long-term changes in boreal lake and stream chemistry: recovery from acid deposition and the role of climate. *In* Acid in the environment: lessons learned and future prospects. *Edited by* G.R. Visgilio and D.M. Whitelaw. Springer, New York. pp. 59-76.

Dodds, W.K., Robinson, C.T., Gaiser, E.E., Hansen, G.J.A., Powell, H., Smith, J.M., Morse, N.B., Johnson, S.L., Gregory, S.V., Bell, T., Kratz, T.K., and McDowell, W.H. 2012. Surprises and insights from long-term aquatic data sets and experiments. BioScience, **62**: 709-721.

Dugan, H.A., Summers, J.C., Skaff, N.K., Krivak-Tetley, F.E., Doubek, J.P., Burke, S.M., Bartlett, S.L., Arvola, L., Jarjanazi, H., Korponai, J., Kleeberg, A., Monet, G., Monteith, D., Moore, K., Rogora, M., Hanson, P.C., and Weathers, K.C. 2017. Long-term chloride concentrations in North American and European freshwater lakes. Scientific Data, **4**: 170101.

Eimers, M.C., Buttle, J., and Watmough, S.A. 2008. Influence of seasonal changes in runoff and extreme events on dissolved organic carbon trends in wetland- and upland-draining streams. Canadian Journal of Fisheries and Aquatic Sciences, **65:** 796-808.

Eimers, M.C., Watmough, S.A., Paterson, A.M., Dillon, P.J., and Yao, H. 2009. Long-term declines in phosphorus export from forested catchments in south-central Ontario. Canadian Journal of Fisheries and Aquatic Sciences, **66**: 1682-1692.

Environment Canada. 2015. Canadian climate normals 1981-2010 station data [online]. Available from http://weather.gc.ca.

Fahnenstiel, G., Nalepa, T., Pothoven, S., Carrick, H., and Scavia, D. 2010. Lake Michigan lower food web: long-term observations and *Dreissena* impact. Journal of Great Lakes Research, **36**: 1-4.

Futter, M. 2003. Patterns and trends in southern Ontario lake ice phenology. Environmental Monitoring and Assessment, **88**: 431-444.

George, J.A., Lonsdale, D.J., Merlo, M.R., and Gobler, C.J. 2015. The interactive roles of temperature, nutrients, and zooplankton grazing in controlling the winter-spring phytoplankton bloom in a temperate, coastal ecosystem, Long Island Sound. Limnology and Oceanography, **60**: 110-126.

Girard, R.E., Clark, B.J., Yan, N.D., Reid, R.A., David, S.M., Ingram, R.G., and Findeis, J.G. 2007. History of chemical, physical and biological methods, sample locations and lake morphometry for the Dorset Environmental Science Centre (1973–2006). Ontario Ministry of the Environment Data Report 2007, Dorset, Ontario.

Hadley, K.R., Paterson, A.M., Hall, R.I., and Smol, J.P. 2013. Effects of multiple stressors on lakes in south-central Ontario: 15 years of change in lakewater chemistry and sedimentary diatom assemblages. Aquatic Sciences, **75**: 349-360.

Hall, R.I. and Smol, J.P. 1996. Paleolimnological assessment of long-term water-quality changes in south-central Ontario lakes affected by cottage development and acidification. 1996. Canadian Journal of Fisheries and Aquatic Sciences, **53**: 1-17.

Hopkins, G.J., and Standke, S.J. 1992. Phytoplankton methods manual: with special emphasis on waterworks operation internal methods manual. Queen's Printer for Ontario, Toronto, Ontario. ISBN 0-7729-8923-0.

Ingram, R.G., Girard, R.E., Clark, B.J., Paterson, A.M., Reid, R.A., and Findeis, J.G. 2006. Dorset Environmental Science Centre: lake sampling methods. Queen's Printer for Ontario, Toronto, Ontario. ISBN 1-4249-2049-3.

Jackson, R.B., Carpenter, S.R., Dahm, C.N., McKnight, D.M., Naiman, R.J., Postel, S.L., and Running, S.W. 2001. Water in a changing world. Ecological Applications, **11**: 1027-1045.

Jankowski, T., Livingstone, D.M., Buhrer, H., Forster, R., and Niederhauser, P. 2006. Consequences of the 2003 European heat wave for lake temperature profiles, thermal stability, and hypolimnetic oxygen depletion: implications for a warmer world. Limnology and Oceanography, **51**: 815-819.

Jeppesen, E., Sondergaard, M., Jensen, J.P., Havens, K.E., Anneville, O., Carvalho, L., Coveney, M.F., Deneke, R., Dokulil, M.T., Foy, B., Gerdeaux, D., Hampton, S.E., Hilt, S., Kangur, K., Kohler, J., Lammens, E.H., Lauridsen, T.L., Manca, M., Miracle, M.R., Moss, B., Noges, P., Persson, G., Phillips, G., Portielje, R., Romo, S., Schelske, C.L., Straile, D., Tatrai, I., Willen, E., and Winder, M. 2005. Lake responses to reduced nutrient loading - an analysis of contemporary long-term data from 35 case studies. Freshwater Biology, **50**: 1747-1771.

Keller, W. 2007. Implications of climate warming for Boreal Shield lakes: a review and synthesis. Environmental Reviews, **15**: 99-112.

Keller, W., Paterson, A.M., Somers, K.M., Dillon, P.J., Heneberry, J., and Ford, A. 2008. Relationships between dissolved organic carbon concentrations, weather, and acidification in small Boreal Shield lakes. Canadian Journal of Fisheries and Aquatic Sciences, **65**: 786-795.

Kerr, J.G. and Eimers, M.C. 2012. Decreasing soil water Ca^{2+} reduces DOC adsorption in mineral soils: implications for long-term DOC trends in an upland forested catchment in southern Ontario, Canada. Science of the Total Environment, **427-428**: 298-307.

Larson, G.L., Collier, R., and Buktenica, M.W. 2007. Long-term limnological research and monitoring at Crater Lake, Oregon. Hydrobiologia, **574**: 1-11.

Leavitt, P.R., Findlay, D.L., Hall, R.I., and Smol, J.P 1999. Algal responses to dissolved organic carbon loss and pH decline during whole-lake acidification: evidence from paleolimnology. Limnology and Oceanography, **44**: 757-773.

Lewandowska, A.M. and Sommer, U. 2010. Climate change and the spring bloom: a mesocosm study on the influence of light and temperature on phytoplankton and mesozooplankton. Marine Ecology Progress Series, **405**: 101-111.

Lewandowska, A.M., Striebel, M., Feudel, U., Hillebrand, H., and Sommer, U. 2015. The importance of phytoplankton trait variability in spring bloom formation. ICES Journal of Marine Science, **72**: 1908-1915.

Lindenmayer, D.B. and Likens, G.E. 2009. Adaptive monitoring: a new paradigm for long-term research and monitoring. Trends in Ecology and Evolution, **24**: 482-486.

MacDougall, M.J., Paterson, A.M., Winter, J.G., Jones, F.C., Knopf, L.A., and Hall, R.I. 2017. Response of periphytic diatom communities to multiple stressors influencing lakes in the Muskoka River Watershed, Ontario, Canada. Freshwater Science, **36**: 77-89.

Meyer, J.L., and Likens, G.E. 1979. Transport and transformation of phosphorus in a forest stream ecosystem. Ecology, **60**: 1255-1269.

Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: synthesis. Island Press, Washington, D.C.

Miller, M.P. and McKnight, D.M. 2015. Limnology of the Green Lakes Valley: phytoplankton ecology and dissolved organic matter biogeochemistry at a long-term ecological research site. Plant Ecology and Diversity, **8**: 689-702.

Ontario Ministry of the Environment. 1983. Handbook of analytical methods for environmental samples. Ontario Ministry of the Environment, Rexdale, Ontario.

Palmer, M.E., Yan, N.D., Paterson, A.M., and Girard, R.E. 2011. Water quality changes in south-central Ontario lakes and the role of local factors in regulating lake response to regional stressors. Canadian Journal of Fisheries and Aquatic Sciences, **68**: 1038-1050.

Paterson, A.M., Cumming, B.F., Smol, J.P., and Hall, R.I. 2004. Marked recent increases of colonial scaled chrysophytes in boreal lakes: implications for the management of taste and odour events. Freshwater Biology, **49**: 199-207.

Paterson, A.M., Winter, J.G., Nicholls, K.H., Clark, B.J., Ramcharan, C.W., Yan, N.D., and Somers, K.M. 2008. Long-term changes in phytoplankton composition in seven Canadian Shield lakes in response to multiple anthropogenic stressors. Canadian Journal of Fisheries and Aquatic Sciences, **65**: 846-861.

Quinlan, R., Hall, R.I., Paterson, A.M., Cumming, B.F., and Smol, J.P. 2008. Long-term assessments of ecological effects of anthropogenic stressors on aquatic ecosystems from paleoecological analyses: challenges to perspectives of lake management. Canadian Journal of Fisheries and Aquatic Sciences, **65**: 933-944.

Schindler, D.W., Bayley, S.E., Parker, B.R., Beaty, K.G., Cruikshank, D.R., Fee, E.J., Schindler, E.U., and Stainton, M.P. 1996. The effects of climate warming on the properties of boreal lakes and streams at the Experimental Lakes Area, northwestern Ontario. Limnology and Oceanography, **41**: 1004-1017.

Smith, V.H. 2003. Eutrophication of freshwater and coastal marine ecosystems **-** a global problem. Environmental Science and Pollution Research, **10**: 126-139.

Smith, V.H., and Schindler, D.W. 2009. Eutrophication science: where do we go from here? Trends in Ecology and Evolution, **24**: 201-207.

Smith, V.H., Tilman, G.D., and Nekola, J.C. 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environmental Pollution, **100**: 179-196.

Smol, J.P. 2010. The power of the past: using sediments to track the effects of multiple stressors on lake ecosystems. Freshwater Biology, **55**: 43-59.

Watmough, S.A., and Aherne, J. 2008. Estimating calcium weathering rates and future lake calcium concentrations in the Muskoka-Haliburton region of Ontario. Canadian Journal of Fisheries and Aquatic Sciences, **65**: 821-833.

Watmough, S.A., and Dillon, P.J. 2004. Major element fluxes from a coniferous catchment in central Ontario, 1983-1999. Biogeochemistry, **67**: 369-398.

Watson, S.B., McCauley, E., and Downing, J.A. 1997. Patterns in phytoplankton taxonomic composition across temperate lakes of differing nutrient status. Limnology and Oceanography, **42**: 487-495.

Wetzel, R.G. 2001. Limnology: lake and river ecosystems. Third edition. Academic Press, San Diego.

Winter, J.G., Keller, W., Paterson, A.M., and Yan, N.D. 2008. Three decades of recovery of the phytoplankton community in Clearwater Lake (Sudbury, Canada) from acid and metal contamination. Verhandlungen des Internationalen Verein Limnologie, **30**: 247-252.

Yan, N.D., and Pawson, T.W. 1998. Seasonal variation in the size and abundance of the invading *Bythotrephes* in Harp Lake, Ontario, Canada. Hydrobiologia, **361**: 157-168.

Yan, N.D., Paterson, A.M., Somers, K.M., and Scheider, W.A. 2008a. An introduction to the Dorset special issue: transforming understanding of factors that regulate aquatic ecosystems on the southern Canadian Shield. Canadian Journal of Fisheries and Aquatic Sciences, **65**: 781-785.

Yan, N.D., Somers, K.M., Girard, R.E., Paterson, A.M., Keller, W., Ramcharan, C.W., Rusak, J.A., Ingram, R., Morgan, G.E., and Gunn, J.M. 2008b. Long-term trends in zooplankton of Dorset, Ontario, lakes: the probable interactive effects of changes in pH, total phosphorus, dissolved organic carbon, and predators. Canadian Journal of Fisheries and Aquatic Sciences, **65**: 862-877.

Yang, Y., Stenger-Kovacs, C., Padisak, J., and Pettersson, K. 2016. Effects of winter severity on spring phytoplankton development in a temperate lake (Lake Erken, Sweden). Hydrobiologia, **780**: 47-57.

Yao, H., Rusak, J.A., Paterson, A.M., Somers, K.M., Mackay, M., Girard, R.E., Ingram, R., and McConnell, C. 2013. The interplay of local and regional factors in generating temporal changes in the ice phenology of Dickie Lake, south-central Ontario, Canada. Inland Waters, **3**: 1-14.

Appendices

Appendix I: Spring phytoplankton and water chemistry sample collection dates

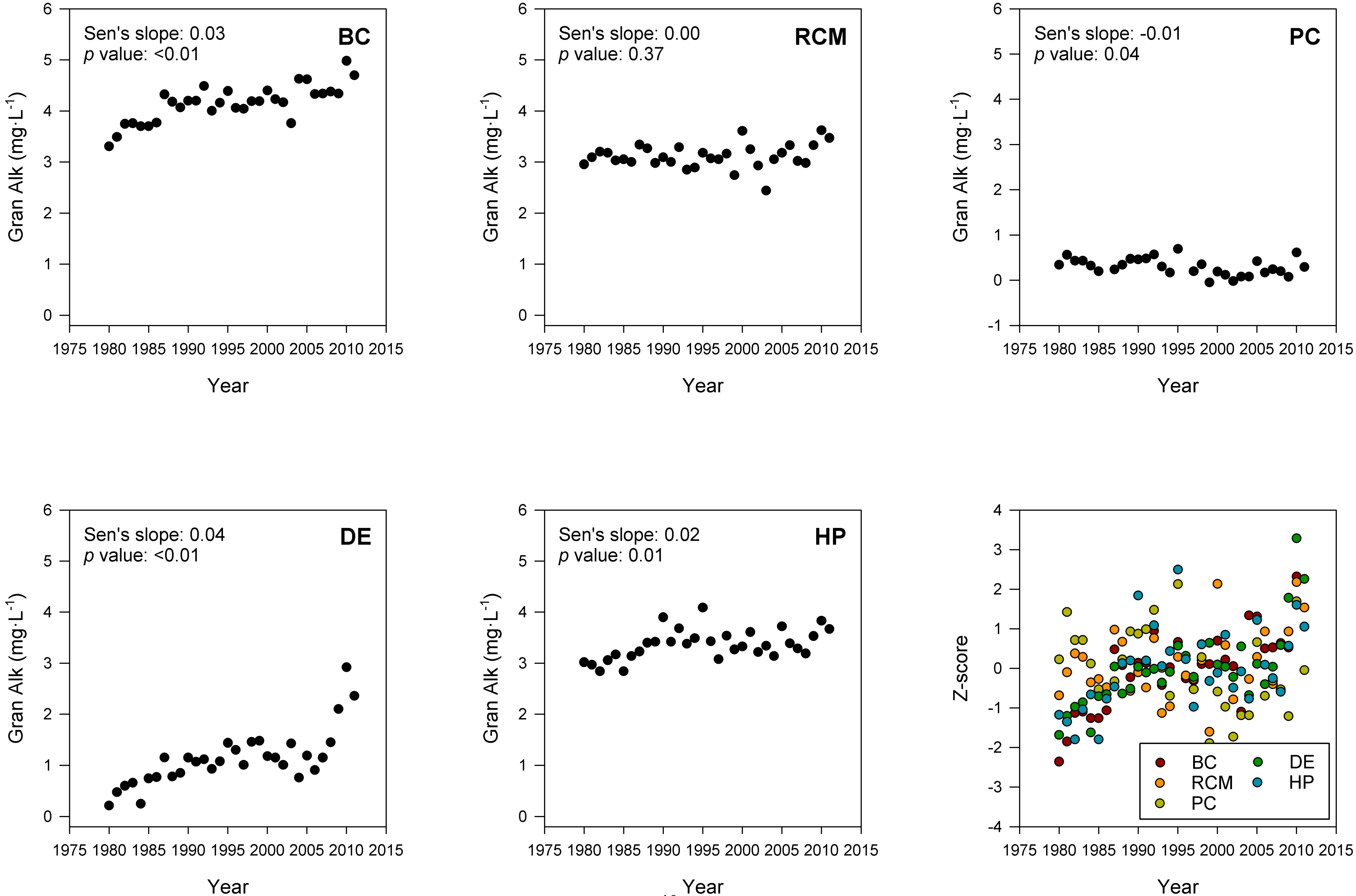
Appendix I. Spring phytoplankton and water chemistry sample collection dates for each of the five study lakes. A dash (-) indicates that no spring phytoplankton sample is available for a specific year. An asterisk (*) indicates that spring water chemistry data were not available for the spring phytoplankton sample collection date; in these instances, data from the first available spring water chemistry sample collection date were used.

Year	Ice-off date	Blue Chalk		Red Chalk (Main)		Plastic		Dickie		Harp	
		Phyto-plankton	Water chemistry	Phyto-plankton	Water chemistry	Phyto-plankton	Water chemistry	Phyto-plankton	Water chemistry	Phyto-plankton	Water chemistry
1976	April 18	-	April 26	April 26	April 26	-	-	April 22	April 30*	April 21	April 29*
1977	April 15	April 21	April 28*	April 21	April 28*	-	-	April 26	April 26	April 19	April 27*
1978	May 6	May 24	May 24	May 24	May 24	-	-	May 8	May 23*	May 10	April 19*
1979	April 22	May 8	May 8	May 8	May 8	May 2	May 2	April 23	April 23	April 23	April 30*
1980	April 21	May 7	May 7	April 30	April 30	April 22	April 22	April 22	April 22	April 23	April 23
1981	April 4	April 8	April 30*	April 8	April 29*	April 9	April 16*	April 7	May 5*	April 6	May 5*
1982	April 29	May 3	May 3	May 3	May 3	April 29	April 29	April 30	April 30	April 30	April 30
1983	April 20	April 21	April 26*	April 21	April 26*	April 21	April 26*	April 21	April 25*	April 22	April 27*
1984	April 17	-	April 24	May 2	April 24*	-	April 27	May 29	May 29	April 26	April 26
1985	April 25	April 29	April 29	-	April 29	May 6	April 18*	May 14	May 14	April 29	April 29
1986	April 13	-	April 23	May 28	May 28	May 12	May 12	-	April 22	-	April 22
1987	April 13	April 13	May 4*	April 13	May 4*	April 29	April 29	April 14	April 28*	April 28	April 28
1988	April 16	April 26	April 26	April 19	April 19	April 26	April 26	May 26	May 26	April 25	April 25
1989	May 1	-	May 1	May 1	May 1	May 3	April 27*	May 3	April 27*	-	April 13
1990	April 26	April 30	April 30	April 30	April 30	May 1	April 23*	May 1	April 23*	-	April 23
1991	April 20	April 17	April 30*	April 17	April 30*	April 23	April 23	April 23	April 23	April 17	April 24*
1992	May 1	May 5	May 5	May 5	May 5	May 6	April 21*	May 7	May 7	May 7	May 7
1993	April 21	April 29	April 29	April 29	April 29	April 22	April 22	April 27	April 27	April 28	April 28
1994	April 23	-	May 2	-	May 2	April 28	April 28	May 4	May 4	-	May 4
1995	April 14	-	May 3	-	May 3	April 18	April 18	April 19	April 19	-	April 20
1996	May 1	May 14	May 14	May 14	May 14	May 8	May 8	May 6	May 6	May 7	May 7
1997	April 29	May 13	May 13	May 13	May 13	May 7	May 7	May 5	May 5	May 6	May 6
1998	April 15	April 23	April 23	April 23	April 23	April 21	April 21	April 20	April 20	May 7	May 7
1999	April 14	April 21	April 21	April 21	April 21	April 13	April 23*	April 14	April 14	April 14	April 16*

Year	Ice-off date	Blue Chalk		Red Chalk (Main)		Plastic		Dickie		Harp	
		Phyto-plankton	Water chemistry	Phyto-plankton	Water chemistry	Phyto-plankton	Water chemistry	Phyto-plankton	Water chemistry	Phyto-plankton	Water chemistry
2000	April 5	April 20	April 20	April 20	April 20	April 11	April 26*	April 11	April 10*	April 19	April 19
2001	April 22	May 3	May 3	May 3	May 3	May 1	May 1	May 1	May 1	May 7	May 7
2002	April 18	May 14	May 14	May 14	May 14	May 13	May 17*	May 13	May 13	May 17	May 17
2003	April 23	-	May 5	-	May 5	May 5	May 5	April 30	April 30	-	May 1
2004	April 19	-	April 27	-	April 27	April 29	April 29	April 28	April 28	-	April 28
2005	April 24	May 4	May 4	-	May 5	May 3	May 3	May 3	May 3	May 4	May 4
2006	April 15	May 2	May 2	-	May 2	May 3	May 3	May 1	May 1	May 2	May 2
2007	April 19	May 1	May 1	-	May 1	May 10	May 10	May 2	May 2	April 30	April 30
2008	April 20	May 1	May 1	May 1	May 1	April 30	April 30	May 5	May 5	May 2	May 2
2009	April 20	April 29	April 29	May 4	May 4	May 19	May 19	April 29	April 29	May 1	May 1
2010	April 1	April 7	April 7	April 7	April 7	April 9	April 9	April 8	April 8	April 8	April 8
2011	April 27	May 4	May 4	May 4	May 4	May 9	May 9	May 6	May 6	May 9	May 9

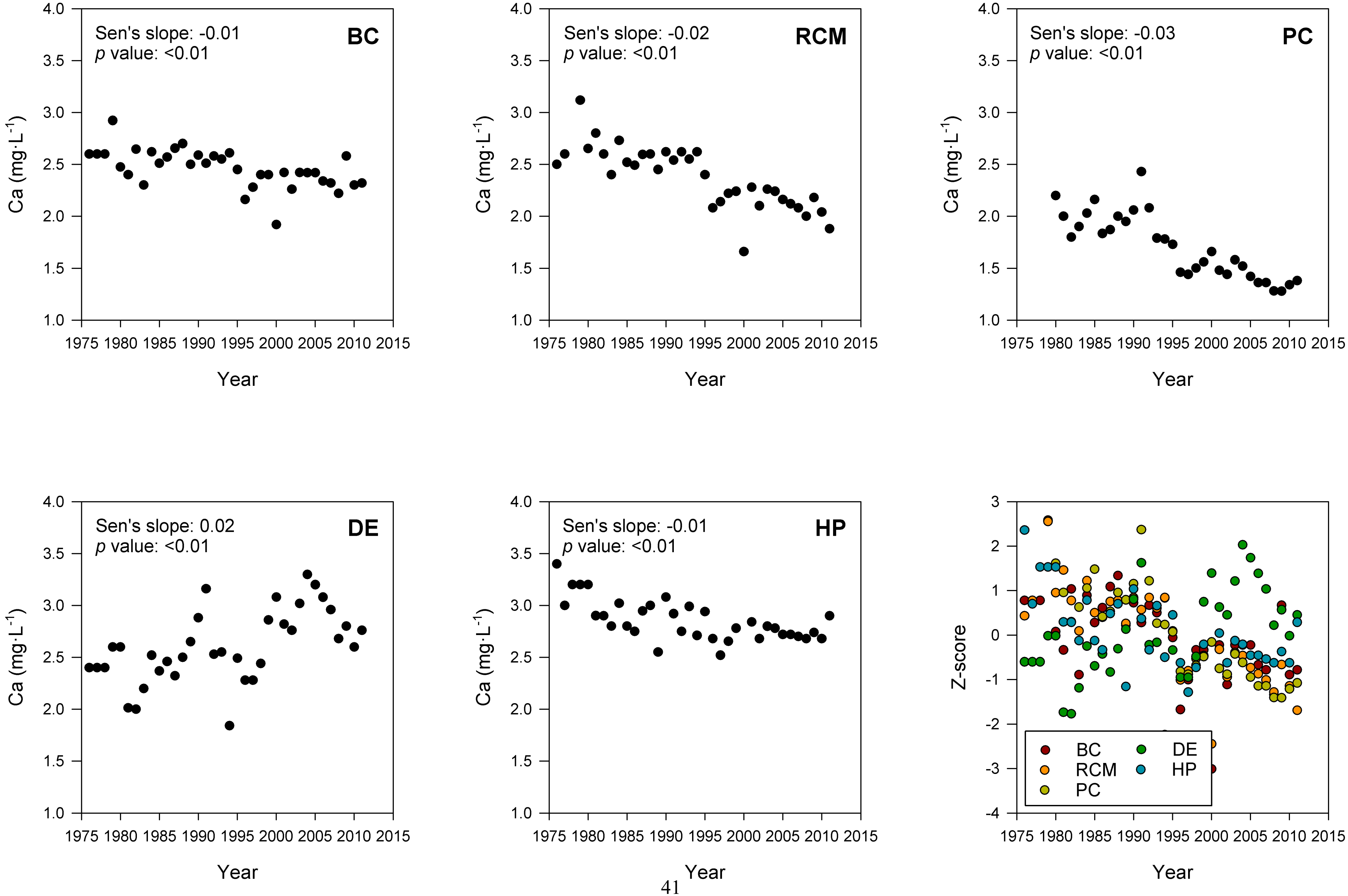
Appendix II: Spring water chemistry plots

Alkalinity



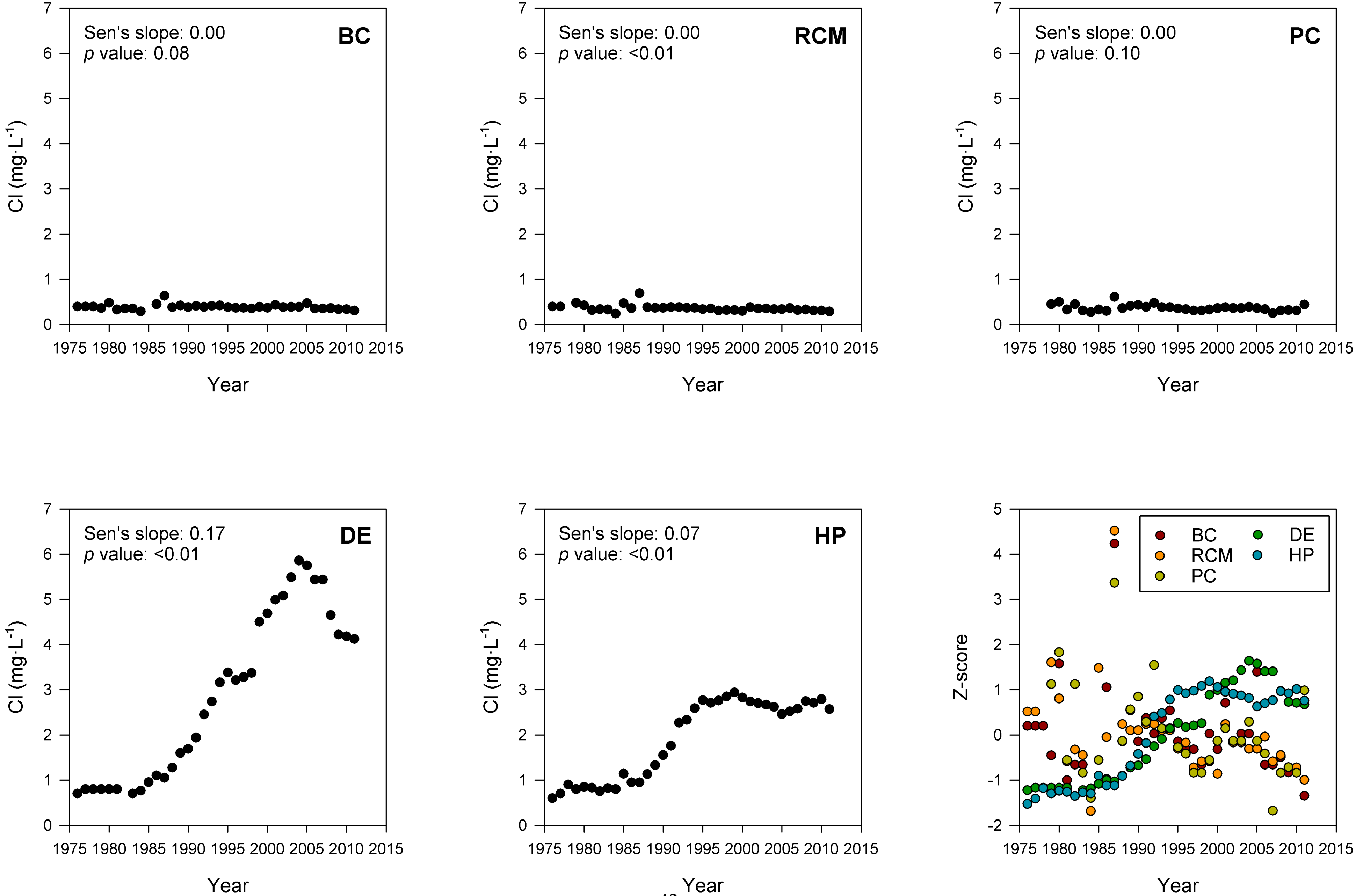
Sen's slope: 0.03
p value: <0.01
BC
Sen's slope: 0.00
p value: 0.37
RCM
Sen's slope: -0.01
p value: 0.04
PC
Sen's slope: 0.04
p value: <0.01
DE
Sen's slope: 0.02
p value: 0.01
HP
BC
RCM
PC
DE
HP
Gran Alk (mg·L-1)
Z-score
Year

Calcium

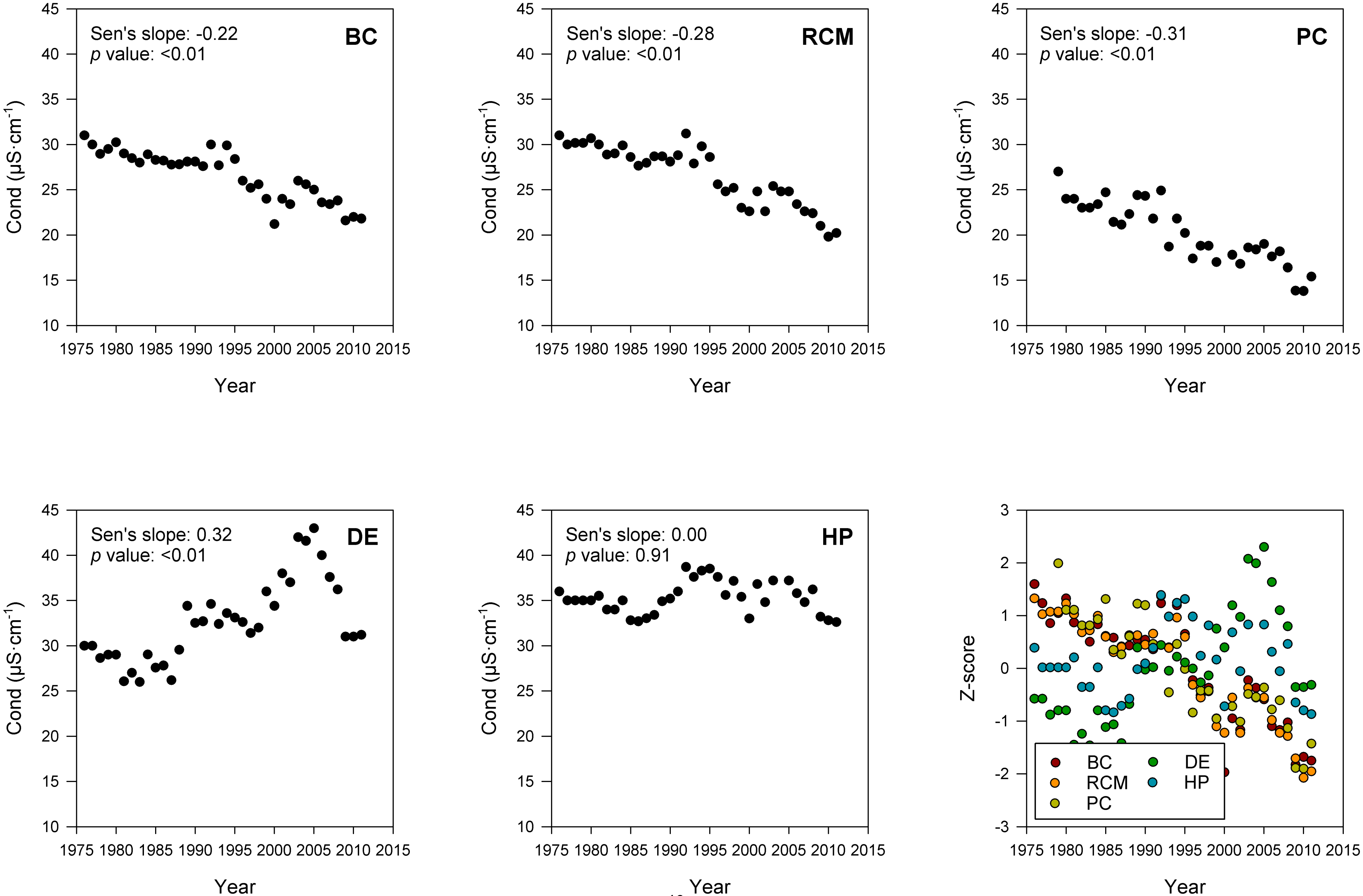


Sen's slope: -0.01
p value: <0.01
BC
Sen's slope: -0.02
p value: <0.01
RCM
Sen's slope: -0.03
p value: <0.01
PC
Sen's slope: 0.02
p value: <0.01
DE
Sen's slope: -0.01
p value: <0.01
HP
Ca (mg·L-1)
Year
Z-score
BC
RCM
PC
DE
HP

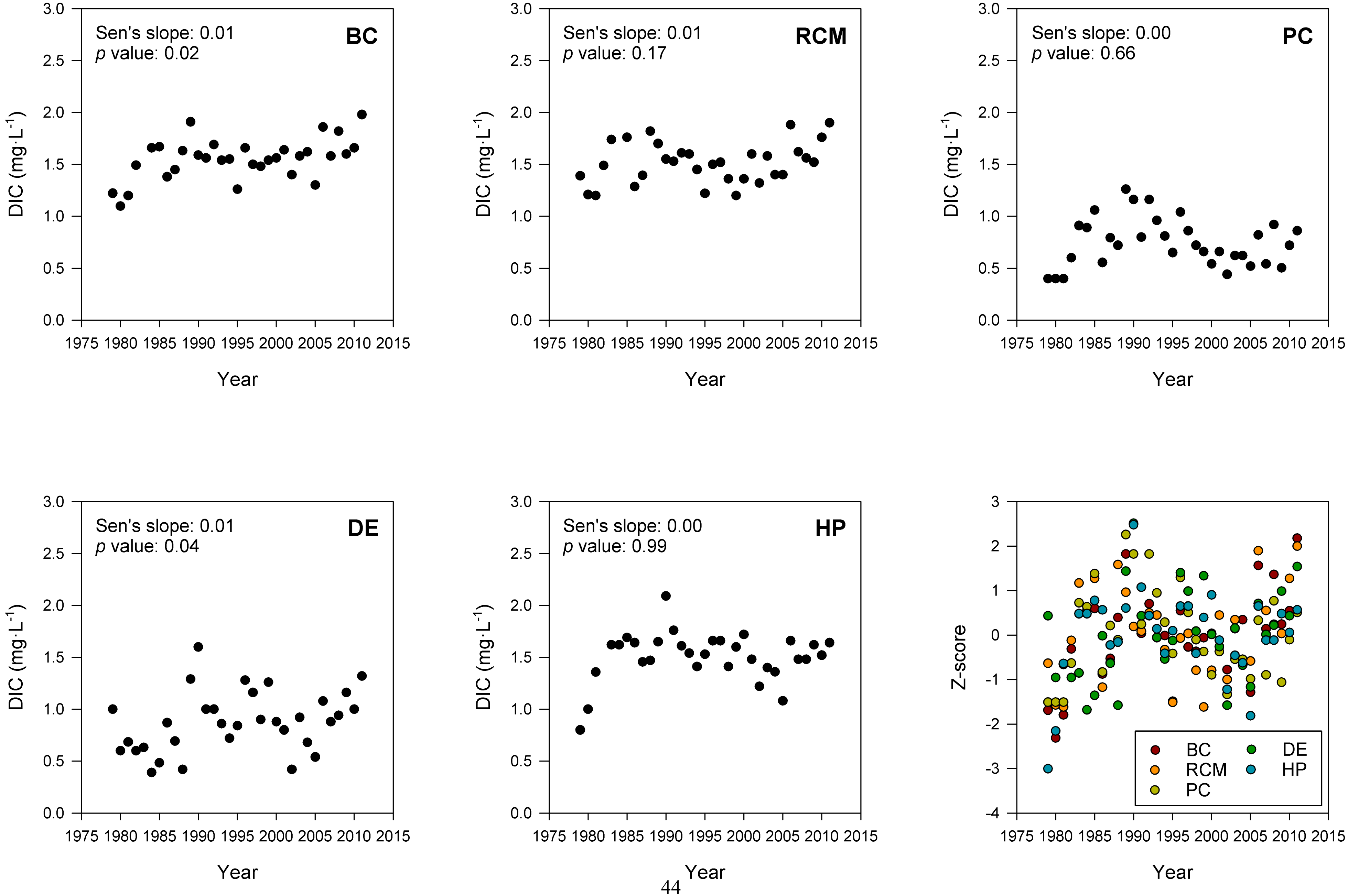
Chloride


Sen's slope: 0.00
p value: 0.08
BC
Cl (mg·L-1)
Year
Sen's slope: 0.00
p value: <0.01
RCM
Cl (mg·L-1)
Year
Sen's slope: 0.00
p value: 0.10
PC
Cl (mg·L-1)
Year
Sen's slope: 0.17
p value: <0.01
DE
Cl (mg·L-1)
Year
Sen's slope: 0.07
p value: <0.01
HP
Cl (mg·L-1)
Year
BC
RCM
PC
DE
HP
Z-score
Year

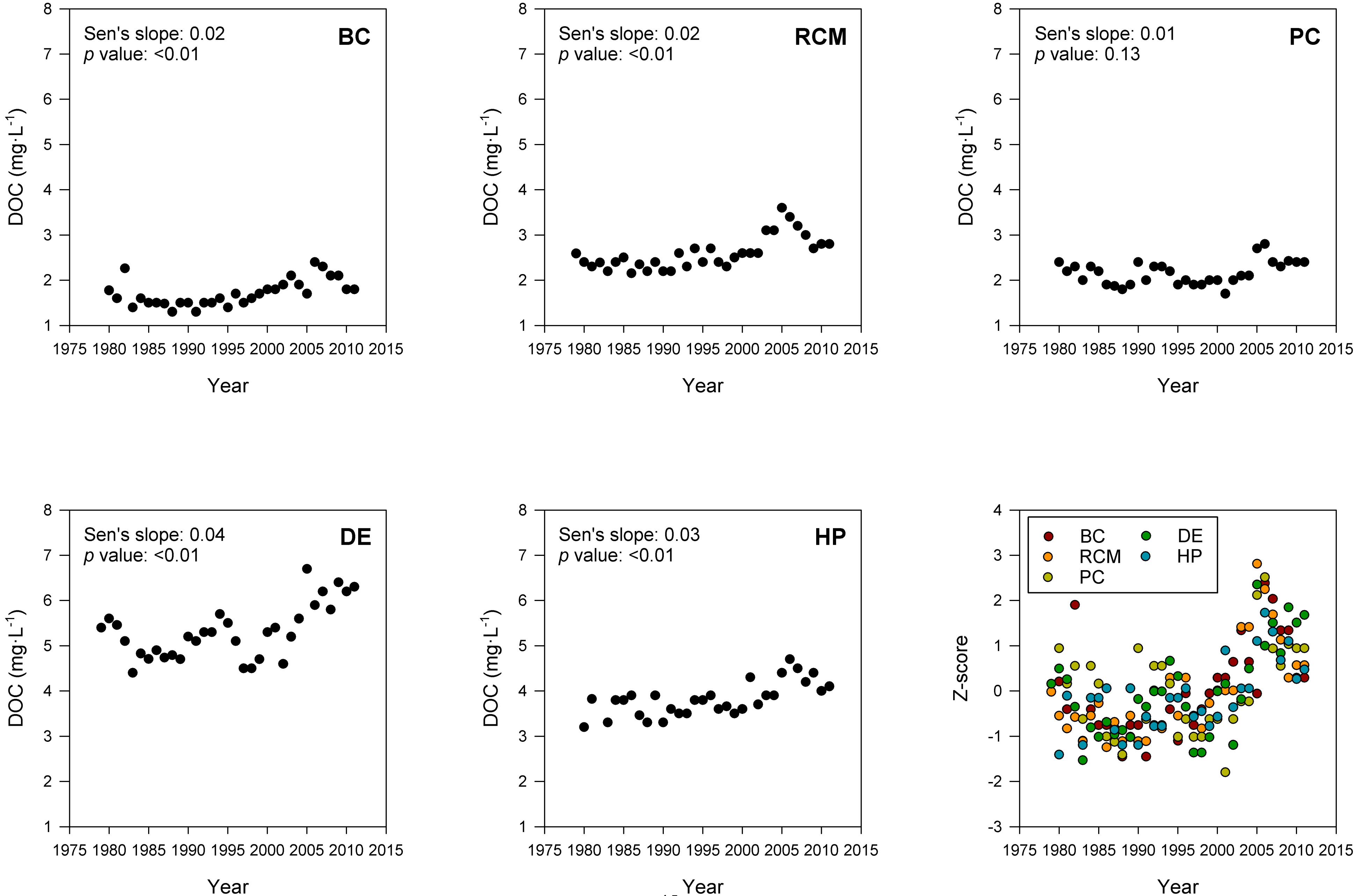
Conductivity



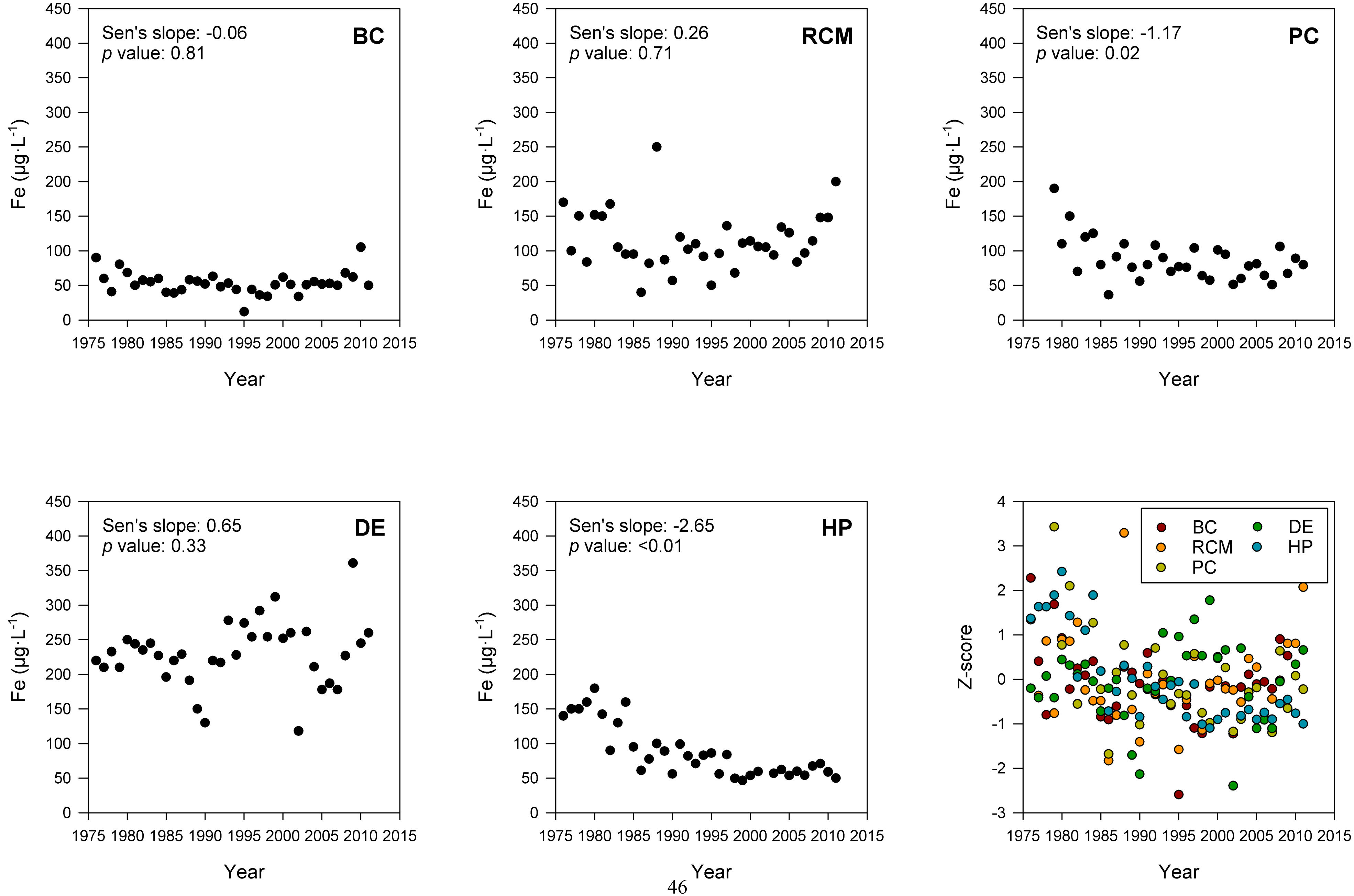
Dissolved inorganic carbon



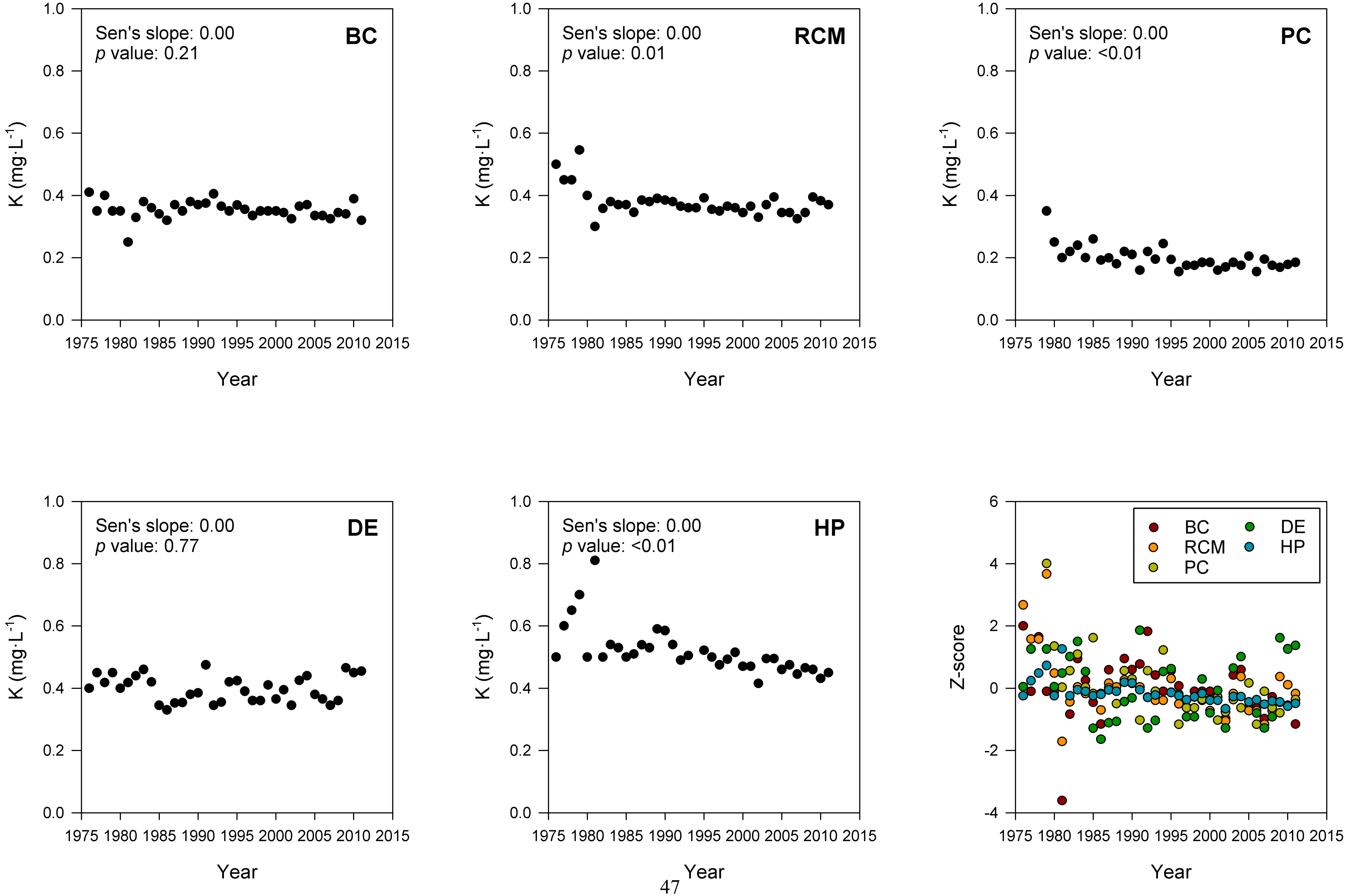
Dissolved organic carbon



Iron

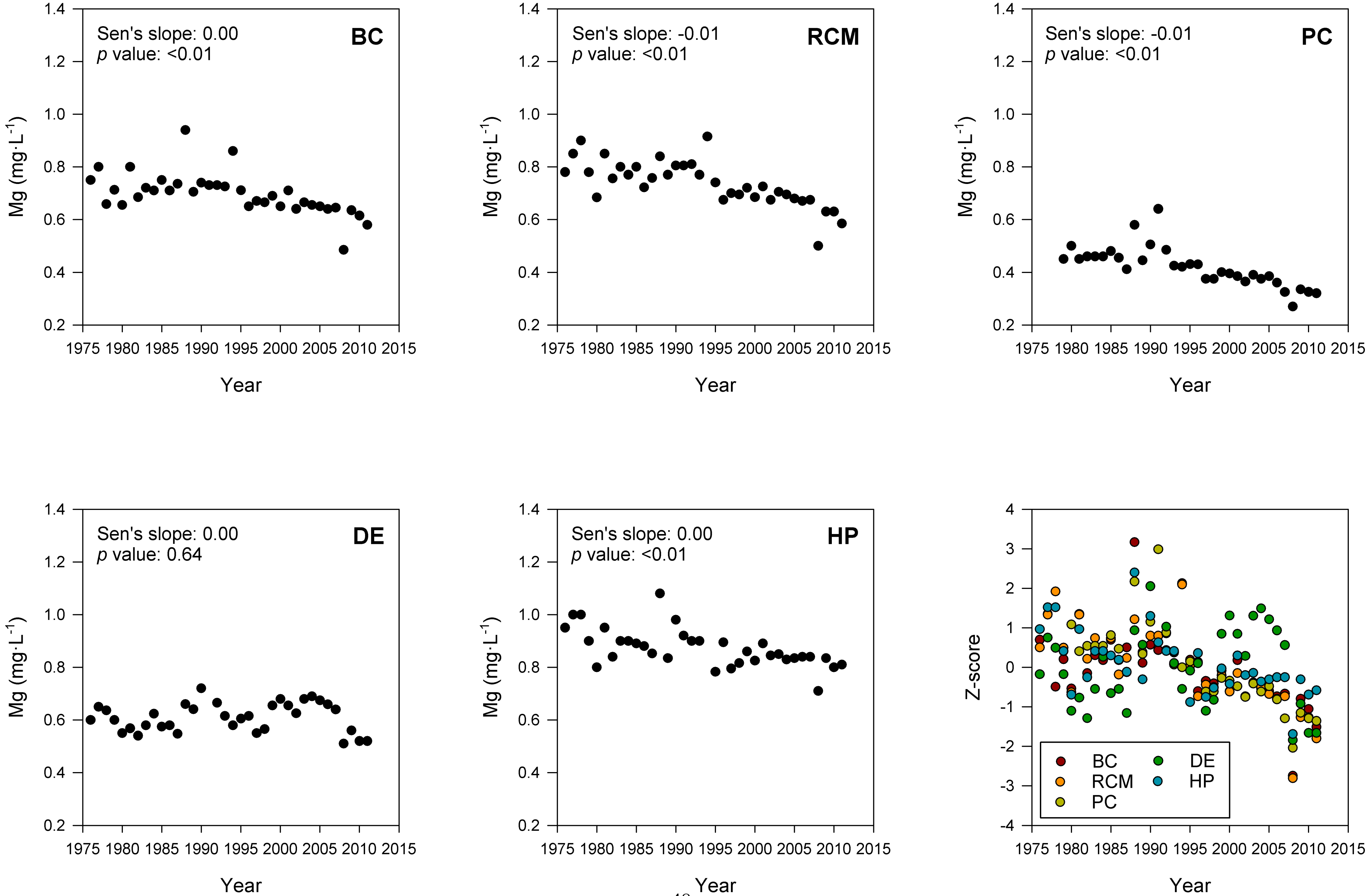

Sen's slope: -0.06
p value: 0.81
BC
Sen's slope: 0.26
p value: 0.71
RCM
Sen's slope: -1.17
p value: 0.02
PC
Sen's slope: 0.65
p value: 0.33
DE
Sen's slope: -2.65
p value: <0.01
HP
Fe (µg·L-1)
Year
Z-score
BC
RCM
PC
DE
HP

Potassium



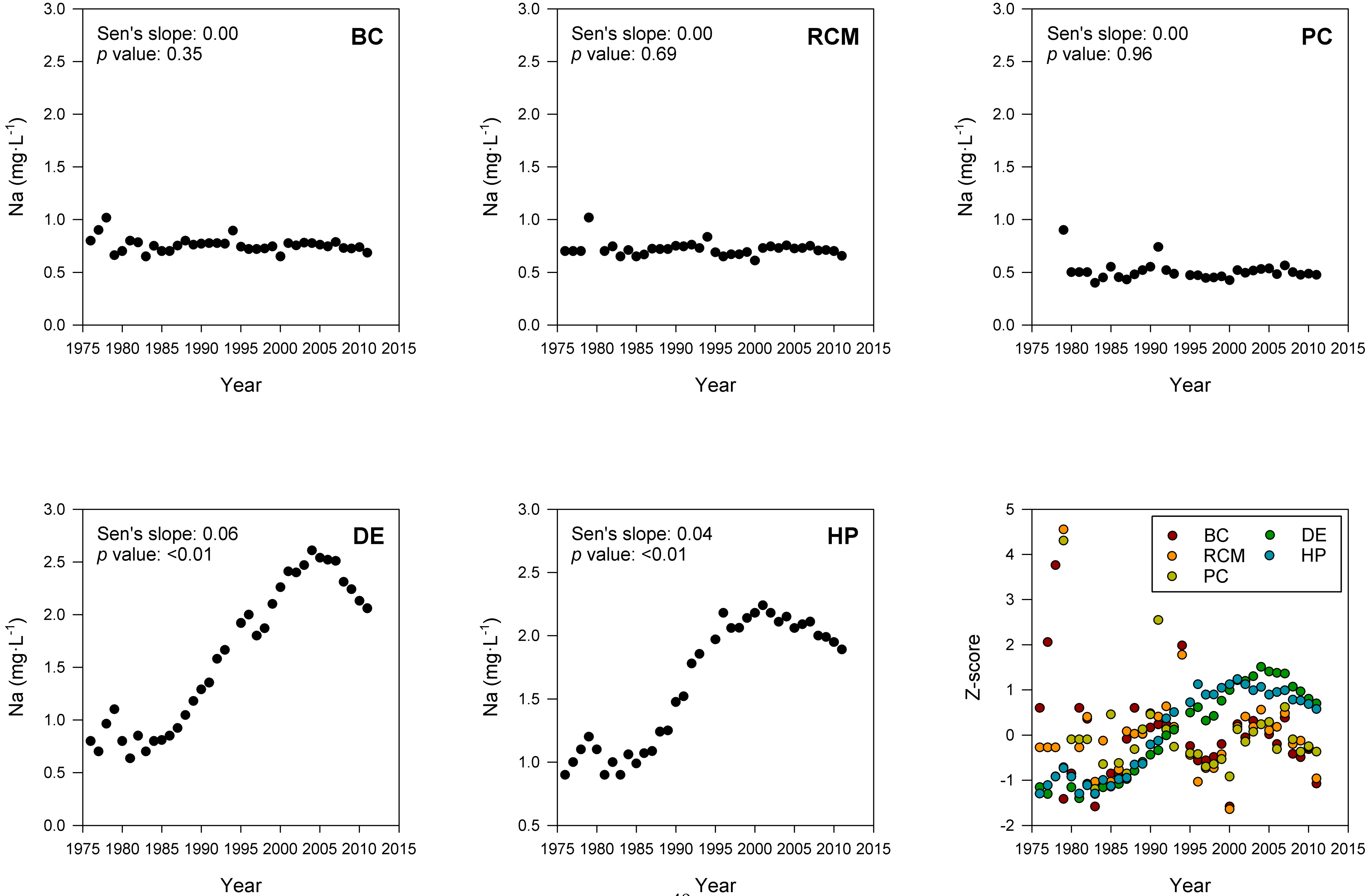
Sen's slope: 0.00
p value: 0.21
BC
Sen's slope: 0.00
p value: 0.01
RCM
Sen's slope: 0.00
p value: <0.01
PC
Sen's slope: 0.00
p value: 0.77
DE
Sen's slope: 0.00
p value: <0.01
HP
BC
RCM
PC
DE
HP
K (mg·L-1)
Z-score
Year

Magnesium



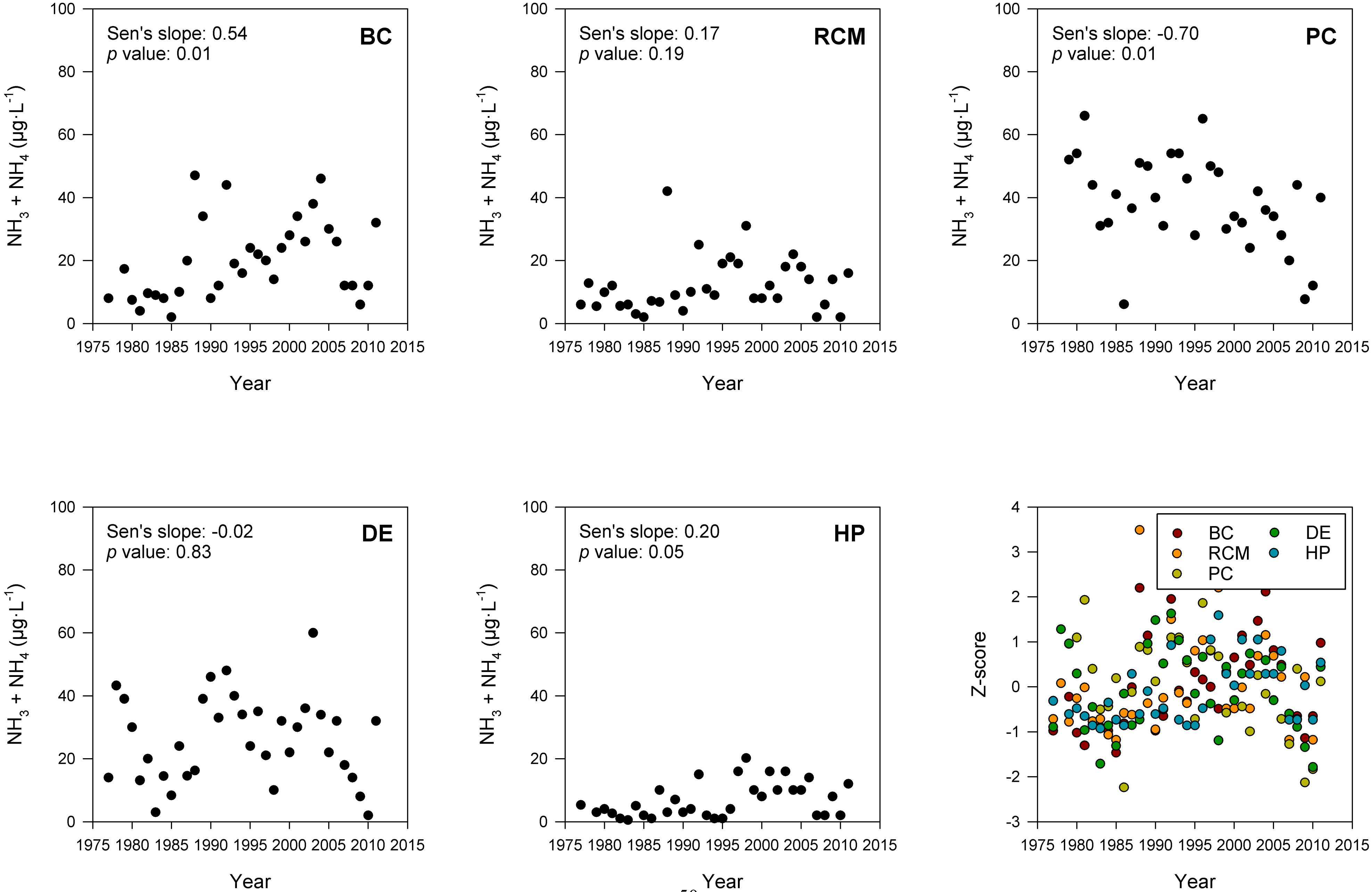
Sen's slope: 0.00
p value: <0.01
BC
Sen's slope: -0.01
p value: <0.01
RCM
Sen's slope: -0.01
p value: <0.01
PC
Sen's slope: 0.00
p value: 0.64
DE
Sen's slope: 0.00
p value: <0.01
HP
Mg (mg·L-1)
Year
Z-score
BC
RCM
PC
DE
HP

Sodium

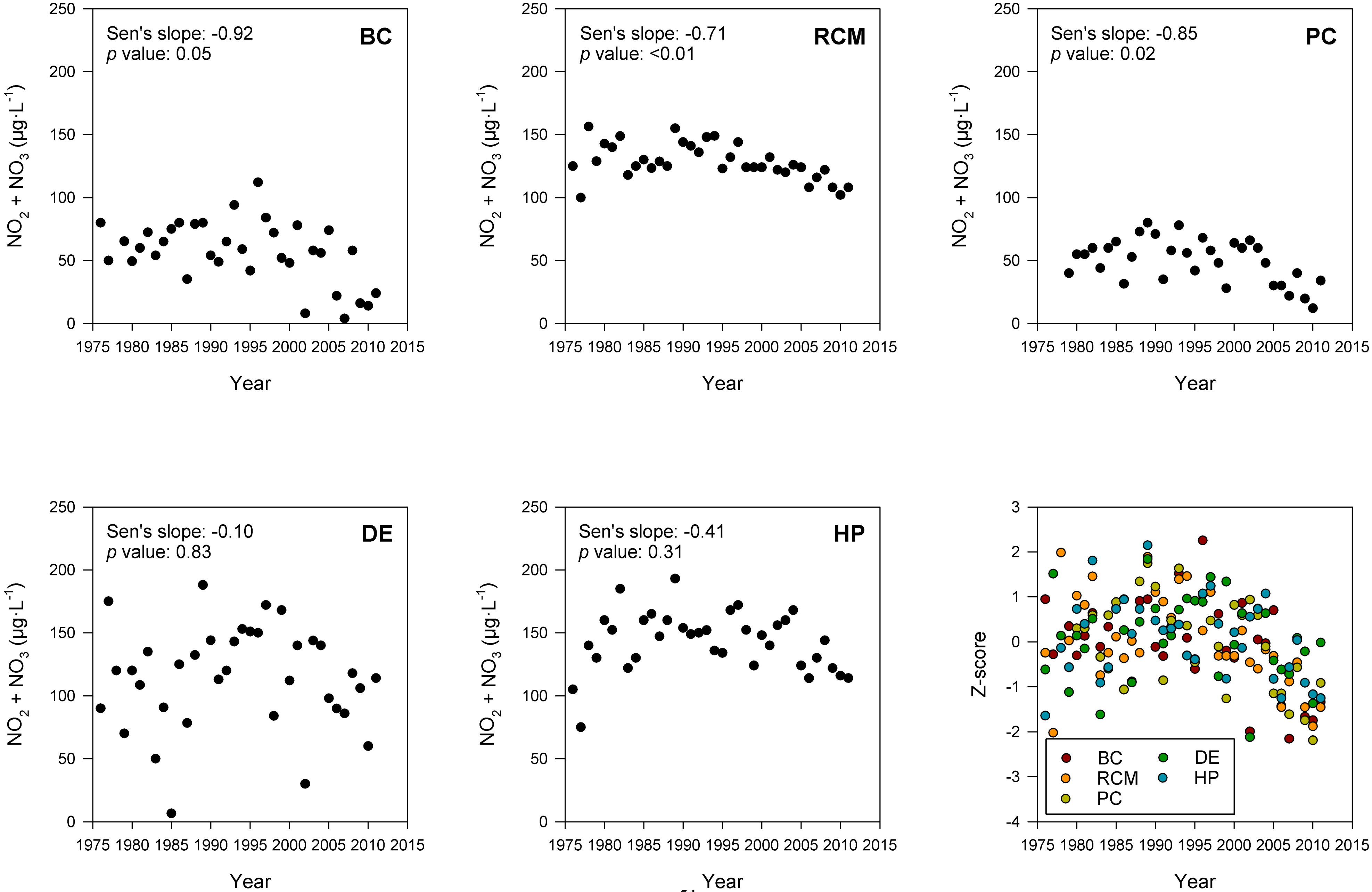


Sen's slope: 0.00
p value: 0.35
BC
Sen's slope: 0.00
p value: 0.69
RCM
Sen's slope: 0.00
p value: 0.96
PC
Sen's slope: 0.06
p value: <0.01
DE
Sen's slope: 0.04
p value: <0.01
HP
BC
RCM
PC
DE
HP
Na (mg·L-1)
Z-score
Year

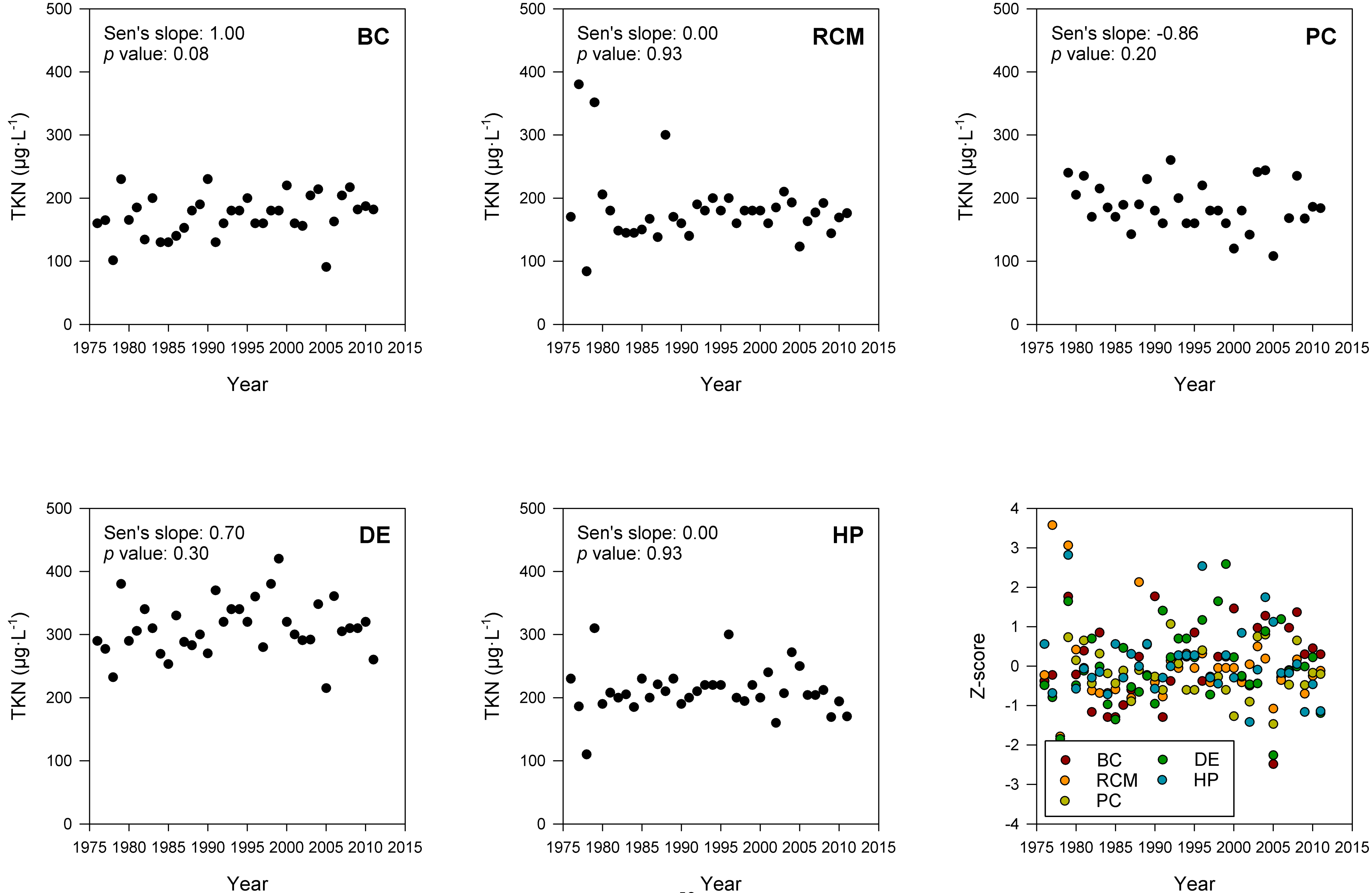
Ammonia + ammonium



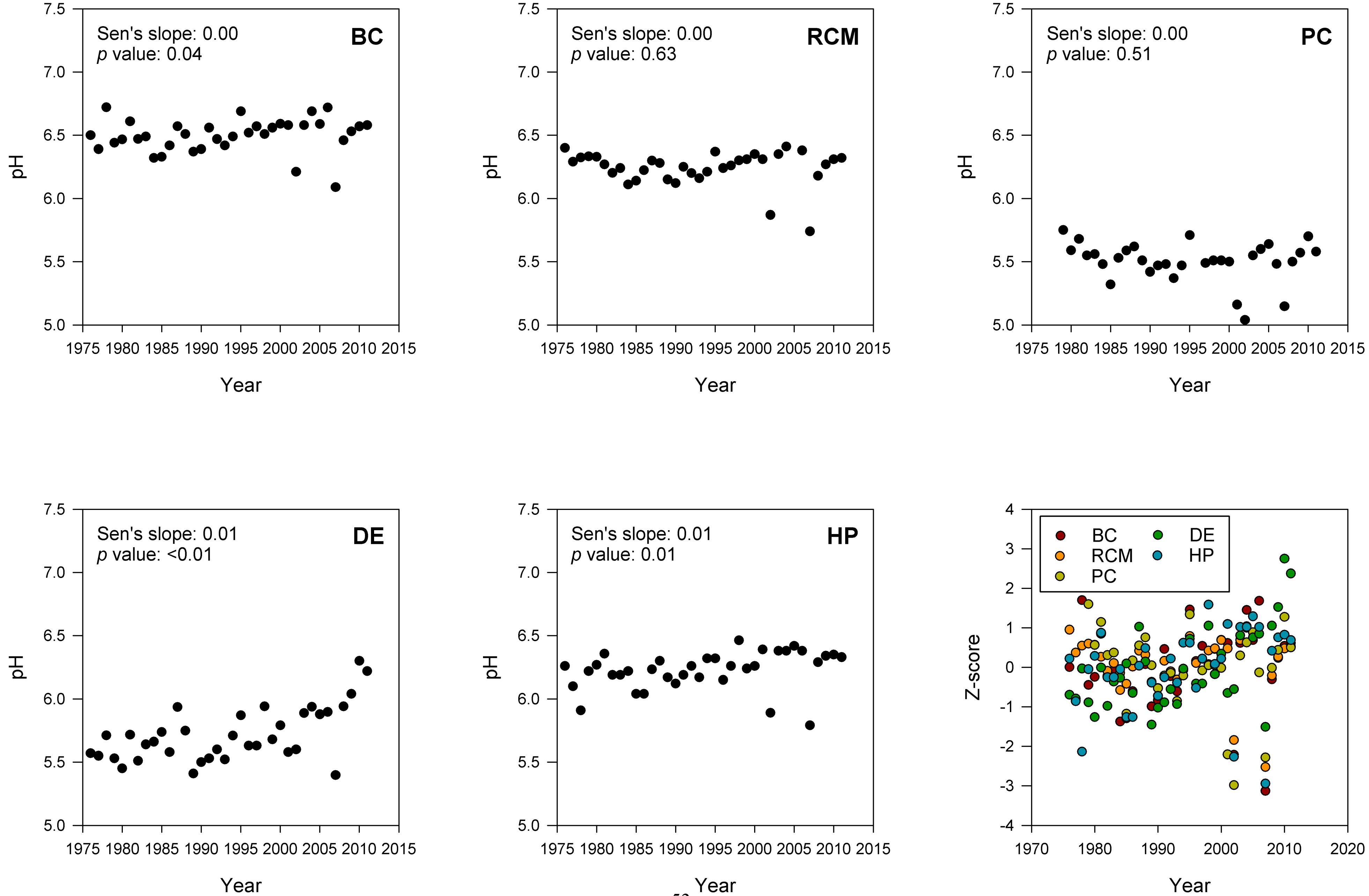
Nitrate + nitrite



Total Kjeldahl nitrogen

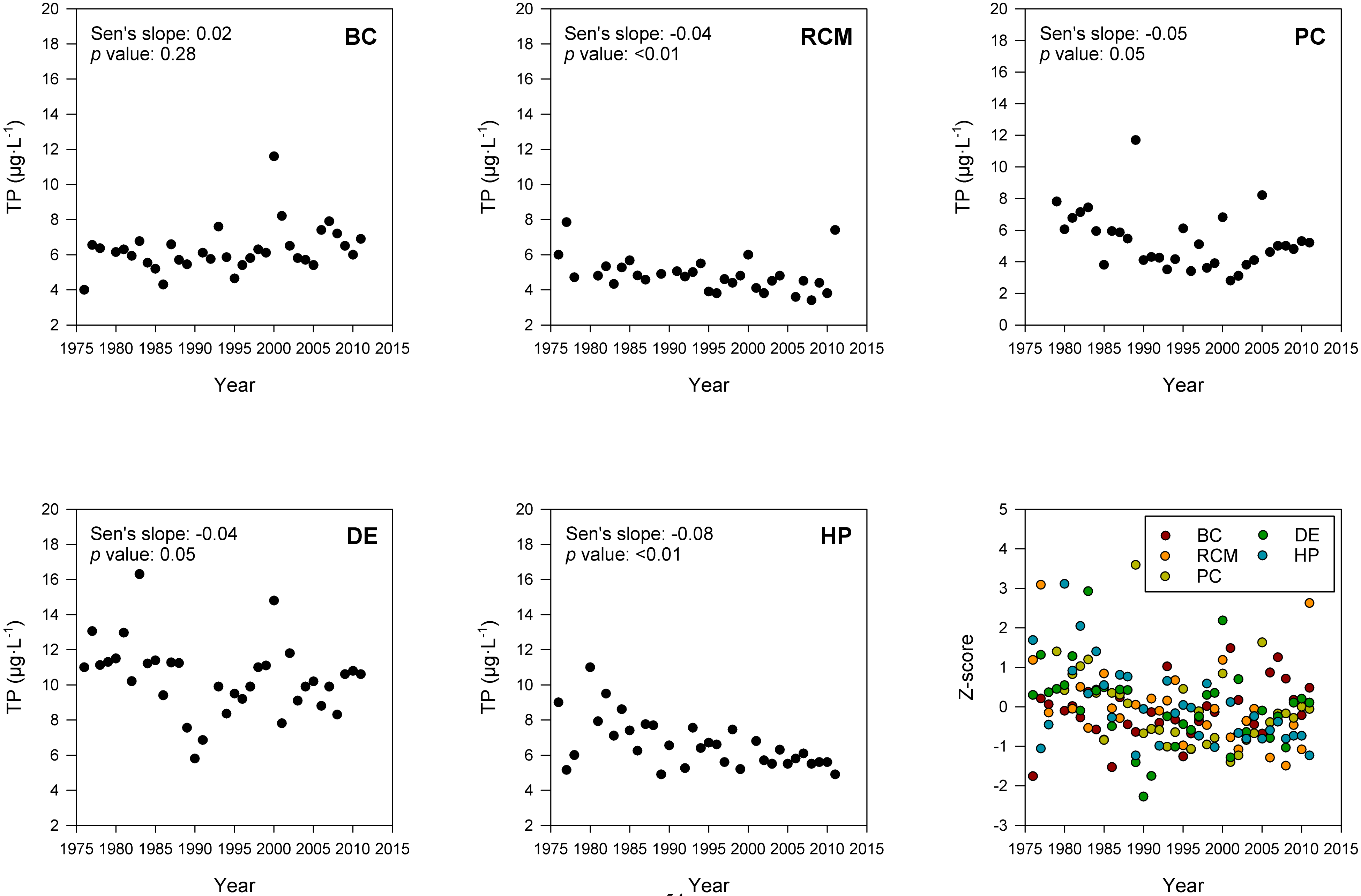


pH

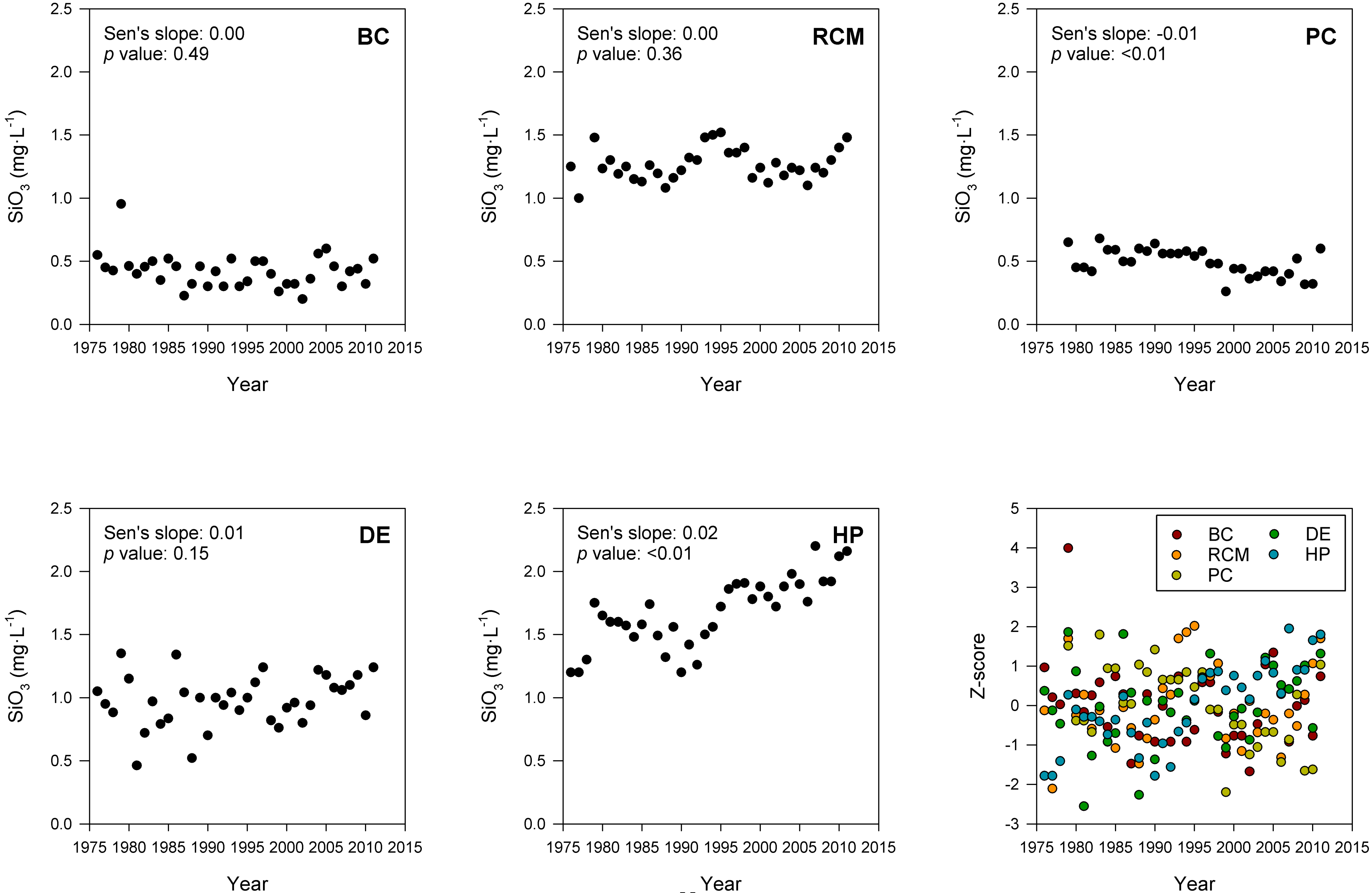


Sen's slope: 0.00
p value: 0.04
BC
Sen's slope: 0.00
p value: 0.63
RCM
Sen's slope: 0.00
p value: 0.51
PC
Sen's slope: 0.01
p value: <0.01
DE
Sen's slope: 0.01
p value: 0.01
HP
BC
RCM
PC
DE
HP
pH
Z-score
Year

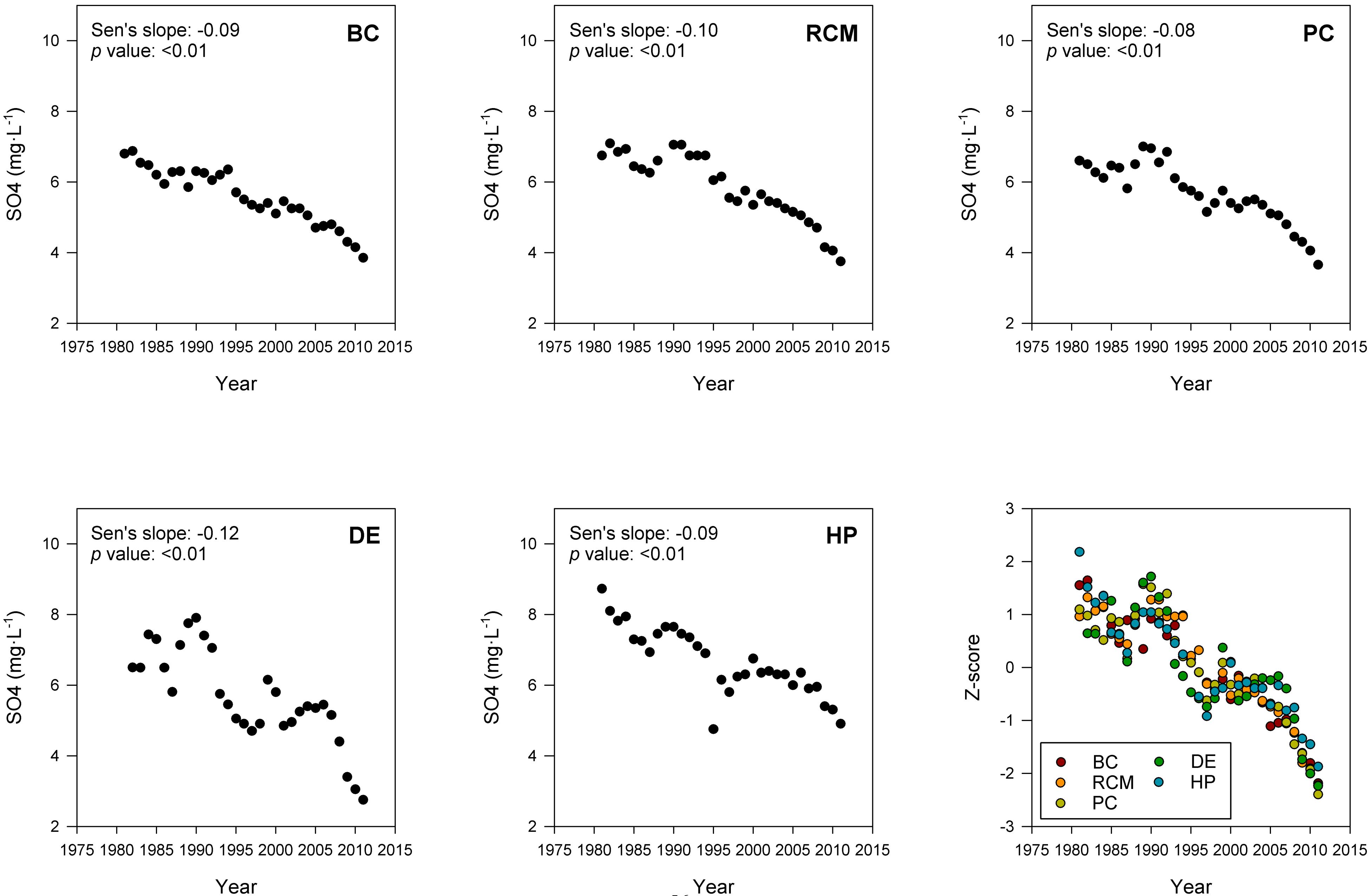
Total phosphorus



Reactive silicate



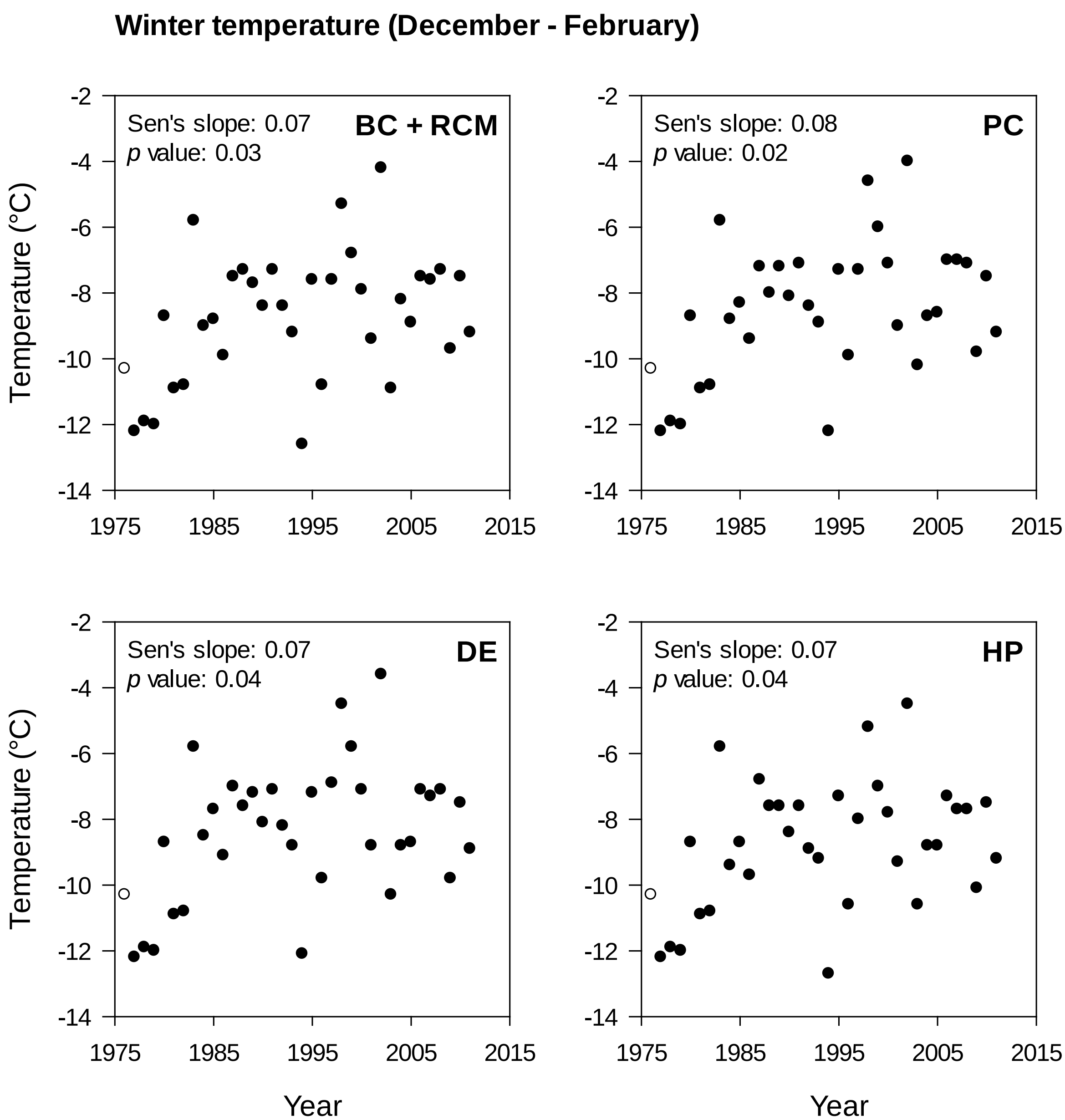
Sulphate



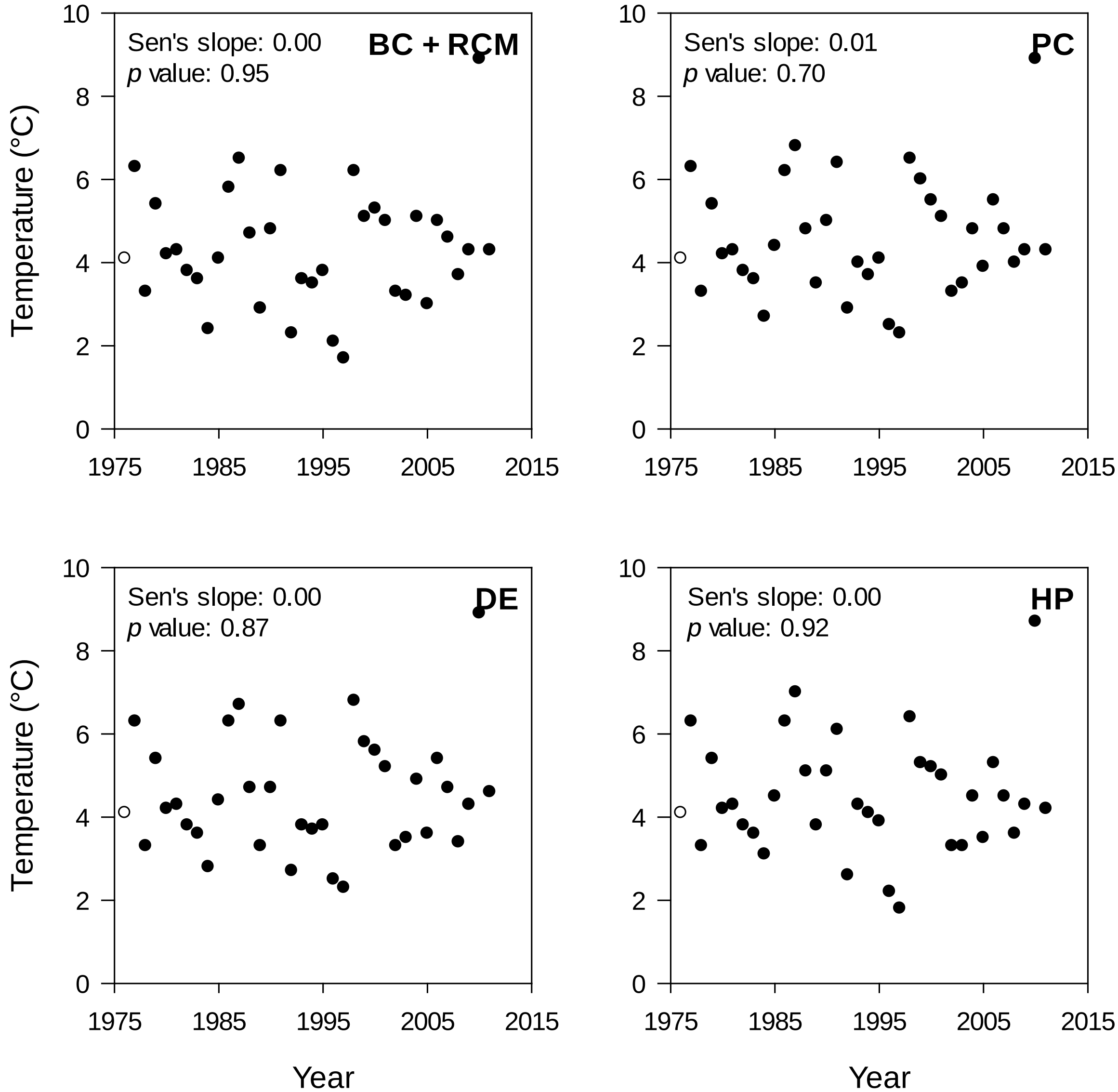
Sen's slope: -0.09
p value: <0.01
BC
Sen's slope: -0.10
p value: <0.01
RCM
Sen's slope: -0.08
p value: <0.01
PC
Sen's slope: -0.12
p value: <0.01
DE
Sen's slope: -0.09
p value: <0.01
HP
SO4 (mg·L-1)
Z-score
Year
1975 1980 1985 1990 1995 2000 2005 2010 2015
BC
RCM
PC
DE
HP

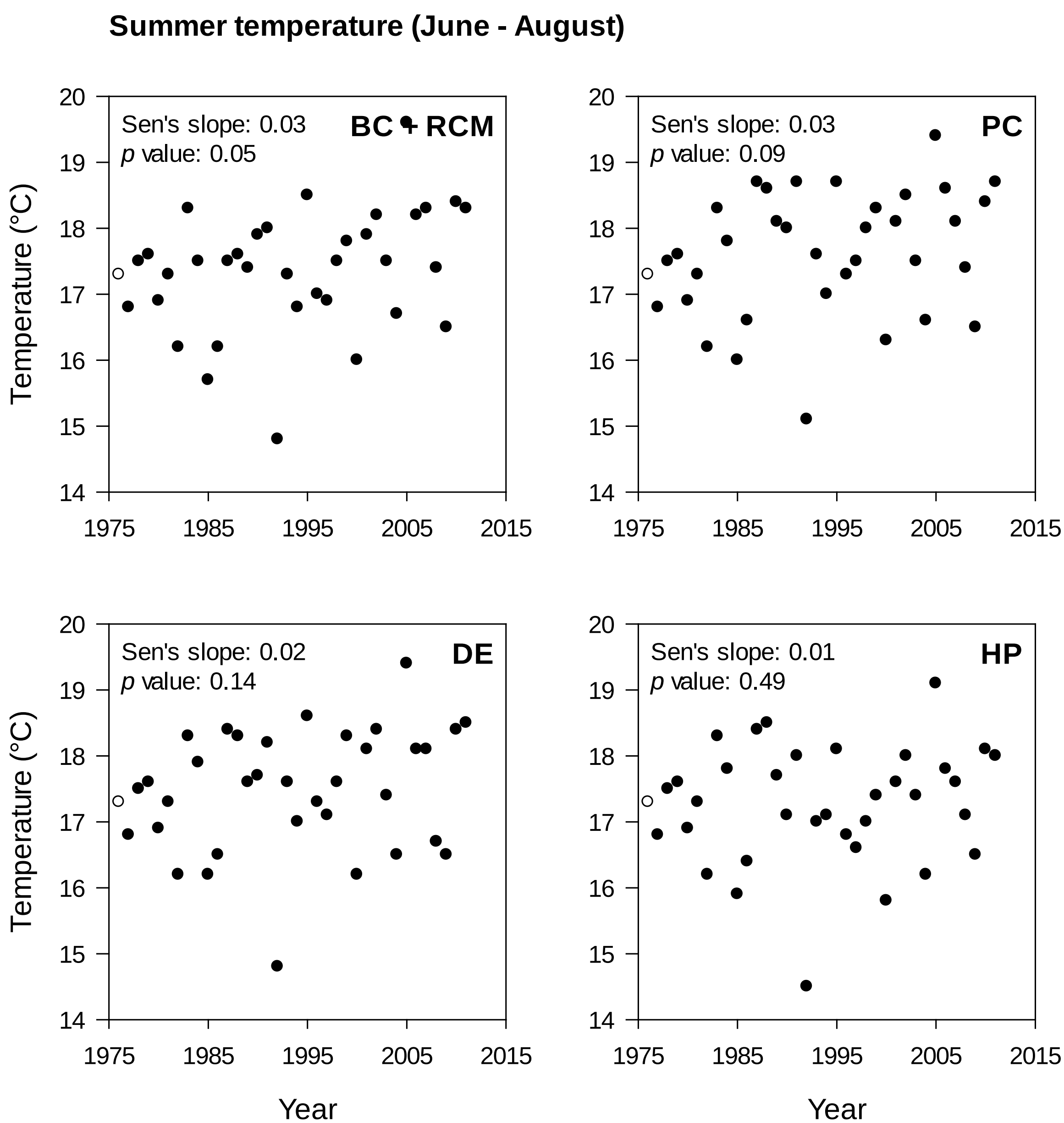
Appendix III: Climate plots

Appendix III. Scatterplots showing climate variables for Blue Chalk (BC), Red Chalk (Main Basin; RCM), Plastic (PC), Dickie (DE), and Harp (HP) lakes from 1976 to 2011. Mann-Kendall monotonic trend test results are also provided on the scatterplots. Temperature values provided are mean air temperature.

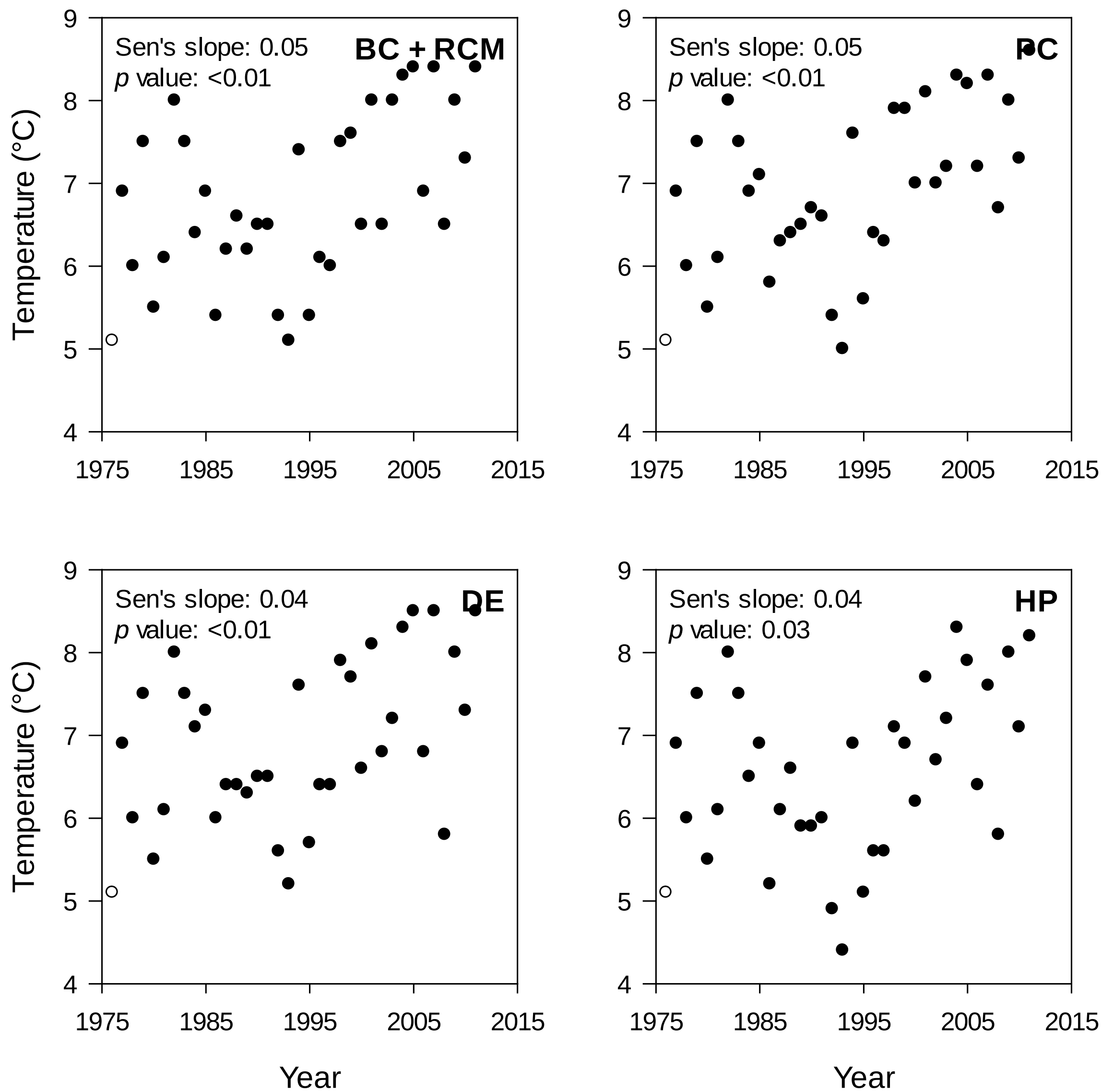


Spring temperature (March - May)

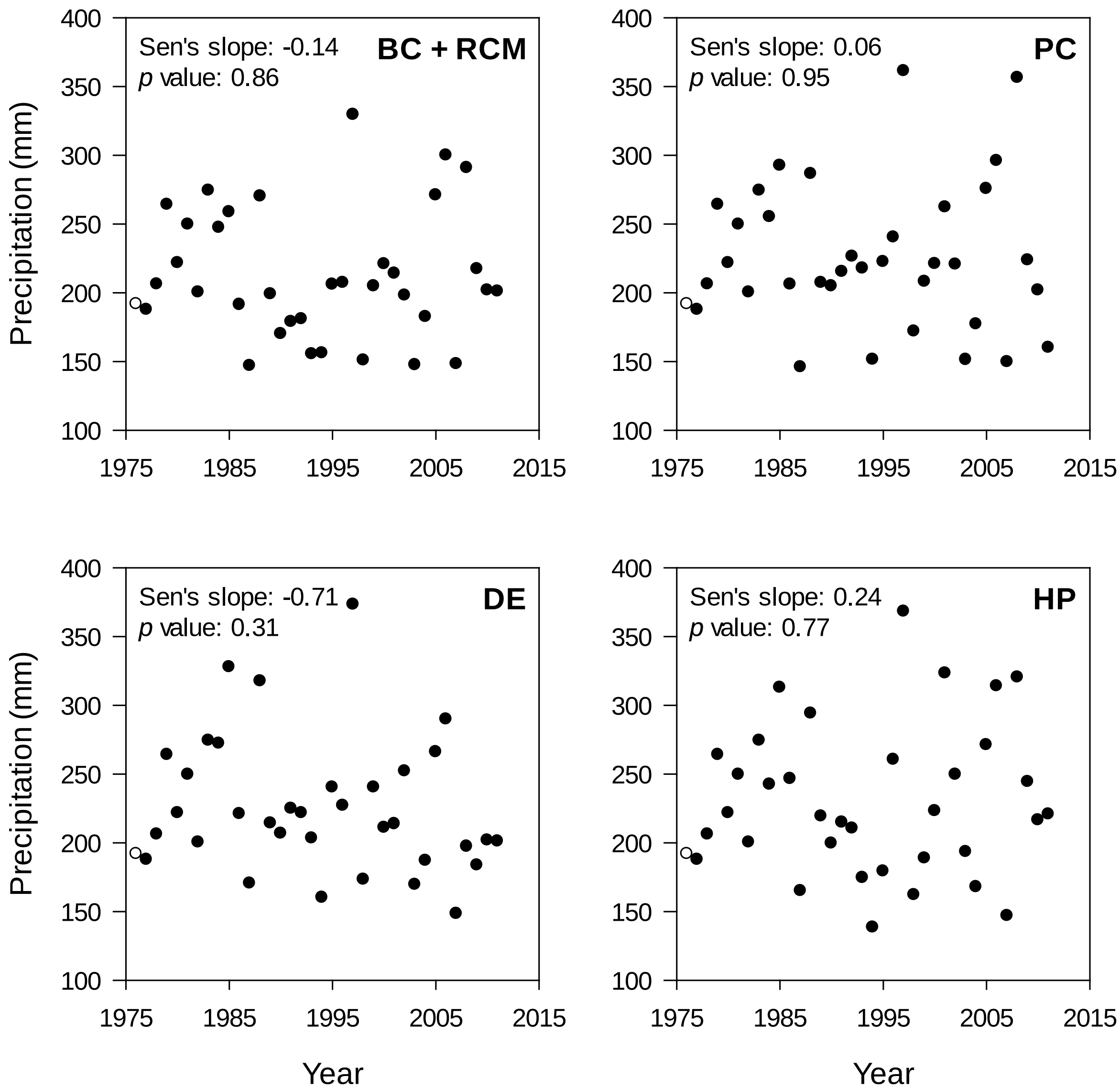



Summer temperature (June - August)
Sen's slope: 0.03
p value: 0.05
BC + RCM
Sen's slope: 0.03
p value: 0.09
PC
Sen's slope: 0.02
p value: 0.14
DE
Sen's slope: 0.01
p value: 0.49
HP
Temperature (°C)
Year
20
19
18
17
16
15
14
1975
1985
1995
2005
2015

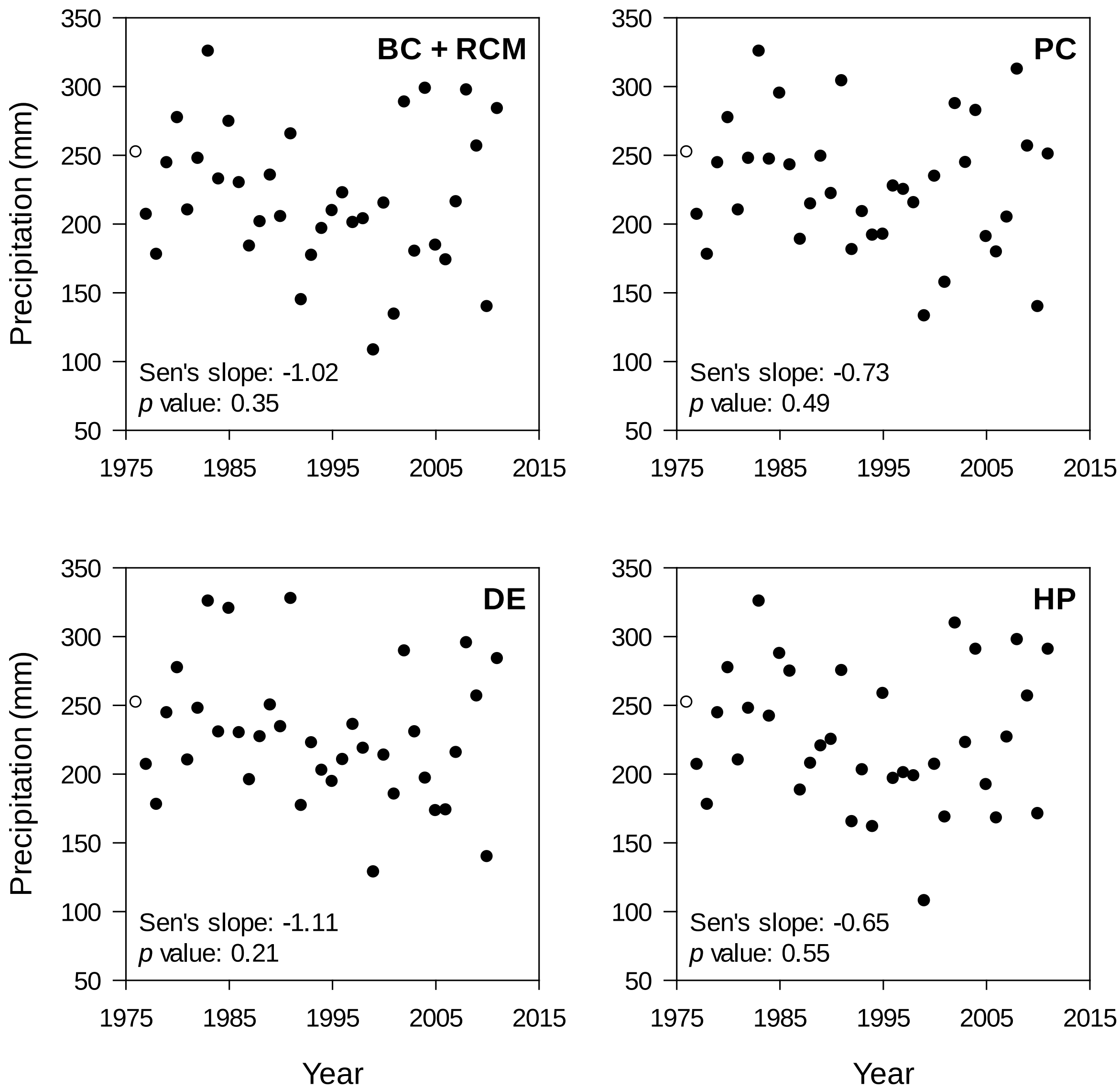
Fall temperature (September - November)

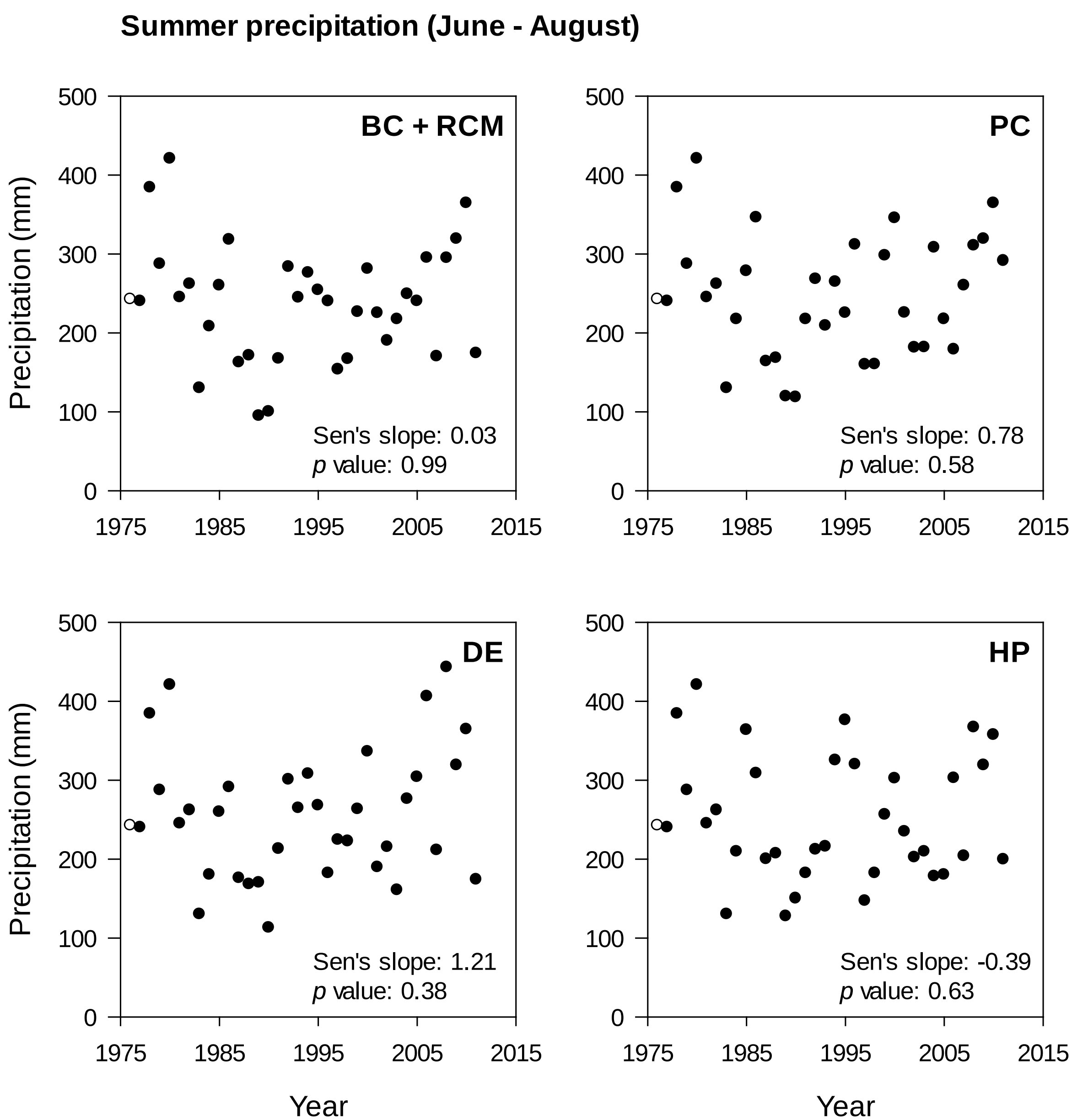


Winter precipitation (December - February)



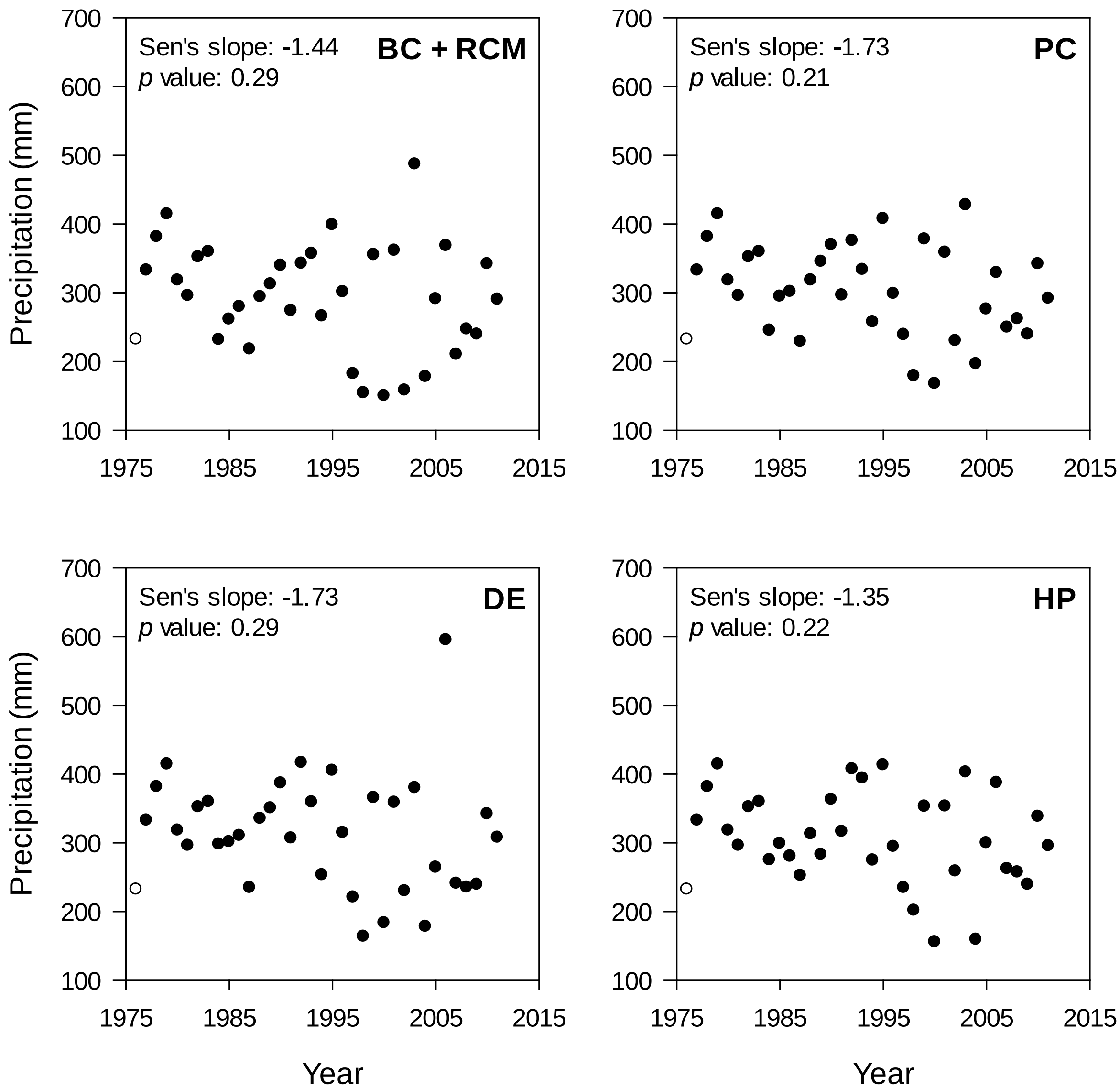
Spring precipitation (March - May)



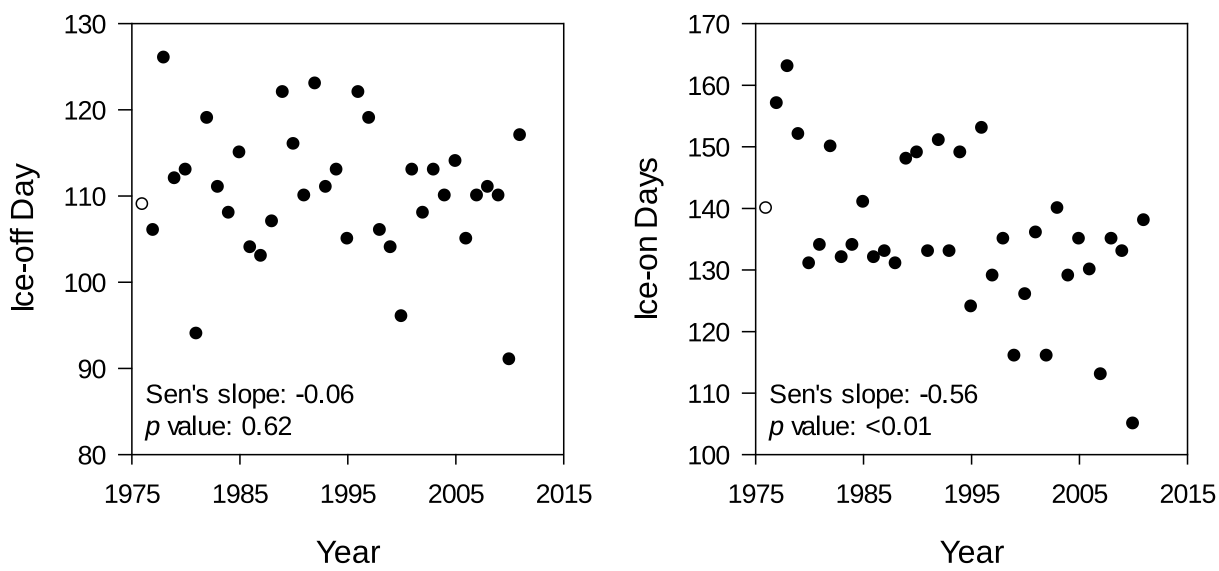


Summer precipitation (June - August)
BC + RCM
Sen's slope: 0.03
p value: 0.99
PC
Sen's slope: 0.78
p value: 0.58
DE
Sen's slope: 1.21
p value: 0.38
HP
Sen's slope: -0.39
p value: 0.63
Precipitation (mm)
Year

Fall precipitation (September - November)

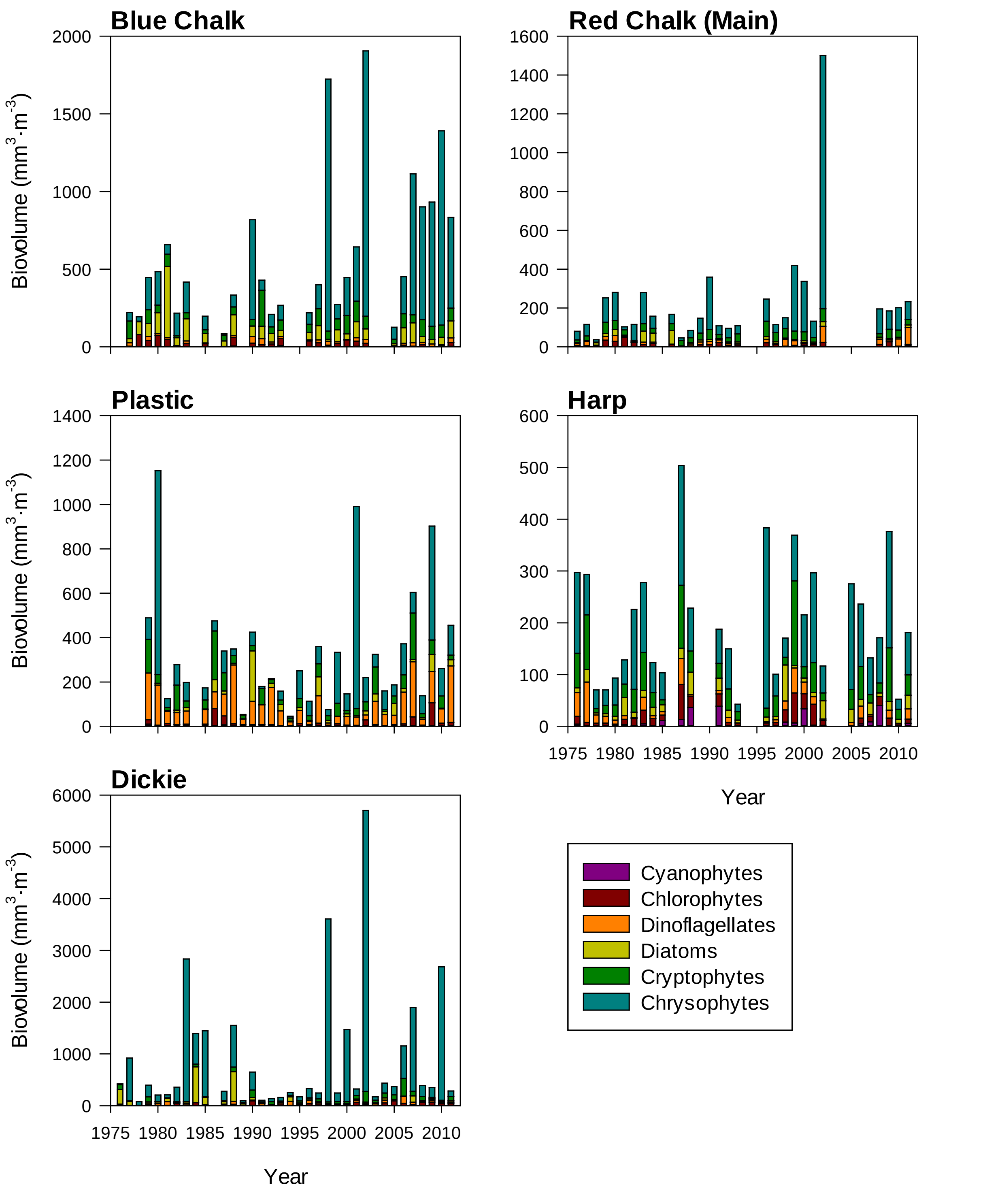


Ice-off Day and Ice-on Days



Appendix IV: Bar charts of spring phytoplankton (absolute biovolume)

Appendix IV. Temporal patterns of absolute biovolume ($mm^3 \cdot m^{-3}$) for the major phytoplankton groups in spring samples from Blue Chalk, Red Chalk (Main Basin), Plastic, Dickie, and Harp lakes, Ontario, Canada from 1976 to 2011 (except for Blue Chalk: 1977 to 2011; Plastic: 1979 to 2011).



Appendix V: Mann-Kendall trend tests for spring phytoplankton (absolute biovolume)

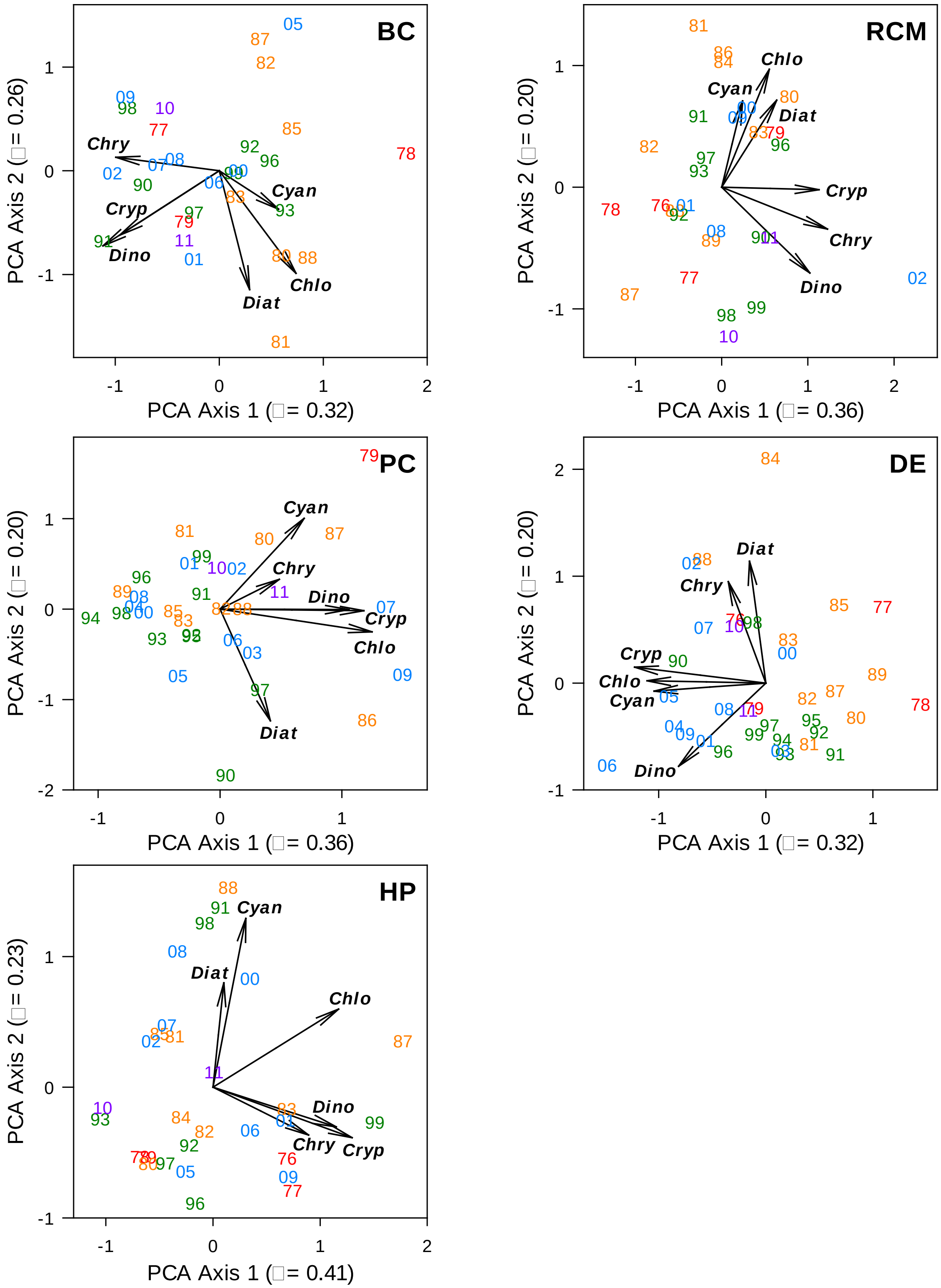
Appendix V. Sen's slopes and *p*-values from Mann-Kendall trend tests for the absolute biovolume of the major phytoplankton groups in spring samples from Blue Chalk (BC), Red Chalk (Main Basin; RCM), Plastic (PC), Dickie (DE), and Harp (HP) lakes, Ontario, Canada from 1976 to 2011 (except for Blue Chalk: 1977 to 2011; Plastic: 1979 to 2011).

	Statistics	BC	DE	HP	PC	RCM
Chlorophytes	Sen's slope ($mm^3 \cdot m^{-3} \cdot year^{-1}$)	-0.80	**0.79**	0.07	0.07	-0.10
	p value	0.06	**0.01**	0.60	0.65	0.58
Chrysophytes	Sen's slope ($mm^3 \cdot m^{-3} \cdot year^{-1}$)	**14.38**	3.73	0.91	1.86	2.28
	p value	**<0.01**	0.20	0.42	0.08	*0.05
Cryptophytes	Sen's slope ($mm^3 \cdot m^{-3} \cdot year^{-1}$)	1.48	**1.75**	-0.01	-0.18	0.55
	p value	*0.05	**<0.01**	1.00	0.78	0.12
Cyanophytes	Sen's slope ($mm^3 \cdot m^{-3} \cdot year^{-1}$)	0.02	**0.04**	0.06	0.00	0.00
	p value	0.31	**<0.01**	0.19	0.88	0.83
Diatoms	Sen's slope ($mm^3 \cdot m^{-3} \cdot year^{-1}$)	-0.71	-0.72	0.09	0.32	-0.01
	p value	0.37	0.13	0.39	0.16	0.95
Dinoflagellates	Sen's slope ($mm^3 \cdot m^{-3} \cdot year^{-1}$)	0.09	0.57	-0.24	-0.51	0.44
	p value	0.49	0.08	0.12	0.75	0.06
Total biovolume	Sen's slope ($mm^3 \cdot m^{-3} \cdot year^{-1}$)	**17.65**	5.75	0.94	1.20	3.79
	p value	**<0.01**	0.22	0.65	0.78	*0.03

Note: Bold values indicate significance at $P < 0.05$ after correcting for the false discovery rate. An asterisk indicates significance at $P < 0.05$ only before correction for the false discovery rate.

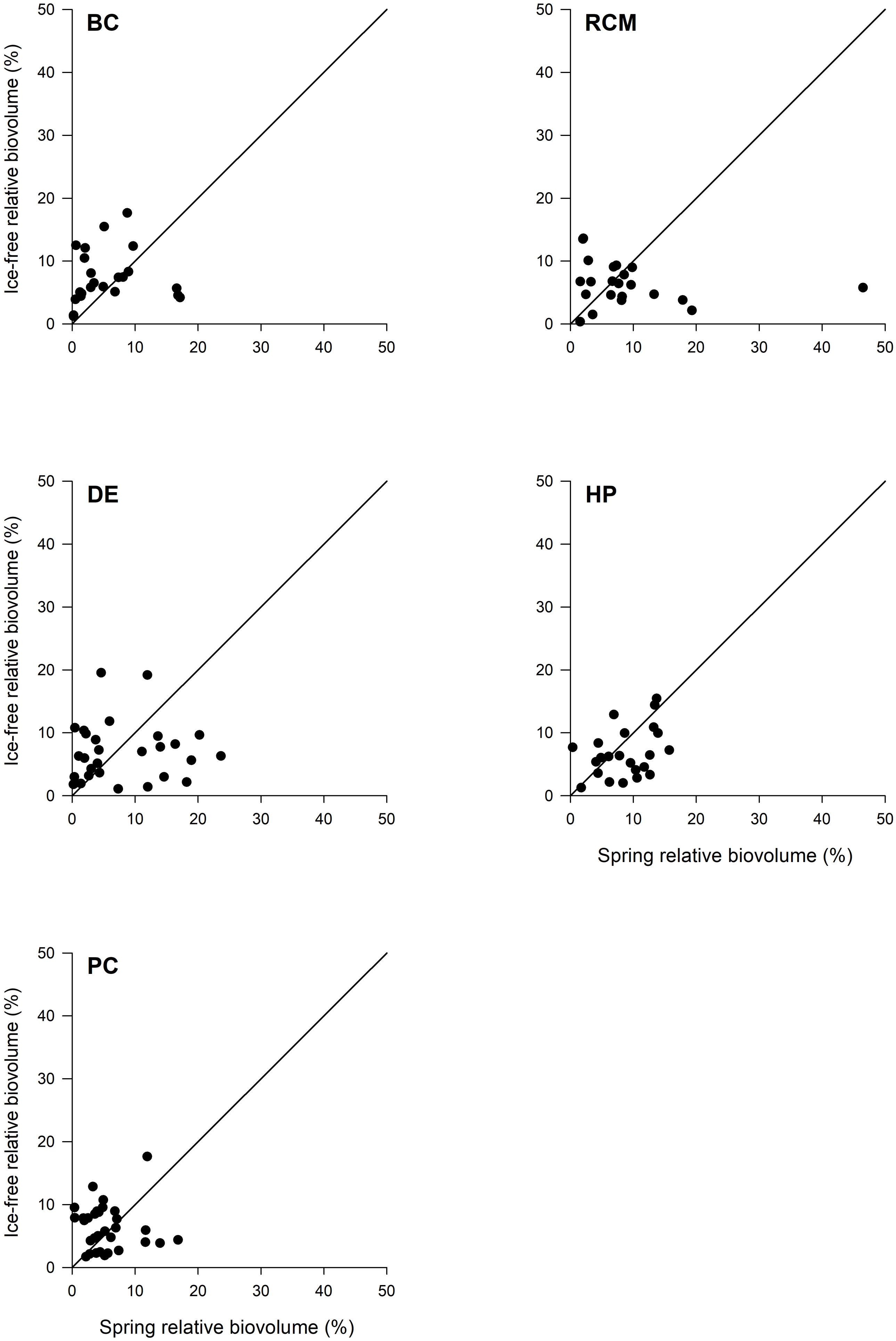
Appendix VI: PCA biplots for spring phytoplankton (absolute biovolume)

Appendix VI. Principal components analysis ordination plots showing the position of site years in relation to the absolute biovolume of major phytoplankton groups. Lake codes: BC, Blue Chalk; RCM, Red Chalk (Main Basin); PC, Plastic; DE, Dickie; HP, Harp. Algal groups: Chry, chrysophytes; Cyan, cyanophytes; Diat, diatoms; Chlo, chlorophytes; Cryp, cryptophytes; Dino, dinoflagellates.

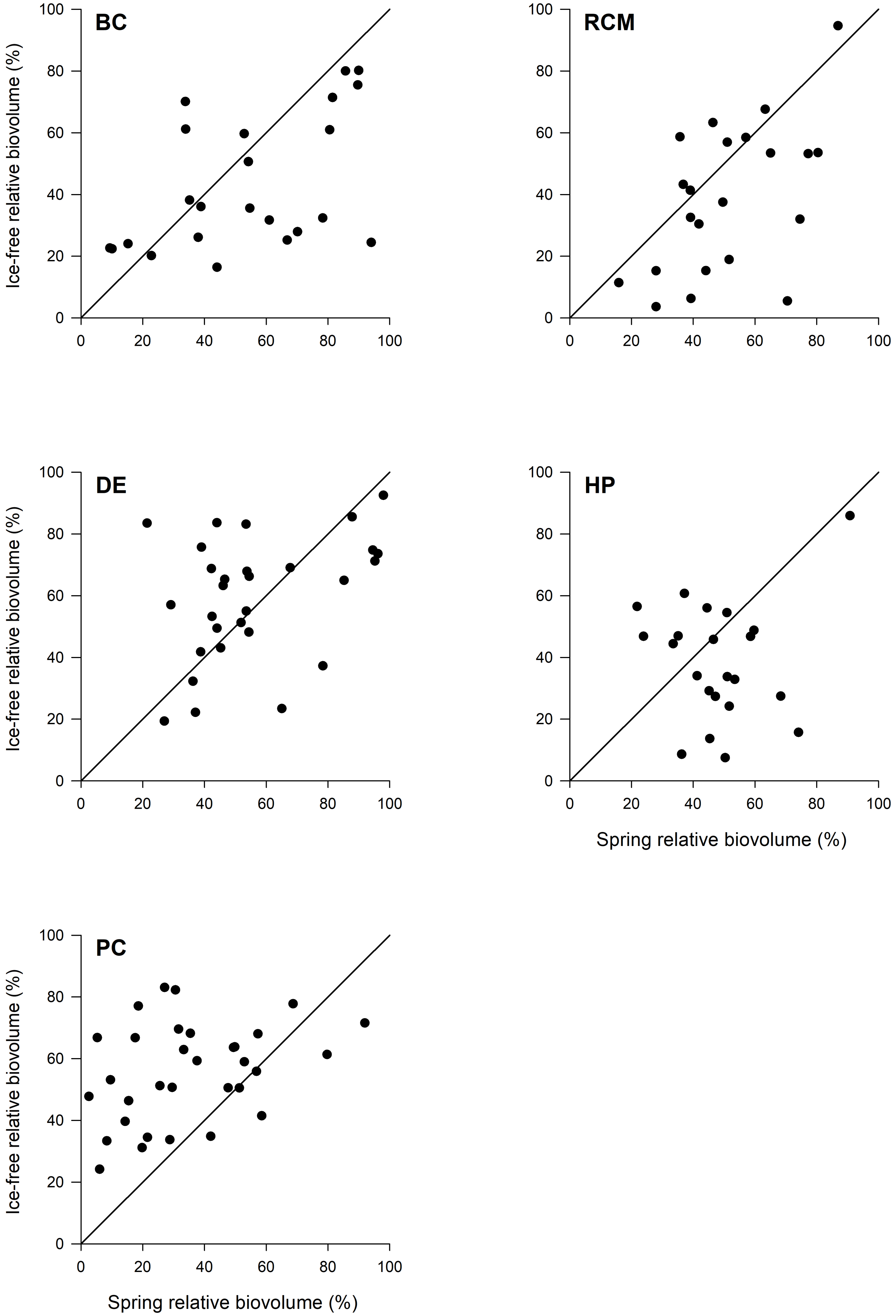


Appendix VII: Spring and ice-free phytoplankton comparisons (relative biovolume)

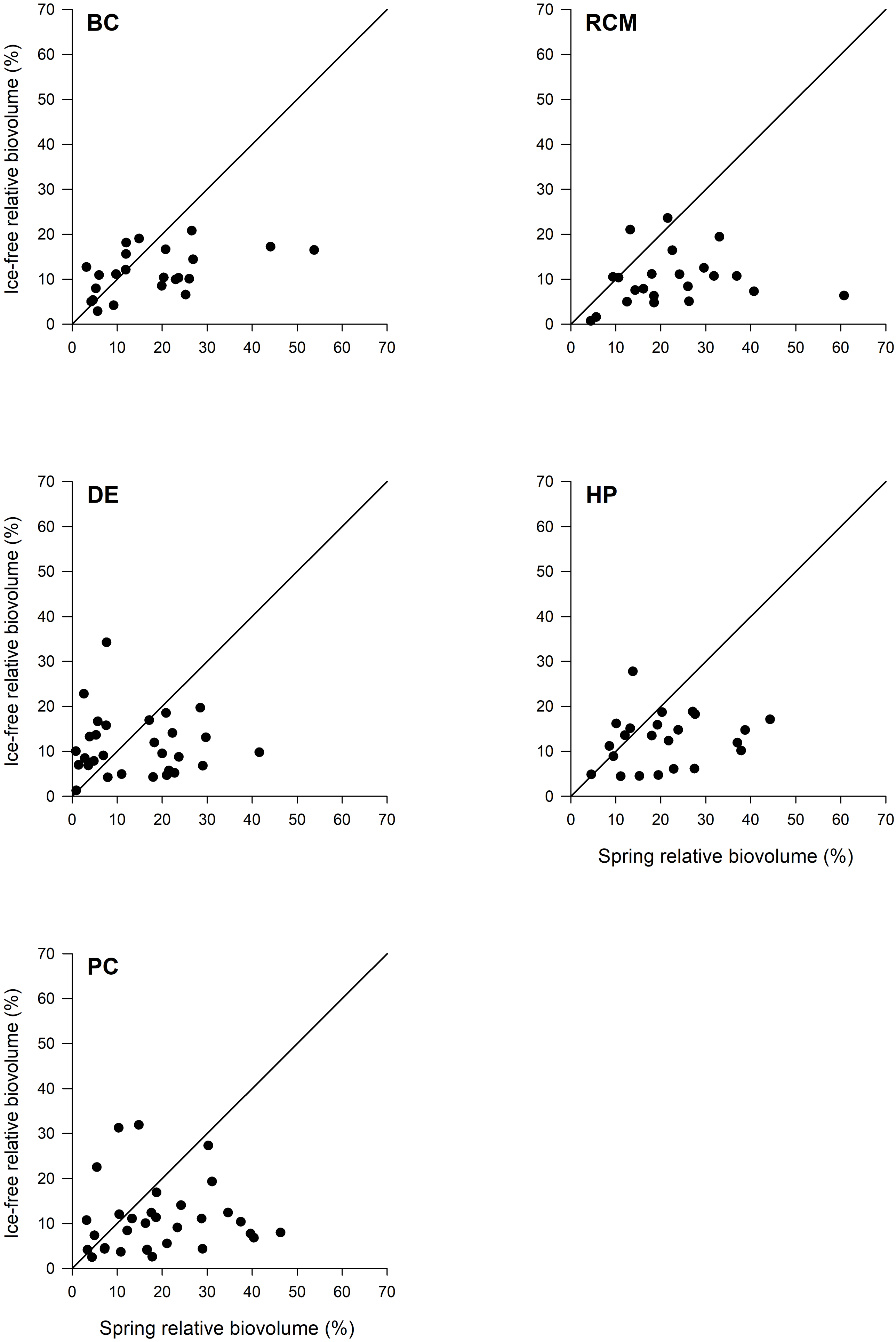
Chlorophytes



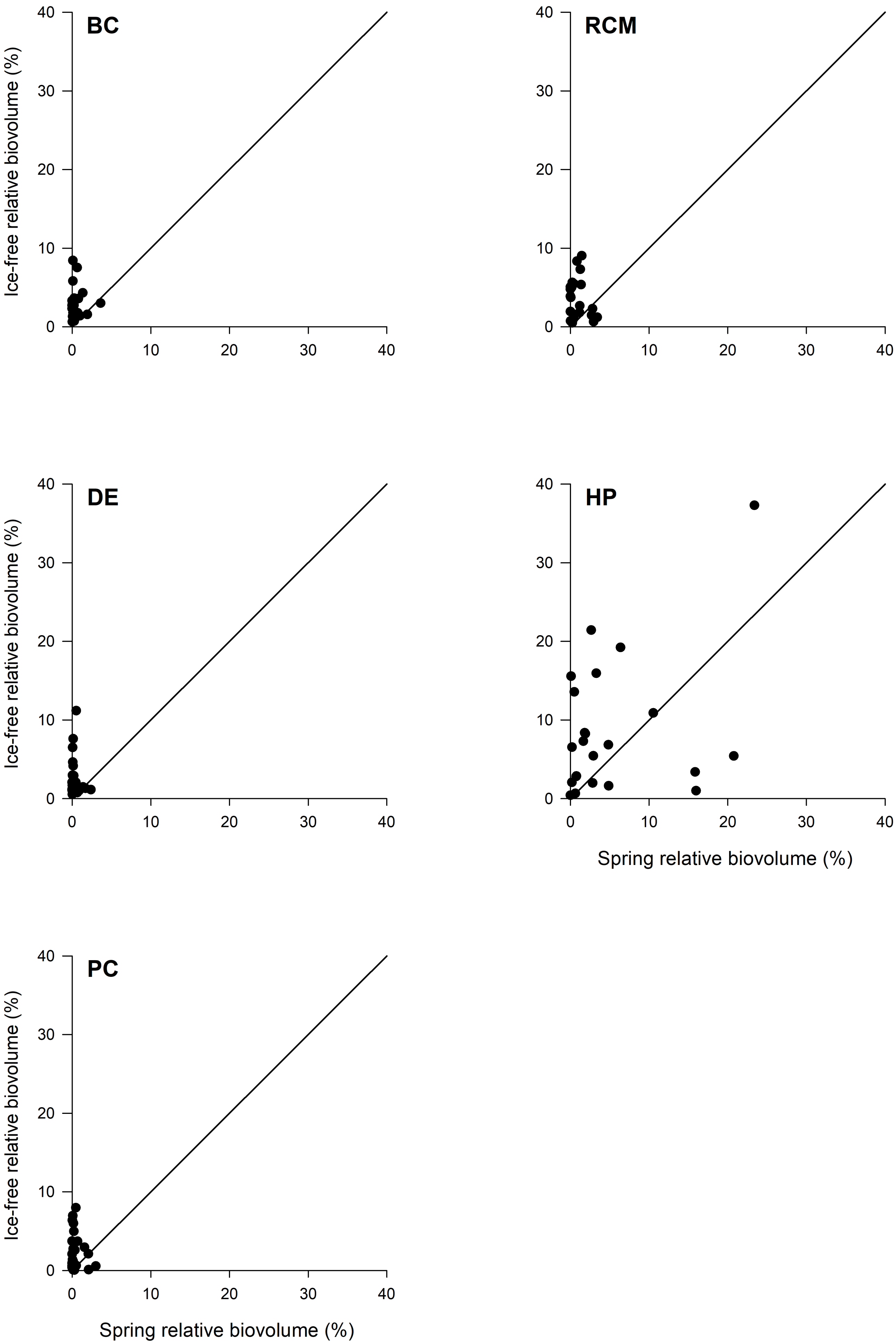
Chrysophytes



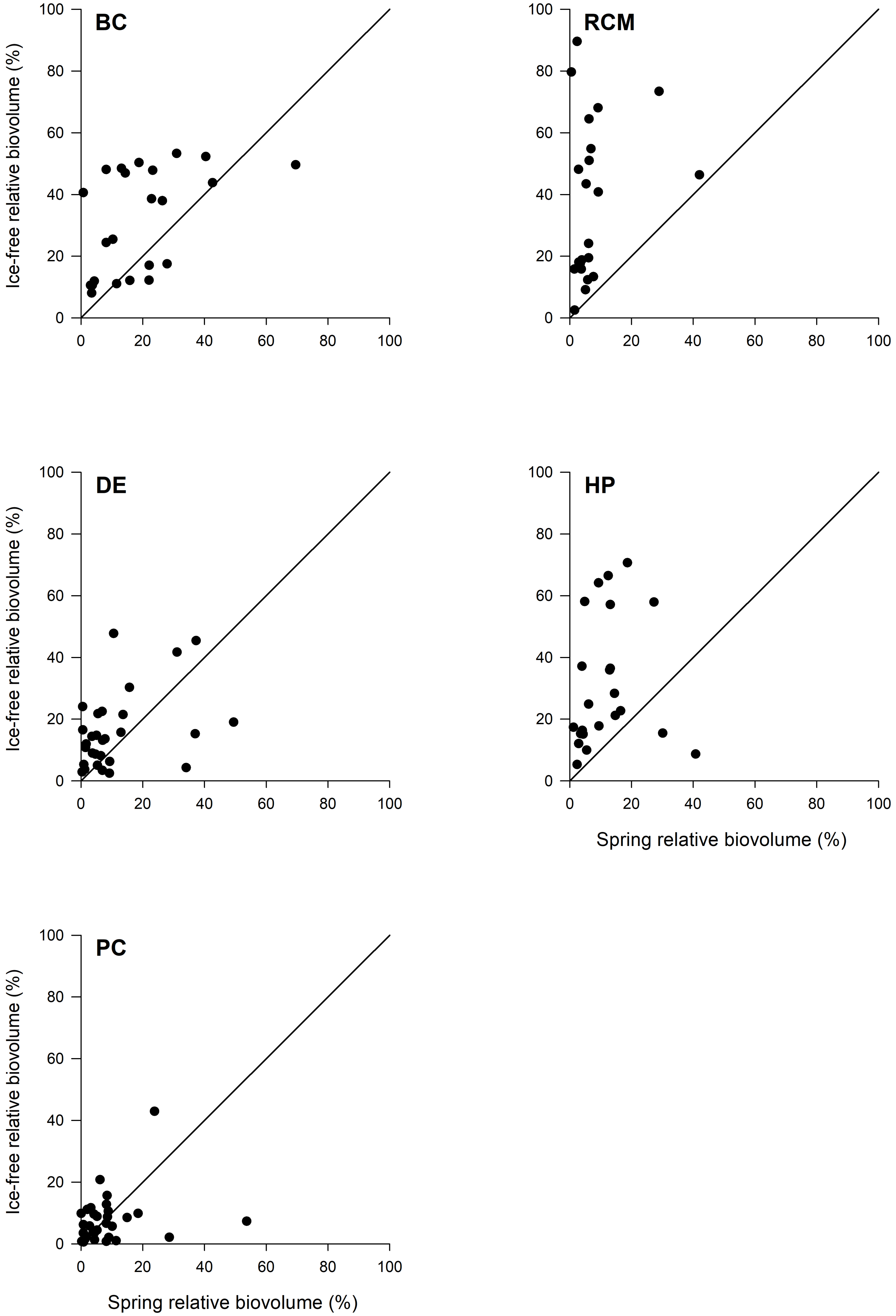
Cryptophytes



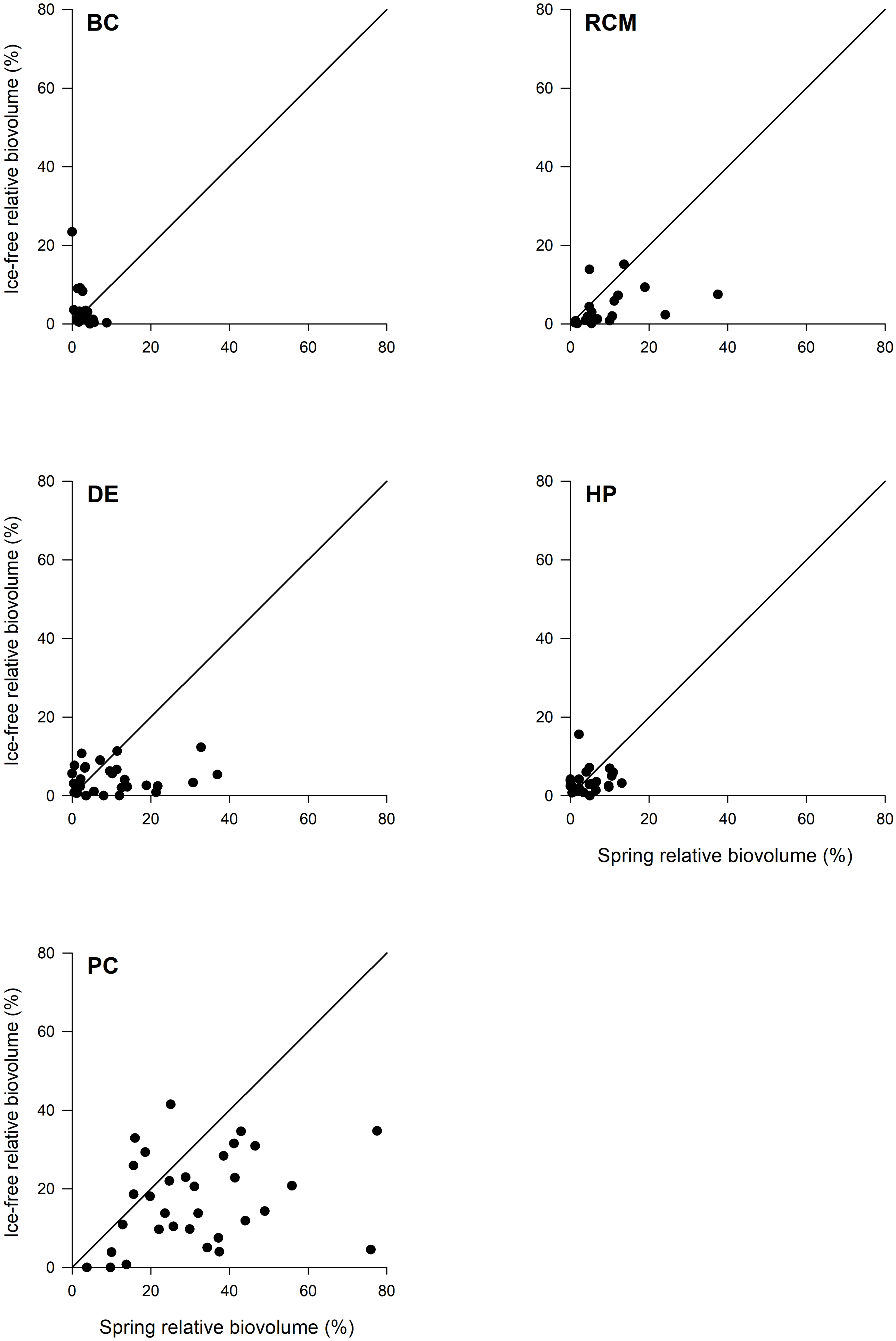
Cyanophytes



Diatoms

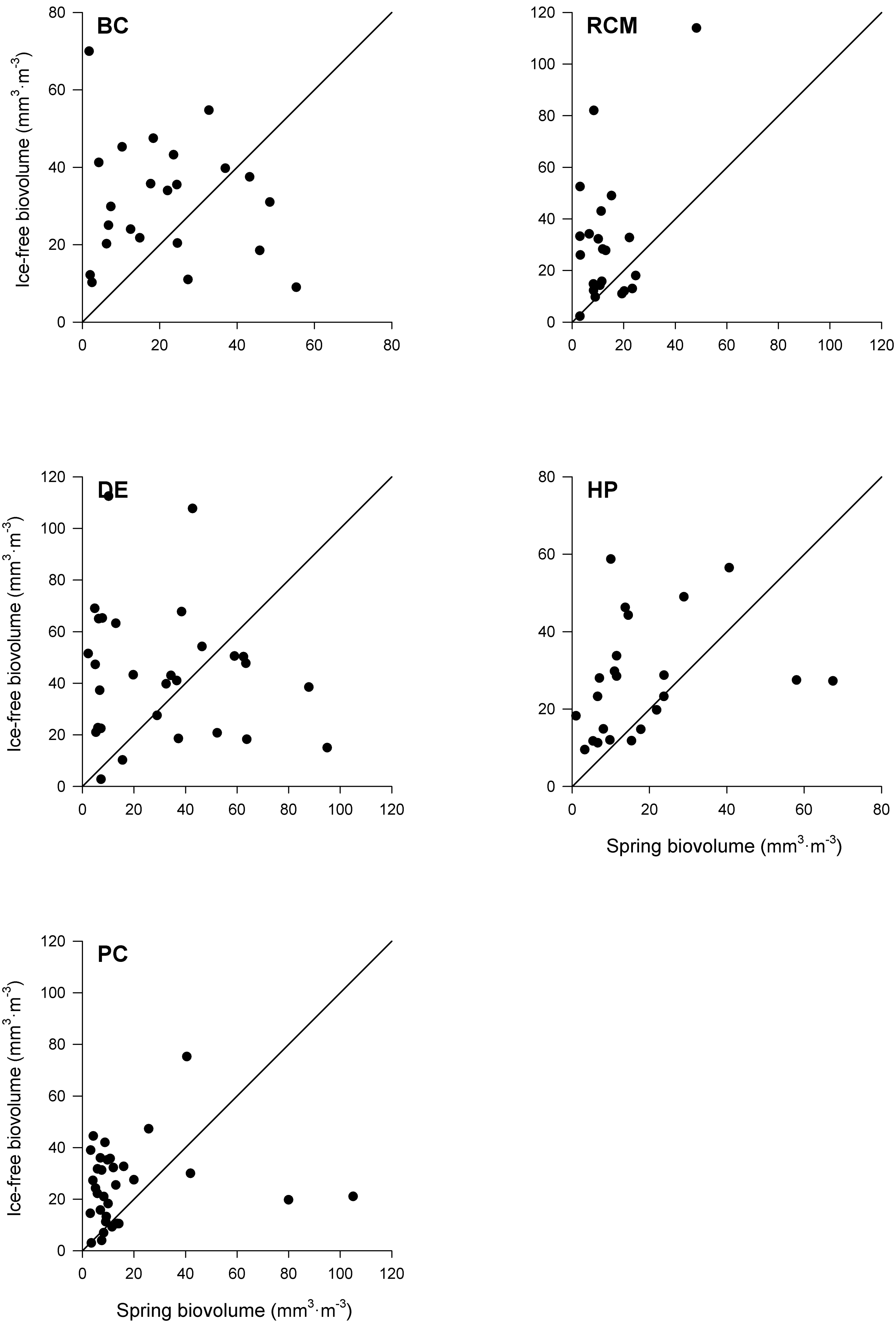

BC
RCM
DE
HP
PC
Ice-free relative biovolume (%)
Spring relative biovolume (%)
0
20
40
60
80
100

Dinoflagellates

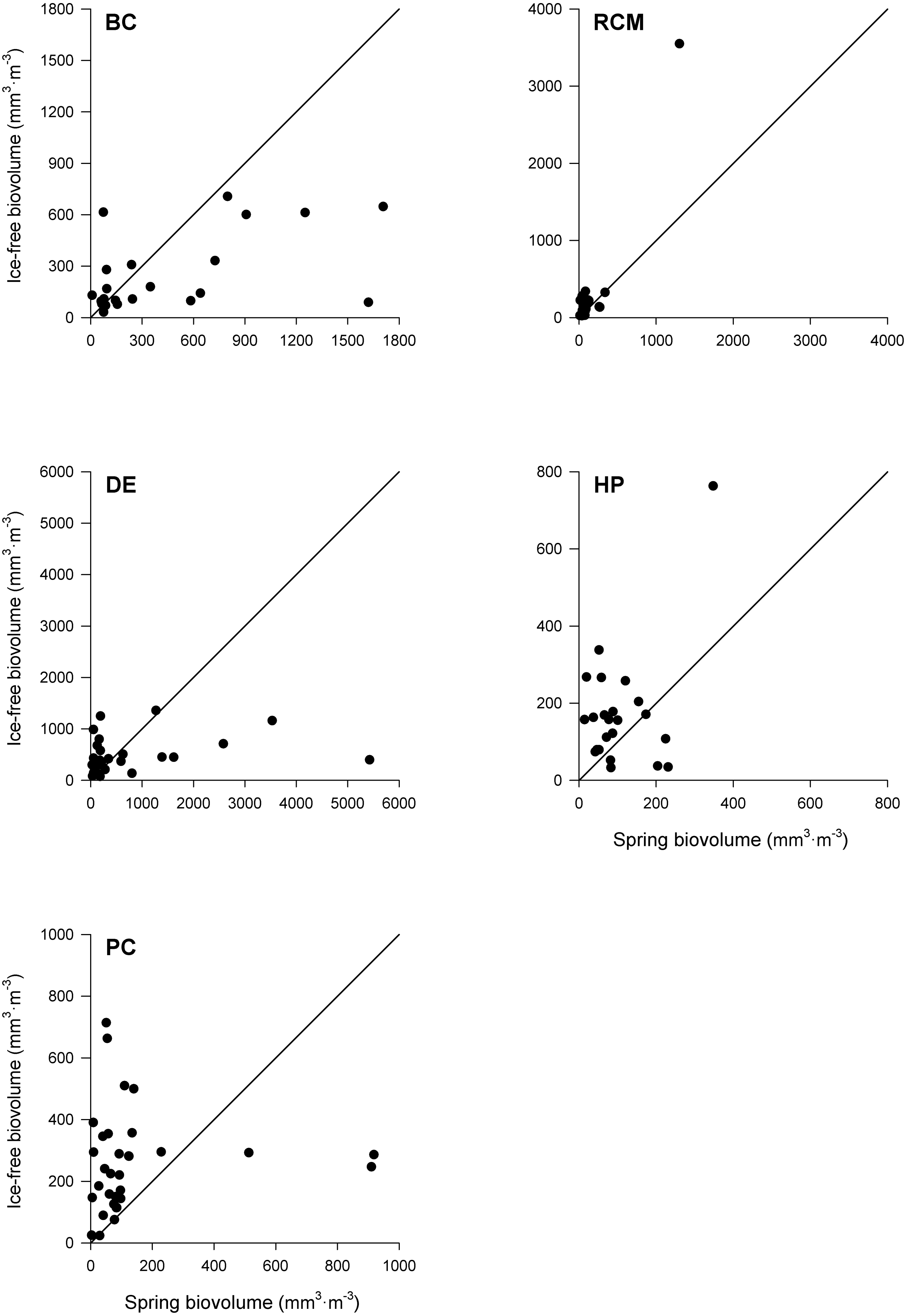


Appendix VIII: Spring and ice-free phytoplankton comparisons (absolute biovolume)

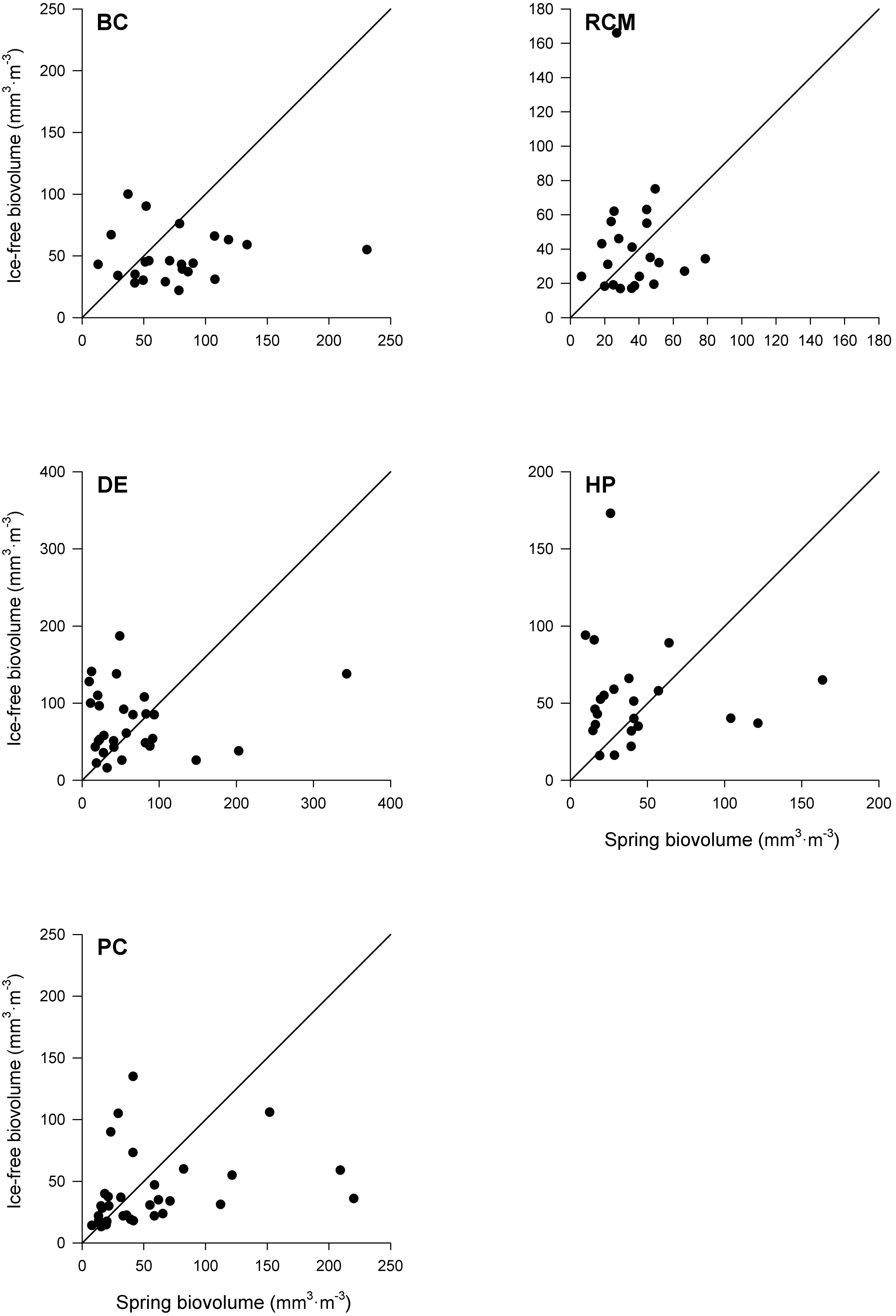
Chlorophytes



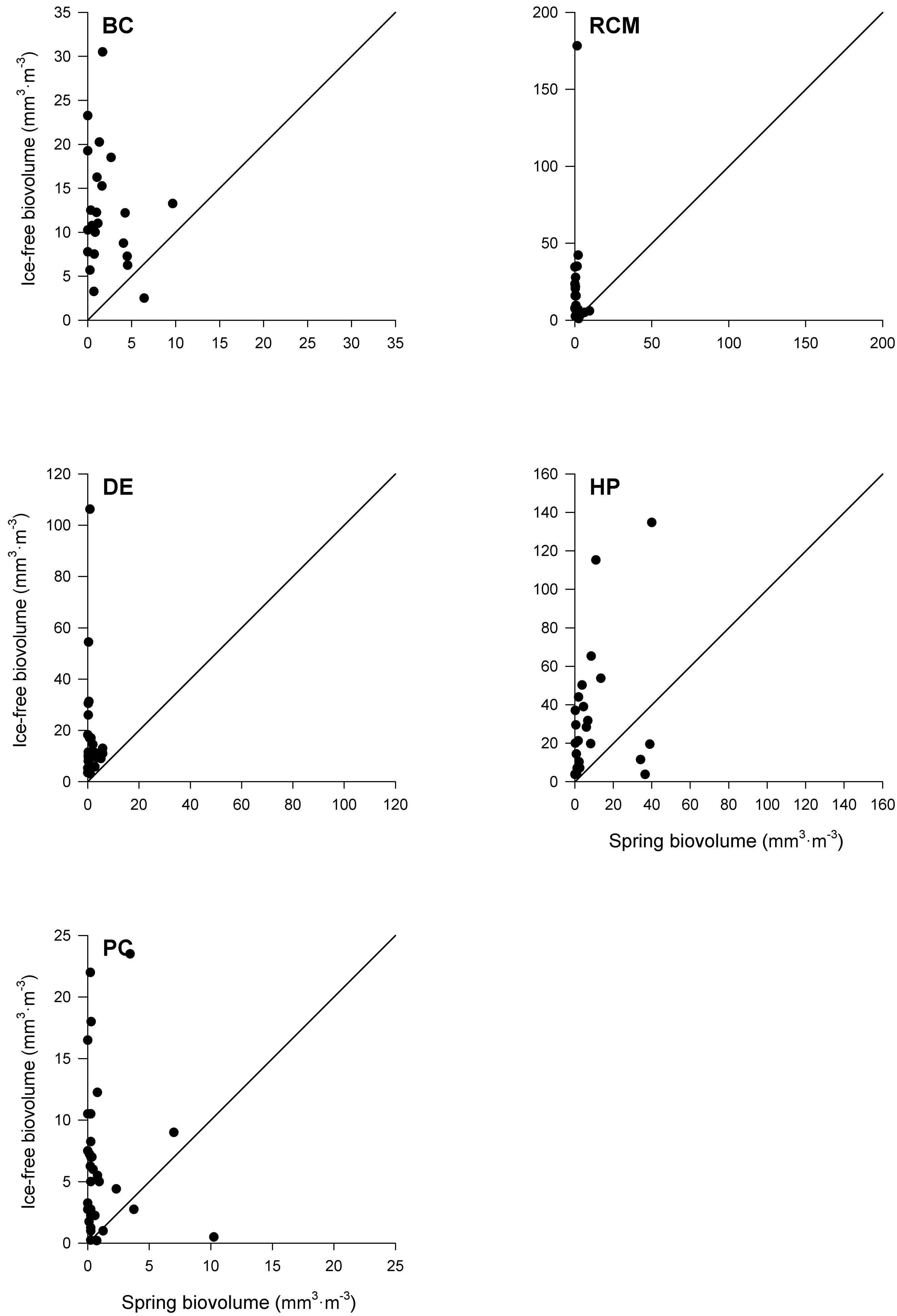
Chrysophytes



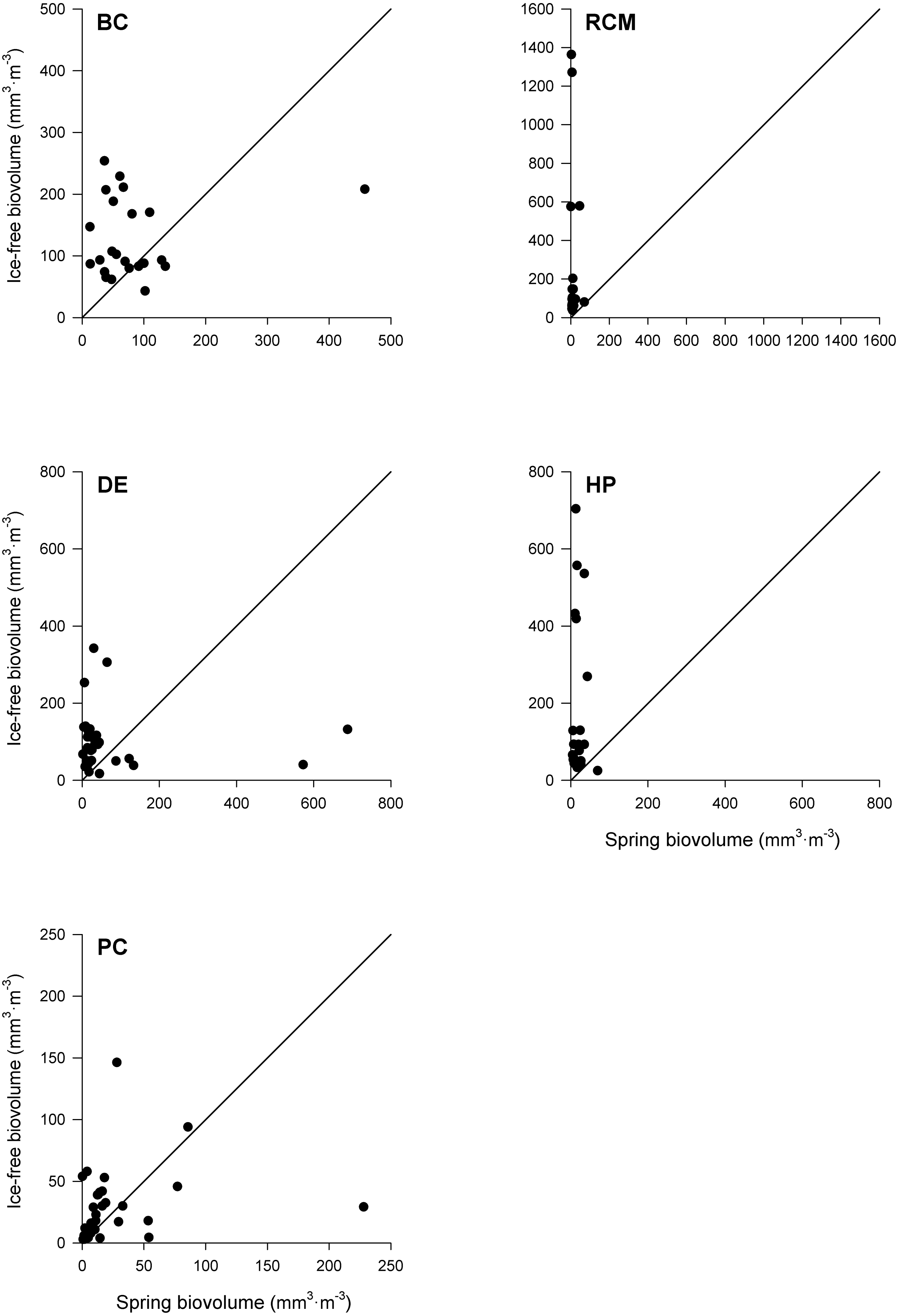
Cryptophytes



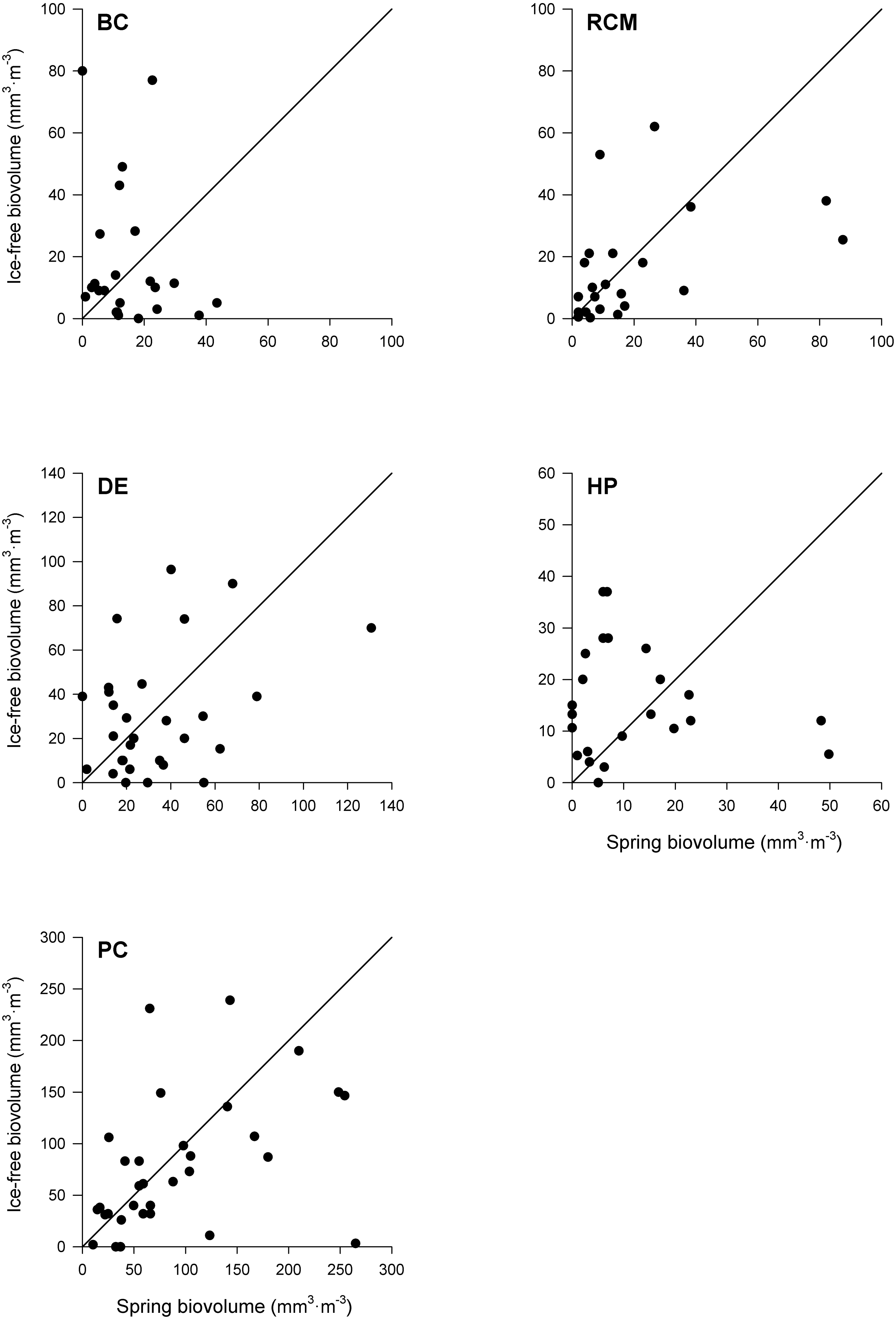
Cyanophytes



Diatom


BC
RCM
DE
HP
PC
Ice-free biovolume (mm^3·m^{-3})
Spring biovolume (mm^3·m^{-3})
0
100
200
300
400
500
600
800
1000
1200
1400
1600
50
150
250

Dinoflagellates



Appendix IX: Correlation matrices (spring water chemistry, climate, and phytoplankton)

Appendix IX. Correlation matrix showing relationship between spring water chemistry, climate, and phytoplankton variables for Blue Chalk Lake (1977-2011). Phytoplankton variables are presented as PCA Axis 1 and Axis 2 scores for the relative spring phytoplankton biovolume. Winter, spring, summer, and fall temperatures are mean air temperatures. The colour gradient indicates the strength of the correlation between variables, with blue representing strong positive correlation, red representing strong negative correlation, and white representing weak correlation.

	Phyto PCA Axis 1	Phyto PCA Axis 2	Alkalinity	Ca	Cl	Cond.	DIC	DOC	Fe	K	Mg	Na	NH3 + NH4	NO2 + NO3	TKN	pH	TP	SiO3	SO4	TN	TN/TP	Winter Temp.	Spring Temp.	Winter Precip.	Spring Precip.	Summer Temp.	Fall Temp.	Summer Precip.	Fall Precip.	Ice-off Date	Ice-on Days
Phyto PCA Axis 1	1.00	0.00	-0.43	0.28	0.38	0.60	-0.17	-0.56	-0.18	0.10	0.58	0.29	0.09	0.54	-0.31	0.35	-0.17	0.17	0.60	0.19	0.38	-0.40	-0.23	0.15	-0.22	-0.18	-0.41	0.06	0.14	0.17	0.38
Phyto PCA Axis 2	0.00	1.00	0.09	0.14	0.10	0.08	0.02	-0.26	0.12	0.00	0.20	-0.19	-0.06	-0.15	0.24	-0.16	0.03	-0.04	0.17	-0.09	-0.18	0.04	0.30	-0.14	0.08	0.14	-0.32	-0.12	-0.01	-0.19	-0.01
Alkalinity	-0.43	0.09	1.00	-0.19	-0.09	-0.67	0.58	0.17	0.30	0.32	-0.38	0.05	0.54	-0.37	0.08	0.15	0.18	-0.24	-0.77	-0.22	-0.34	0.21	0.34	-0.16	-0.37	0.14	0.34	-0.08	-0.34	-0.16	-0.28
Ca	0.28	0.14	-0.19	1.00	0.27	0.65	-0.29	-0.29	0.11	0.17	0.53	0.34	-0.14	0.13	-0.15	-0.05	-0.49	0.24	0.48	0.01	0.15	-0.42	0.13	-0.16	-0.10	-0.26	-0.48	0.05	-0.10	0.26	0.47
Cl	0.38	0.10	-0.09	0.27	1.00	0.34	-0.38	-0.32	-0.15	0.30	0.24	0.17	0.18	0.14	-0.41	0.08	-0.09	-0.24	0.28	-0.25	-0.15	0.03	0.07	-0.24	-0.24	-0.36	-0.16	-0.08	-0.10	0.05	0.07
Cond.	0.60	0.08	-0.67	0.65	0.34	1.00	-0.50	-0.54	-0.10	0.19	0.61	0.32	-0.30	0.47	-0.21	-0.07	-0.46	0.26	0.90	0.21	0.44	-0.40	-0.15	-0.07	0.06	-0.24	-0.52	-0.07	0.20	0.33	0.62
DIC	-0.17	0.02	0.58	-0.29	-0.38	-0.50	1.00	0.20	-0.04	0.25	-0.32	0.00	0.25	-0.14	0.11	0.12	0.18	-0.13	-0.47	-0.01	-0.03	0.18	0.02	0.02	-0.05	0.38	0.22	-0.27	-0.24	0.16	0.00
DOC	-0.56	-0.26	0.17	-0.29	-0.32	-0.54	0.20	1.00	0.17	-0.37	-0.66	-0.02	-0.02	-0.47	0.11	-0.12	0.33	0.00	-0.54	-0.27	-0.45	-0.15	0.00	0.05	0.04	0.44	0.42	0.29	0.03	-0.05	-0.20
Fe	-0.18	0.12	0.30	0.11	-0.15	-0.10	-0.04	0.17	1.00	0.19	-0.14	-0.20	-0.10	-0.25	0.37	0.10	0.12	0.20	-0.29	0.10	-0.14	-0.18	0.57	0.09	-0.01	-0.03	0.24	0.23	0.03	-0.43	-0.22
K	0.10	0.00	0.32	0.17	0.30	0.19	0.25	-0.37	0.19	1.00	0.01	0.13	0.27	0.12	-0.09	0.10	-0.07	-0.11	0.06	0.12	0.11	0.10	0.10	-0.27	-0.20	-0.20	0.04	-0.45	0.00	0.31	0.21
Mg	0.58	0.20	-0.38	0.53	0.24	0.61	-0.32	-0.66	-0.14	0.01	1.00	0.26	-0.07	0.32	-0.10	-0.03	-0.24	-0.08	0.74	0.12	0.27	-0.17	0.11	-0.10	-0.24	-0.33	-0.60	-0.08	-0.07	-0.11	0.21
Na	0.29	-0.19	0.05	0.34	0.17	0.32	0.00	-0.02	-0.20	0.13	0.26	1.00	0.01	0.01	-0.48	0.09	-0.20	-0.23	0.30	-0.26	0.02	-0.37	-0.01	-0.28	-0.40	-0.15	-0.28	-0.16	-0.20	0.20	0.36
NH3 + NH4	0.09	-0.06	0.54	-0.14	0.18	-0.30	0.25	-0.02	-0.10	0.27	-0.07	0.01	1.00	0.08	-0.04	0.26	0.22	-0.23	-0.26	0.02	-0.11	0.24	-0.14	-0.01	-0.42	0.10	0.20	-0.12	-0.10	0.12	-0.11
NO2 + NO3	0.54	-0.15	-0.37	0.13	0.14	0.47	-0.14	-0.47	-0.25	0.12	0.32	0.01	0.08	1.00	-0.21	0.20	-0.29	0.40	0.49	0.55	0.72	-0.33	-0.44	0.20	-0.14	-0.31	-0.47	-0.19	-0.13	0.44	0.55
TKN	-0.31	0.24	0.08	-0.15	-0.41	-0.21	0.11	0.11	0.37	-0.09	-0.10	-0.48	-0.04	-0.21	1.00	-0.27	0.57	-0.06	-0.14	0.71	-0.01	0.15	0.25	-0.01	0.14	0.11	0.01	0.10	0.19	-0.38	-0.23
pH	0.35	-0.16	0.15	-0.05	0.08	-0.07	0.12	-0.12	0.10	0.10	-0.03	0.09	0.26	0.20	-0.27	1.00	0.00	0.20	-0.09	0.01	0.07	-0.21	0.08	0.32	-0.34	-0.06	0.11	0.09	-0.21	-0.08	0.18
TP	-0.17	0.03	0.18	-0.49	-0.09	-0.46	0.18	0.33	0.12	-0.07	-0.24	-0.20	0.22	-0.29	0.57	0.00	1.00	-0.23	-0.23	0.27	-0.62	0.10	0.22	-0.15	-0.03	-0.01	0.20	0.15	0.17	-0.36	-0.24
SiO3	0.17	-0.04	-0.24	0.24	-0.24	0.26	-0.13	0.00	0.20	-0.11	-0.08	-0.23	-0.23	0.40	-0.06	0.20	-0.23	1.00	-0.07	0.25	0.30	-0.54	-0.22	0.45	0.31	-0.01	-0.11	0.32	0.20	0.32	0.46
SO4	0.60	0.17	-0.77	0.48	0.28	0.90	-0.47	-0.54	-0.29	0.06	0.74	0.30	-0.26	0.49	-0.14	-0.09	-0.23	-0.07	1.00	0.26	0.35	-0.14	-0.16	-0.10	0.04	-0.34	-0.57	-0.20	0.16	0.13	0.43
TN	0.19	-0.09	-0.22	0.01	-0.25	0.21	-0.01	-0.27	0.10	0.12	0.12	-0.26	0.02	0.55	0.71	0.01	0.27	0.25	0.26	1.00	0.58	-0.22	-0.14	0.12	-0.02	-0.16	-0.32	-0.05	0.13	0.08	0.33
TN/TP	0.38	-0.18	-0.34	0.15	-0.15	0.44	-0.03	-0.45	-0.14	0.11	0.27	0.02	-0.11	0.72	-0.01	0.07	-0.62	0.30	0.35	0.58	1.00	-0.17	-0.37	0.23	-0.02	-0.10	-0.40	-0.19	-0.10	0.34	0.37
Winter Temp.	-0.40	0.04	0.21	-0.42	0.03	-0.40	0.18	-0.15	-0.18	0.10	-0.17	-0.37	0.24	-0.33	0.15	-0.21	0.10	-0.54	-0.14	-0.22	-0.17	1.00	0.10	-0.01	0.11	0.07	0.49	-0.43	-0.15	-0.29	-0.70
Spring Temp.	-0.23	0.30	0.34	0.13	0.07	-0.15	0.02	0.00	0.57	0.10	0.11	-0.01	-0.14	-0.44	0.25	0.08	0.22	-0.22	-0.16	-0.14	-0.37	0.10	1.00	-0.35	-0.22	-0.12	0.00	0.07	-0.25	-0.71	-0.33
Winter Precip.	0.15	-0.14	-0.16	-0.16	-0.24	-0.07	0.02	0.05	0.09	-0.27	-0.10	-0.28	-0.01	0.20	-0.01	0.32	-0.15	0.45	-0.10	0.12	0.23	-0.01	-0.35	1.00	0.22	0.22	0.38	0.10	-0.10	0.04	-0.02
Spring Precip.	-0.22	0.08	-0.37	-0.10	-0.24	0.06	-0.05	0.04	-0.01	-0.20	-0.24	-0.40	-0.42	-0.14	0.14	-0.34	-0.03	0.31	0.04	-0.02	-0.02	0.11	-0.22	0.22	1.00	0.25	0.16	0.06	0.47	0.17	0.09
Summer Temp.	-0.18	0.14	0.14	-0.26	-0.36	-0.24	0.38	0.44	-0.03	-0.20	-0.33	-0.15	0.10	-0.31	0.11	-0.06	-0.01	-0.01	-0.34	-0.16	-0.10	0.07	-0.12	0.22	0.25	1.00	0.32	-0.21	0.20	0.11	0.03
Fall Temp.	-0.41	-0.32	0.34	-0.48	-0.16	-0.52	0.22	0.42	0.24	0.04	-0.60	-0.28	0.20	-0.47	0.01	0.11	0.20	-0.11	-0.57	-0.32	-0.40	0.49	0.00	0.38	0.16	0.32	1.00	-0.11	-0.08	-0.14	-0.49
Summer Precip.	0.06	-0.12	-0.08	0.05	-0.08	-0.07	-0.27	0.29	0.23	-0.45	-0.08	-0.16	-0.12	-0.19	0.10	0.09	0.15	0.32	-0.20	-0.05	-0.19	-0.43	0.07	0.10	0.06	-0.21	-0.11	1.00	0.30	-0.24	-0.08
Fall Precip.	0.14	-0.01	-0.34	-0.10	-0.10	0.20	-0.24	0.03	0.03	0.00	-0.07	-0.20	-0.10	-0.13	0.19	-0.21	0.17	0.20	0.16	0.13	-0.10	-0.15	-0.25	-0.10	0.47	0.20	-0.08	0.30	1.00	0.18	0.11
Ice-off Date	0.17	-0.19	-0.16	0.26	0.05	0.33	0.16	-0.05	-0.43	0.31	-0.11	0.20	0.12	0.44	-0.38	-0.08	-0.36	0.32	0.13	0.08	0.34	-0.29	-0.71	0.04	0.17	0.11	-0.14	-0.24	0.18	1.00	0.64
Ice-on Days	0.38	-0.01	-0.28	0.47	0.07	0.62	0.00	-0.20	-0.22	0.21	0.21	0.36	-0.11	0.55	-0.23	0.18	-0.24	0.46	0.43	0.33	0.37	-0.70	-0.33	-0.02	0.09	0.03	-0.49	-0.08	0.11	0.64	1.00

Appendix IX. Correlation matrix showing relationship between spring water chemistry, climate, and phytoplankton variables for Red Chalk Lake (1976-2011). Phytoplankton variables are presented as PCA Axis 1 and Axis 2 scores for the relative spring phytoplankton biovolume. Winter, spring, summer, and fall temperatures are mean air temperatures. The colour gradient indicates the strength of the correlation between variables, with blue representing strong positive correlation, red representing strong negative correlation, and white representing weak correlation.

	Phyto PCA Axis 1	Phyto PCA Axis 2	Alkalinity	Ca	Cl	Cond.	DIC	DOC	Fe	K	Mg	Na	NH3 + NH4	NO2 + NO3	TKN	pH	TP	SiO3	SO4	TN	TN/TP	Winter Temp.	Spring Temp.	Winter Precip.	Spring Precip.	Summer Temp.	Fall Temp.	Summer Precip.	Fall Precip.	Ice-off Date	Ice-on Days
Phyto PCA Axis 1	1.00	0.00	0.05	-0.43	-0.08	-0.46	0.09	0.42	-0.04	0.06	-0.36	0.02	-0.31	-0.30	0.13	-0.27	-0.13	-0.19	-0.33	0.03	0.25	0.42	0.16	-0.14	0.00	0.26	0.48	-0.30	-0.22	0.00	-0.24
Phyto PCA Axis 2	0.00	1.00	-0.35	0.21	-0.20	0.26	-0.38	-0.21	-0.18	-0.09	0.24	0.07	-0.37	0.39	-0.41	-0.29	-0.24	-0.25	0.44	-0.29	-0.01	-0.20	-0.32	0.22	0.11	-0.15	0.28	-0.05	0.23	0.14	0.11
Alkalinity	0.05	-0.35	1.00	-0.39	-0.03	-0.36	0.43	0.33	0.29	0.19	-0.16	-0.30	-0.03	-0.51	-0.05	0.45	0.24	0.15	-0.44	-0.25	-0.35	-0.09	0.41	-0.04	-0.10	0.05	0.07	0.34	-0.06	-0.29	-0.09
Ca	-0.43	0.21	-0.39	1.00	0.45	0.85	-0.20	-0.54	-0.16	0.42	0.72	0.68	-0.12	0.37	0.29	-0.02	0.17	-0.14	0.80	0.43	-0.16	-0.42	-0.01	-0.05	-0.04	-0.18	-0.43	0.06	0.16	0.11	0.44
Cl	-0.08	-0.20	-0.03	0.45	1.00	0.41	-0.18	-0.20	-0.19	0.45	0.31	0.45	0.03	0.19	0.24	0.19	-0.02	-0.11	0.27	0.32	0.07	-0.14	0.28	-0.33	-0.10	-0.25	-0.39	0.20	0.01	0.06	0.27
Cond.	-0.46	0.26	-0.36	0.85	0.41	1.00	-0.18	-0.65	-0.12	0.38	0.79	0.35	0.05	0.51	0.10	0.06	0.28	-0.27	0.94	0.32	-0.21	-0.39	-0.23	-0.07	0.04	-0.08	-0.35	-0.12	0.27	0.28	0.58
DIC	0.09	-0.38	0.43	-0.20	-0.18	-0.18	1.00	0.17	0.36	0.15	-0.07	-0.07	0.09	-0.21	-0.02	0.01	0.15	0.09	-0.22	-0.08	-0.16	0.08	-0.07	0.11	0.08	0.04	0.10	-0.09	-0.08	0.32	0.13
DOC	0.42	-0.21	0.33	-0.54	-0.20	-0.65	0.17	1.00	0.29	0.06	-0.77	0.02	-0.10	-0.47	0.14	0.06	-0.23	0.22	-0.76	-0.04	0.33	-0.10	-0.05	0.17	0.00	0.45	0.37	0.26	-0.09	0.05	-0.10
Fe	-0.04	-0.18	0.29	-0.16	-0.19	-0.12	0.36	0.29	1.00	0.03	-0.04	-0.11	0.28	-0.05	0.00	0.30	0.22	0.00	-0.28	0.00	-0.29	-0.09	-0.14	0.33	0.09	0.27	0.17	0.23	0.02	0.03	-0.12
K	0.06	-0.09	0.19	0.42	0.45	0.38	0.15	0.06	0.03	1.00	0.29	0.52	-0.16	-0.08	0.25	0.43	0.38	0.01	-0.09	0.33	-0.40	-0.45	0.18	-0.07	0.05	0.10	-0.04	0.09	0.04	0.23	0.46
Mg	-0.36	0.24	-0.16	0.72	0.31	0.79	-0.07	-0.77	-0.04	0.29	1.00	0.23	0.09	0.42	-0.01	0.06	0.34	-0.31	0.86	0.21	-0.35	-0.33	-0.05	-0.17	-0.27	-0.24	-0.45	-0.12	0.11	0.13	0.46
Na	0.02	0.07	-0.30	0.68	0.45	0.35	-0.07	0.02	-0.11	0.52	0.23	1.00	-0.18	0.19	0.36	-0.13	-0.18	0.17	0.34	0.47	0.17	-0.25	0.08	0.02	-0.01	0.03	-0.21	0.13	0.13	0.17	0.26
NH3 + NH4	-0.31	-0.37	-0.03	-0.12	0.03	0.05	0.09	-0.10	0.28	-0.16	0.09	-0.18	1.00	0.19	0.09	0.19	0.01	0.13	-0.01	0.15	0.07	0.07	-0.35	0.03	-0.09	0.09	-0.36	-0.05	-0.13	0.35	0.20
NO2 + NO3	-0.30	0.39	-0.51	0.37	0.19	0.51	-0.21	-0.47	-0.05	-0.08	0.42	0.19	0.19	1.00	-0.38	-0.16	-0.15	0.04	0.75	-0.09	0.03	-0.12	-0.48	-0.04	-0.11	-0.14	-0.26	-0.20	0.31	0.53	0.39
TKN	0.13	-0.41	-0.05	0.29	0.24	0.10	-0.02	0.14	0.00	0.25	-0.01	0.36	0.09	-0.38	1.00	0.08	0.31	-0.12	-0.06	0.94	0.31	-0.15	0.19	0.17	0.03	0.18	-0.26	0.13	-0.07	-0.21	0.06
pH	-0.27	-0.29	0.45	-0.02	0.19	0.06	0.01	0.06	0.30	0.43	0.06	-0.13	0.19	-0.16	0.08	1.00	0.35	0.06	-0.26	0.07	-0.43	-0.40	0.38	0.05	-0.25	-0.07	-0.09	0.34	-0.24	-0.17	0.10
TP	-0.13	-0.24	0.24	0.17	-0.02	0.28	0.15	-0.23	0.22	0.38	0.34	-0.18	0.01	-0.15	0.31	0.35	1.00	-0.16	0.07	0.36	-0.76	-0.44	0.09	-0.23	0.05	0.15	-0.21	0.09	0.11	0.00	0.33
SiO3	-0.19	-0.25	0.15	-0.14	-0.11	-0.27	0.09	0.22	0.00	0.01	-0.31	0.17	0.13	0.04	-0.12	0.06	-0.16	1.00	-0.35	-0.15	-0.01	0.01	0.00	-0.07	0.10	-0.10	-0.03	0.40	0.39	0.06	-0.12
SO4	-0.33	0.44	-0.44	0.80	0.27	0.94	-0.22	-0.76	-0.28	-0.09	0.86	0.34	-0.01	0.75	-0.06	-0.26	0.07	-0.35	1.00	0.27	-0.04	-0.15	-0.27	-0.11	-0.06	-0.18	-0.42	-0.36	0.27	0.20	0.44
TN	0.03	-0.29	-0.25	0.43	0.32	0.32	-0.08	-0.04	0.00	0.33	0.21	0.47	0.15	-0.09	0.94	0.07	0.36	-0.15	0.27	1.00	0.31	-0.27	0.07	0.16	-0.02	0.14	-0.40	0.08	0.02	-0.02	0.28
TN/TP	0.25	-0.01	-0.35	-0.16	0.07	-0.21	-0.16	0.33	-0.29	-0.40	-0.35	0.17	0.07	0.03	0.31	-0.43	-0.76	-0.01	-0.04	0.31	1.00	0.29	-0.13	0.19	-0.06	0.01	-0.03	-0.13	-0.17	0.02	-0.14
Winter Temp.	0.42	-0.20	-0.09	-0.42	-0.14	-0.39	0.08	-0.10	-0.09	-0.45	-0.33	-0.25	0.07	-0.12	-0.15	-0.40	-0.44	0.01	-0.15	-0.27	0.29	1.00	0.06	0.00	0.11	0.02	0.43	-0.43	-0.16	-0.21	-0.66
Spring Temp.	0.16	-0.32	0.41	-0.01	0.28	-0.23	-0.07	-0.05	-0.14	0.18	-0.05	0.08	-0.35	-0.48	0.19	0.38	0.09	0.00	-0.27	0.07	-0.13	0.06	1.00	-0.38	-0.24	-0.31	-0.01	0.17	-0.37	-0.69	-0.36
Winter Precip.	-0.14	0.22	-0.04	-0.05	-0.33	-0.07	0.11	0.17	0.33	-0.07	-0.17	0.02	0.03	-0.04	0.17	0.05	-0.23	-0.07	-0.11	0.16	0.19	0.00	-0.38	1.00	0.29	0.20	0.27	0.13	0.10	0.04	-0.12
Spring Precip.	0.00	0.11	-0.10	-0.04	-0.10	0.04	0.08	0.00	0.09	0.05	-0.27	-0.01	-0.09	-0.11	0.03	-0.25	0.05	0.10	-0.06	-0.02	-0.06	0.11	-0.24	0.29	1.00	0.35	0.33	0.05	0.49	0.14	0.07
Summer Temp.	0.26	-0.15	0.05	-0.18	-0.25	-0.08	0.04	0.45	0.27	0.10	-0.24	0.03	0.09	-0.14	0.18	-0.07	0.15	-0.10	-0.18	0.14	0.01	0.02	-0.31	0.20	0.35	1.00	0.28	-0.31	0.20	0.23	0.17
Fall Temp.	0.48	0.28	0.07	-0.43	-0.39	-0.35	0.10	0.37	0.17	-0.04	-0.45	-0.21	-0.36	-0.26	-0.26	-0.09	-0.21	-0.03	-0.42	-0.40	-0.03	0.43	-0.01	0.27	0.33	0.28	1.00	-0.17	-0.01	-0.15	-0.49
Summer Precip.	-0.30	-0.05	0.34	0.06	0.20	-0.12	-0.09	0.26	0.23	0.09	-0.12	0.13	-0.05	-0.20	0.13	0.34	0.09	0.40	-0.36	0.08	-0.13	-0.43	0.17	0.13	0.05	-0.31	-0.17	1.00	0.22	-0.25	-0.05
Fall Precip.	-0.22	0.23	-0.06	0.16	0.01	0.27	-0.08	-0.09	0.02	0.04	0.11	0.13	-0.13	0.31	-0.07	-0.24	0.11	0.39	0.27	0.02	-0.17	-0.16	-0.37	0.10	0.49	0.20	-0.01	0.22	1.00	0.24	0.20
Ice-off Date	0.00	0.14	-0.29	0.11	0.06	0.28	0.32	0.05	0.03	0.23	0.13	0.17	0.35	0.53	-0.21	-0.17	0.00	0.06	0.20	-0.02	0.02	-0.21	-0.69	0.04	0.14	0.23	-0.15	-0.25	0.24	1.00	0.68
Ice-on Days	-0.24	0.11	-0.09	0.44	0.27	0.58	0.13	-0.10	-0.12	0.46	0.46	0.26	0.20	0.39	0.06	0.10	0.33	-0.12	0.44	0.28	-0.14	-0.66	-0.36	-0.12	0.07	0.17	-0.49	-0.05	0.20	0.68	1.00

Appendix IX. Correlation matrix showing relationship between spring water chemistry, climate, and phytoplankton variables for Plastic Lake (1979-2011). Phytoplankton variables are presented as PCA Axis 1 and Axis 2 scores for the relative spring phytoplankton biovolume. Winter, spring, summer, and fall temperatures are mean air temperatures. The colour gradient indicates the strength of the correlation between variables, with blue representing strong positive correlation, red representing strong negative correlation, and white representing weak correlation.

	Phyto PCA Axis 1	Phyto PCA Axis 2	Alkalinity	Ca	Cl	Cond.	DIC	DOC	Fe	K	Mg	Na	NH3 + NH4	NO2 + NO3	TKN	pH	TP	SiO3	SO4	TN	TN/TP	Winter Temp.	Spring Temp.	Winter Precip.	Spring Precip.	Summer Temp.	Fall Temp.	Summer Precip.	Fall Precip.	Ice-off Date	Ice-on Days
Phyto PCA Axis 1	1.00	0.00	0.32	0.33	0.00	0.38	0.23	-0.07	-0.11	0.21	0.30	0.26	0.04	0.04	0.03	0.11	0.35	0.33	0.43	0.03	-0.28	-0.08	0.02	-0.20	0.09	0.15	-0.37	-0.20	0.11	0.08	0.21
Phyto PCA Axis 2	0.00	1.00	-0.22	-0.24	-0.12	-0.19	-0.41	-0.30	-0.07	-0.03	-0.27	-0.02	-0.21	-0.24	-0.17	-0.03	0.09	-0.33	-0.17	-0.24	-0.23	0.12	0.28	-0.13	0.02	-0.14	0.03	0.29	-0.03	-0.37	-0.26
Alkalinity	0.32	-0.22	1.00	0.44	0.14	0.45	0.25	0.09	0.40	0.27	0.40	0.16	0.23	0.00	0.04	0.48	0.51	0.44	0.34	0.01	-0.37	-0.09	0.10	0.01	-0.10	-0.20	-0.14	0.10	0.07	-0.04	0.17
Ca	0.33	-0.24	0.44	1.00	0.45	0.88	0.25	-0.22	0.25	0.52	0.91	0.35	0.34	0.44	-0.02	0.11	0.19	0.54	0.87	0.11	-0.15	-0.12	0.00	-0.06	0.25	-0.05	-0.36	-0.25	0.28	0.12	0.36
Cl	0.00	-0.12	0.14	0.45	1.00	0.43	0.13	-0.01	0.30	0.35	0.36	0.20	0.37	0.37	-0.01	0.22	0.15	0.27	0.31	0.11	-0.04	-0.26	-0.02	-0.27	-0.01	0.01	-0.30	0.15	0.29	0.28	0.47
Cond.	0.38	-0.19	0.45	0.88	0.43	1.00	0.16	-0.16	0.38	0.72	0.72	0.38	0.48	0.47	0.11	0.18	0.42	0.61	0.91	0.25	-0.21	-0.28	-0.17	0.07	0.21	0.01	-0.40	-0.07	0.28	0.27	0.56
DIC	0.23	-0.41	0.25	0.25	0.13	0.16	1.00	-0.04	-0.04	-0.01	0.17	-0.12	0.29	0.40	0.25	-0.14	-0.11	0.52	0.34	0.35	0.28	0.15	-0.23	0.13	0.03	0.21	-0.20	-0.41	0.02	0.51	0.42
DOC	-0.07	-0.30	0.09	-0.22	-0.01	-0.16	-0.04	1.00	-0.06	0.17	-0.28	0.22	-0.10	-0.40	0.24	0.11	0.11	-0.24	-0.34	0.11	0.07	-0.22	-0.02	0.04	-0.06	0.16	0.26	0.09	0.05	0.04	0.00
Fe	-0.11	-0.07	0.40	0.25	0.30	0.38	-0.04	-0.06	1.00	0.43	0.18	0.26	0.56	0.17	0.17	0.43	0.34	0.37	0.06	0.20	-0.16	-0.25	-0.11	0.44	0.09	-0.13	-0.18	0.53	0.17	-0.04	0.21
K	0.21	-0.03	0.27	0.52	0.35	0.72	-0.01	0.17	0.43	1.00	0.25	0.41	0.31	0.14	-0.01	0.28	0.46	0.47	0.45	0.03	-0.37	-0.39	-0.12	0.00	0.17	-0.15	-0.24	0.21	0.24	0.21	0.42
Mg	0.30	-0.27	0.40	0.91	0.36	0.72	0.17	-0.28	0.18	0.25	1.00	0.32	0.31	0.41	-0.04	0.13	0.11	0.49	0.82	0.08	-0.07	-0.12	-0.01	0.03	0.18	0.02	-0.36	-0.34	0.22	0.17	0.35
Na	0.26	-0.02	0.16	0.35	0.20	0.38	-0.12	0.22	0.26	0.41	0.32	1.00	0.14	-0.08	0.10	0.02	0.05	0.24	0.19	0.05	-0.02	-0.38	0.10	0.03	0.15	0.15	-0.19	-0.06	0.20	0.20	0.29
NH3 + NH4	0.04	-0.21	0.23	0.34	0.37	0.48	0.29	-0.10	0.56	0.31	0.31	0.14	1.00	0.66	0.25	0.18	0.04	0.47	0.39	0.44	0.20	-0.30	-0.48	0.18	0.06	0.18	-0.56	0.03	0.28	0.39	0.60
NO2 + NO3	0.04	-0.24	0.00	0.44	0.37	0.47	0.40	-0.40	0.17	0.14	0.41	-0.08	0.66	1.00	0.02	-0.26	-0.10	0.45	0.61	0.34	0.26	-0.07	-0.50	0.07	0.17	0.08	-0.48	-0.20	0.26	0.40	0.50
TKN	0.03	-0.17	0.04	-0.02	-0.01	0.11	0.25	0.24	0.17	-0.01	-0.04	0.10	0.25	0.02	1.00	0.15	-0.05	0.07	0.06	0.94	0.60	-0.15	-0.11	0.22	0.05	0.32	-0.04	-0.07	0.13	0.13	0.24
pH	0.11	-0.03	0.48	0.11	0.22	0.18	-0.14	0.11	0.43	0.28	0.13	0.02	0.18	-0.26	0.15	1.00	0.59	0.13	-0.02	0.04	-0.43	-0.37	0.21	0.03	-0.07	-0.13	-0.08	0.31	0.01	-0.23	0.16
TP	0.35	0.09	0.51	0.19	0.15	0.42	-0.11	0.11	0.34	0.46	0.11	0.05	0.04	-0.10	-0.05	0.59	1.00	0.19	0.16	-0.09	-0.77	-0.14	0.00	0.10	0.13	-0.07	0.08	0.31	0.10	-0.06	0.10
SiO3	0.33	-0.33	0.44	0.54	0.27	0.61	0.52	-0.24	0.37	0.47	0.49	0.24	0.47	0.45	0.07	0.13	0.19	1.00	0.47	0.20	-0.09	-0.20	-0.28	0.14	0.37	-0.04	-0.41	-0.05	0.37	0.43	0.61
SO4	0.43	-0.17	0.34	0.87	0.31	0.91	0.34	-0.34	0.06	0.45	0.82	0.19	0.39	0.61	0.06	-0.02	0.16	0.47	1.00	0.24	-0.01	-0.09	-0.18	0.00	0.11	-0.03	-0.44	-0.39	0.17	0.22	0.47
TN	0.03	-0.24	0.01	0.11	0.11	0.25	0.35	0.11	0.20	0.03	0.08	0.05	0.44	0.34	0.94	0.04	-0.09	0.20	0.24	1.00	0.66	-0.14	-0.25	0.24	0.10	0.34	-0.17	-0.13	0.21	0.22	0.37
TN/TP	-0.28	-0.23	-0.37	-0.15	-0.04	-0.21	0.28	0.07	-0.16	-0.37	-0.07	-0.02	0.20	0.26	0.60	-0.43	-0.77	-0.09	-0.01	0.66	1.00	0.03	-0.16	0.10	-0.11	0.26	-0.09	-0.28	0.00	0.19	0.15
Winter Temp.	-0.08	0.12	-0.09	-0.12	-0.26	-0.28	0.15	-0.22	-0.25	-0.39	-0.12	-0.38	-0.30	-0.07	-0.15	-0.37	-0.14	-0.20	-0.09	-0.14	0.03	1.00	0.20	0.11	0.07	0.12	0.55	-0.37	-0.15	-0.21	-0.58
Spring Temp.	0.02	0.28	0.10	0.00	-0.02	-0.17	-0.23	-0.02	-0.11	-0.12	-0.01	0.10	-0.48	-0.50	-0.11	0.21	0.00	-0.28	-0.18	-0.25	-0.16	0.20	1.00	-0.29	-0.33	-0.21	0.18	0.03	-0.21	-0.71	-0.46
Winter Precip.	-0.20	-0.13	0.01	-0.06	-0.27	0.07	0.13	0.04	0.44	0.00	0.03	0.03	0.18	0.07	0.22	0.03	0.10	0.14	0.00	0.24	0.10	0.11	-0.29	1.00	0.19	0.00	0.25	0.21	-0.21	0.11	0.04
Spring Precip.	0.09	0.02	-0.10	0.25	-0.01	0.21	0.03	-0.06	0.09	0.17	0.18	0.15	0.06	0.17	0.05	-0.07	0.13	0.37	0.11	0.10	-0.11	0.07	-0.33	0.19	1.00	0.09	0.11	-0.12	0.48	0.28	0.21
Summer Temp.	0.15	-0.14	-0.20	-0.05	0.01	0.01	0.21	0.16	-0.13	-0.15	0.02	0.15	0.18	0.08	0.32	-0.13	-0.07	-0.04	-0.03	0.34	0.26	0.12	-0.21	0.00	0.09	1.00	0.13	-0.47	0.08	0.27	0.17
Fall Temp.	-0.37	0.03	-0.14	-0.36	-0.30	-0.40	-0.20	0.26	-0.18	-0.24	-0.36	-0.19	-0.56	-0.48	-0.04	-0.08	0.08	-0.41	-0.44	-0.17	-0.09	0.55	0.18	0.25	0.11	0.13	1.00	-0.03	-0.26	-0.25	-0.58
Summer Precip.	-0.20	0.29	0.10	-0.25	0.15	-0.07	-0.41	0.09	0.53	0.21	-0.34	-0.06	0.03	-0.20	-0.07	0.31	0.31	-0.05	-0.39	-0.13	-0.28	-0.37	0.03	0.21	-0.12	-0.47	-0.03	1.00	0.00	-0.27	-0.04
Fall Precip.	0.11	-0.03	0.07	0.28	0.29	0.28	0.02	0.05	0.17	0.24	0.22	0.20	0.28	0.26	0.13	0.01	0.10	0.37	0.17	0.21	0.00	-0.15	-0.21	-0.21	0.48	0.08	-0.26	0.00	1.00	0.16	0.20
Ice-off Date	0.08	-0.37	-0.04	0.12	0.28	0.27	0.51	0.04	-0.04	0.21	0.17	0.20	0.39	0.40	0.13	-0.23	-0.06	0.43	0.22	0.22	0.19	-0.21	-0.71	0.11	0.28	0.27	-0.25	-0.27	0.16	1.00	0.68
Ice-on Days	0.21	-0.26	0.17	0.36	0.47	0.56	0.42	0.00	0.21	0.42	0.35	0.29	0.60	0.50	0.24	0.16	0.10	0.61	0.47	0.37	0.15	-0.58	-0.46	0.04	0.21	0.17	-0.58	-0.04	0.20	0.68	1.00

Appendix IX. Correlation matrix showing relationship between spring water chemistry, climate, and phytoplankton variables for Dickie Lake (1976-2011). Phytoplankton variables are presented as PCA Axis 1 and Axis 2 scores for the relative spring phytoplankton biovolume. Winter, spring, summer, and fall temperatures are mean air temperatures. The colour gradient indicates the strength of the correlation between variables, with blue representing strong positive correlation, red representing strong negative correlation, and white representing weak correlation.

	Phyto PCA Axis 1	Phyto PCA Axis 2	Alkalinity	Ca	Cl	Cond.	DIC	DOC	Fe	K	Mg	Na	NH3 + NH4	NO2 + NO3	TKN	pH	TP	SiO3	SO4	TN	TN/TP	Winter Temp.	Spring Temp.	Winter Precip.	Spring Precip.	Summer Temp.	Fall Temp.	Summer Precip.	Fall Precip.	Ice-off Date	Ice-on Days
Phyto PCA Axis 1	1.00	0.00	-0.12	-0.17	-0.19	-0.34	-0.34	-0.36	-0.22	-0.14	-0.11	-0.18	-0.45	-0.47	-0.11	0.00	0.57	-0.30	0.08	-0.38	-0.54	0.31	0.30	0.06	0.09	-0.04	0.15	-0.08	0.14	-0.21	-0.13
Phyto PCA Axis 2	0.00	1.00	-0.57	-0.40	-0.62	-0.44	-0.39	-0.30	-0.30	0.00	-0.15	-0.66	-0.18	-0.08	-0.19	-0.27	0.12	-0.28	0.45	-0.18	-0.13	-0.14	-0.04	0.07	0.29	0.28	-0.16	-0.20	0.27	-0.17	0.09
Alkalinity	-0.12	-0.57	1.00	0.25	0.56	0.32	0.55	0.33	0.22	0.09	-0.05	0.61	0.04	0.05	0.17	0.57	-0.24	0.24	-0.71	0.13	0.20	0.14	0.36	-0.33	-0.26	-0.07	0.04	0.26	-0.36	-0.10	-0.19
Ca	-0.17	-0.40	0.25	1.00	0.63	0.73	0.21	0.37	-0.16	-0.01	0.55	0.71	0.30	-0.01	0.04	0.17	-0.27	0.33	-0.07	0.02	0.21	0.30	0.22	-0.07	-0.09	0.21	0.46	-0.10	-0.09	-0.10	-0.36
Cl	-0.19	-0.62	0.56	0.63	1.00	0.86	0.15	0.49	0.09	-0.13	0.21	0.96	0.15	0.08	0.19	0.41	-0.26	0.27	-0.63	0.18	0.20	0.29	0.06	-0.23	-0.31	0.12	0.37	0.16	-0.22	-0.12	-0.48
Cond.	-0.34	-0.44	0.32	0.73	0.86	1.00	0.15	0.37	-0.18	-0.21	0.55	0.83	0.44	0.22	0.10	0.13	-0.43	0.28	-0.20	0.21	0.35	0.20	-0.08	-0.17	-0.32	0.24	0.36	-0.11	-0.22	0.06	-0.25
DIC	-0.34	-0.39	0.55	0.21	0.15	0.15	1.00	0.14	0.17	0.15	0.10	0.28	0.37	0.46	0.29	0.05	-0.47	0.28	-0.17	0.48	0.61	-0.03	0.10	-0.20	-0.16	0.16	-0.16	0.12	-0.01	0.23	0.19
DOC	-0.36	-0.30	0.33	0.37	0.49	0.37	0.14	1.00	0.10	0.25	-0.07	0.46	-0.02	0.00	-0.19	0.42	-0.20	0.39	-0.56	-0.12	0.00	-0.41	0.14	-0.34	-0.25	-0.04	0.16	0.59	-0.06	-0.12	-0.14
Fe	-0.22	-0.30	0.22	-0.16	0.09	-0.18	0.17	0.10	1.00	0.36	-0.37	0.11	-0.20	0.25	0.29	0.34	0.20	0.20	-0.47	0.35	-0.04	-0.15	0.04	-0.09	-0.15	-0.36	-0.15	0.37	-0.27	-0.13	-0.13
K	-0.14	0.00	0.09	-0.01	-0.13	-0.21	0.15	0.25	0.36	1.00	-0.20	-0.18	-0.05	0.13	0.15	0.19	0.08	0.14	-0.22	0.19	0.09	-0.45	0.21	-0.17	0.12	-0.20	-0.13	0.18	-0.05	-0.07	0.15
Mg	-0.11	-0.15	-0.05	0.55	0.21	0.55	0.10	-0.07	-0.37	-0.20	1.00	0.25	0.55	0.29	-0.01	-0.33	-0.18	-0.16	0.50	0.18	0.29	-0.01	-0.10	0.01	-0.39	0.20	0.01	-0.31	-0.05	0.11	0.13
Na	-0.18	-0.66	0.61	0.71	0.96	0.83	0.28	0.46	0.11	-0.18	0.25	1.00	0.18	0.05	0.18	0.41	-0.28	0.35	-0.63	0.15	0.19	0.37	0.08	-0.15	-0.29	0.12	0.40	0.16	-0.20	-0.10	-0.49
NH3 + NH4	-0.45	-0.18	0.04	0.30	0.15	0.44	0.37	-0.02	-0.20	-0.05	0.55	0.18	1.00	0.41	0.09	-0.32	-0.50	0.15	0.22	0.33	0.52	-0.23	-0.35	-0.15	-0.13	0.25	-0.12	-0.21	0.18	0.51	0.38
NO2 + NO3	-0.47	-0.08	0.05	-0.01	0.08	0.22	0.46	0.00	0.25	0.13	0.29	0.05	0.41	1.00	0.15	-0.23	-0.41	0.04	0.08	0.74	0.64	-0.31	-0.22	-0.18	-0.34	0.01	-0.39	-0.14	-0.13	0.28	0.30
TKN	-0.11	-0.19	0.17	0.04	0.19	0.10	0.29	-0.19	0.29	0.15	-0.01	0.18	0.09	0.15	1.00	-0.06	-0.10	0.04	-0.02	0.77	0.44	0.16	0.32	-0.14	-0.17	0.06	-0.12	0.06	0.02	-0.24	-0.19
pH	0.00	-0.27	0.57	0.17	0.41	0.13	0.05	0.42	0.34	0.19	-0.33	0.41	-0.32	-0.23	-0.06	1.00	0.10	0.12	-0.69	-0.19	-0.24	0.12	0.37	-0.10	-0.22	-0.03	0.31	0.23	-0.40	-0.39	-0.32
TP	0.57	0.12	-0.24	-0.27	-0.26	-0.43	-0.47	-0.20	0.20	0.08	-0.18	-0.28	-0.50	-0.41	-0.10	0.10	1.00	-0.13	-0.10	-0.33	-0.85	0.05	0.09	0.19	0.08	-0.17	0.14	0.22	0.03	-0.40	-0.16
SiO3	-0.30	-0.28	0.24	0.33	0.27	0.28	0.28	0.39	0.20	0.14	-0.16	0.35	0.15	0.04	0.04	0.12	-0.13	1.00	-0.53	0.05	0.06	-0.10	-0.10	-0.10	0.12	-0.02	0.13	0.23	0.18	0.31	0.05
SO4	0.08	0.45	-0.71	-0.07	-0.63	-0.20	-0.17	-0.56	-0.47	-0.22	0.50	-0.63	0.22	0.08	-0.02	-0.69	-0.10	-0.53	1.00	0.04	0.22	0.07	-0.21	0.29	0.18	0.17	-0.16	-0.68	0.19	0.27	0.39
TN	-0.38	-0.18	0.13	0.02	0.18	0.21	0.48	-0.12	0.35	0.19	0.18	0.15	0.33	0.74	0.77	-0.19	-0.33	0.05	0.04	1.00	0.71	-0.09	0.07	-0.21	-0.33	0.05	-0.33	-0.05	-0.07	0.02	0.07
TN/TP	-0.54	-0.13	0.20	0.21	0.20	0.35	0.61	0.00	-0.04	0.09	0.29	0.19	0.52	0.64	0.44	-0.24	-0.85	0.06	0.22	0.71	1.00	-0.03	-0.02	-0.22	-0.11	0.13	-0.27	-0.25	0.01	0.28	0.18
Winter Temp.	0.31	-0.14	0.14	0.30	0.29	0.20	-0.03	-0.41	-0.15	-0.45	-0.01	0.37	-0.23	-0.31	0.16	0.12	0.05	-0.10	0.07	-0.09	-0.03	1.00	0.15	0.24	0.15	0.08	0.52	-0.30	-0.06	-0.24	-0.66
Spring Temp.	0.30	-0.04	0.36	0.22	0.06	-0.08	0.10	0.14	0.04	0.21	-0.10	0.08	-0.35	-0.22	0.32	0.37	0.09	-0.10	-0.21	0.07	-0.02	0.15	1.00	-0.27	-0.26	-0.18	0.02	0.19	-0.24	-0.66	-0.36
Winter Precip.	0.06	0.07	-0.33	-0.07	-0.23	-0.17	-0.20	-0.34	-0.09	-0.17	0.01	-0.15	-0.15	-0.18	-0.14	-0.10	0.19	-0.10	0.29	-0.21	-0.22	0.24	-0.27	1.00	0.17	0.12	0.26	-0.25	-0.12	0.05	-0.08
Spring Precip.	0.09	0.29	-0.26	-0.09	-0.31	-0.32	-0.16	-0.25	-0.15	0.12	-0.39	-0.29	-0.13	-0.34	-0.17	-0.22	0.08	0.12	0.18	-0.33	-0.11	0.15	-0.26	0.17	1.00	0.14	0.04	-0.21	0.36	0.24	0.11
Summer Temp.	-0.04	0.28	-0.07	0.21	0.12	0.24	0.16	-0.04	-0.36	-0.20	0.20	0.12	0.25	0.01	0.06	-0.03	-0.17	-0.02	0.17	0.05	0.13	0.08	-0.18	0.12	0.14	1.00	0.25	-0.30	0.12	0.13	0.08
Fall Temp.	0.15	-0.16	0.04	0.46	0.37	0.36	-0.16	0.16	-0.15	-0.13	0.01	0.40	-0.12	-0.39	-0.12	0.31	0.14	0.13	-0.16	-0.33	-0.27	0.52	0.02	0.26	0.04	0.25	1.00	-0.17	-0.23	-0.20	-0.52
Summer Precip.	-0.08	-0.20	0.26	-0.10	0.16	-0.11	0.12	0.59	0.37	0.18	-0.31	0.16	-0.21	-0.14	0.06	0.23	0.22	0.23	-0.68	-0.05	-0.25	-0.30	0.19	-0.25	-0.21	-0.30	-0.17	1.00	0.03	-0.27	-0.15
Fall Precip.	0.14	0.27	-0.36	-0.09	-0.22	-0.22	-0.01	-0.06	-0.27	-0.05	-0.05	-0.20	0.18	-0.13	0.02	-0.40	0.03	0.18	0.19	-0.07	0.01	-0.06	-0.24	-0.12	0.36	0.12	-0.23	0.03	1.00	0.20	0.06
Ice-off Date	-0.21	-0.17	-0.10	-0.10	-0.12	0.06	0.23	-0.12	-0.13	-0.07	0.11	-0.10	0.51	0.28	-0.24	-0.39	-0.40	0.31	0.27	0.02	0.28	-0.24	-0.66	0.05	0.24	0.13	-0.20	-0.27	0.20	1.00	0.66
Ice-on Days	-0.13	0.09	-0.19	-0.36	-0.48	-0.25	0.19	-0.14	-0.13	0.15	0.13	-0.49	0.38	0.30	-0.19	-0.32	-0.16	0.05	0.39	0.07	0.18	-0.66	-0.36	-0.08	0.11	0.08	-0.52	-0.15	0.06	0.66	1.00

Appendix IX. Correlation matrix showing relationship between spring water chemistry, climate, and phytoplankton variables for Harp Lake (1976-2011). Phytoplankton variables are presented as PCA Axis 1 and Axis 2 scores for the relative spring phytoplankton biovolume. Winter, spring, summer, and fall temperatures are mean air temperatures. The colour gradient indicates the strength of the correlation between variables, with blue representing strong positive correlation, red representing strong negative correlation, and white representing weak correlation.

	Phyto PCA Axis 1	Phyto PCA Axis 2	Alkalinity	Ca	Cl	Cond.	DIC	DOC	Fe	K	Mg	Na	NH3 + NH4	NO2 + NO3	TKN	pH
Phyto PCA Axis 1	1.00	0.00	-0.10	-0.15	0.08	-0.18	0.16	-0.29	-0.07	0.10	0.05	0.00	-0.09	0.12	-0.24	-0.02
Phyto PCA Axis 2	0.00	1.00	-0.01	-0.30	0.23	0.05	0.05	0.09	-0.29	-0.32	-0.21	0.24	-0.26	0.52	0.15	-0.13
Alkalinity	-0.10	-0.01	1.00	-0.17	0.62	0.25	0.03	0.37	-0.60	-0.44	-0.05	0.62	0.47	-0.52	0.07	0.40
Ca	-0.15	-0.30	-0.17	1.00	-0.70	0.08	-0.46	0.05	0.67	0.46	0.47	-0.66	-0.10	-0.21	0.02	-0.11
Cl	0.08	0.23	0.62	-0.70	1.00	0.23	0.31	0.19	-0.89	-0.66	-0.56	0.98	0.36	0.06	0.02	0.19
Cond.	-0.18	0.05	0.25	0.08	0.23	1.00	-0.11	0.04	-0.09	0.05	0.03	0.29	0.25	0.12	0.33	0.14
DIC	0.16	0.05	0.03	-0.46	0.31	-0.11	1.00	-0.32	-0.38	-0.29	0.05	0.20	0.03	0.00	-0.32	-0.03
DOC	-0.29	0.09	0.37	0.05	0.19	0.04	-0.32	1.00	-0.16	0.04	-0.22	0.27	0.08	-0.50	0.40	0.04
Fe	-0.07	-0.29	-0.60	0.67	-0.89	-0.09	-0.38	-0.16	1.00	0.67	0.51	-0.87	-0.24	-0.05	-0.13	-0.25
K	0.10	-0.32	-0.44	0.46	-0.66	0.05	-0.29	0.04	0.67	1.00	0.57	-0.65	-0.10	-0.02	0.12	-0.03
Mg	0.05	-0.21	-0.05	0.47	-0.56	0.03	0.05	-0.22	0.51	0.57	1.00	-0.52	0.00	-0.13	-0.02	-0.23
Na	0.00	0.24	0.62	-0.66	0.98	0.29	0.20	0.27	-0.87	-0.65	-0.52	1.00	0.40	0.05	0.08	0.15
NH3 + NH4	-0.09	-0.26	0.47	-0.10	0.36	0.25	0.03	0.08	-0.24	-0.10	0.00	0.40	1.00	-0.10	-0.29	0.15
NO2 + NO3	0.12	0.52	-0.52	-0.21	0.06	0.12	0.00	-0.50	-0.05	-0.02	-0.13	0.05	-0.10	1.00	0.10	-0.08
TKN	-0.24	0.15	0.07	0.02	0.02	0.33	-0.32	0.40	-0.13	0.12	-0.02	0.08	-0.29	0.10	1.00	0.24
pH	-0.02	-0.13	0.40	-0.11	0.19	0.14	-0.03	0.04	-0.25	-0.03	-0.23	0.15	0.15	-0.08	0.24	1.00
TP	0.05	0.15	-0.58	0.56	-0.64	-0.06	-0.35	-0.50	0.54	0.27	0.18	-0.61	-0.39	0.42	0.15	0.05
SiO3	-0.02	0.30	0.31	-0.55	0.70	-0.18	-0.05	0.50	-0.68	-0.49	-0.74	0.68	0.00	0.03	0.11	0.16
SO4	0.20	0.00	-0.60	0.34	-0.82	0.08	0.04	-0.53	0.79	0.74	0.61	-0.78	-0.43	0.43	0.07	-0.10
TN	-0.14	0.38	-0.22	-0.09	0.04	0.33	-0.27	0.12	-0.13	0.09	-0.08	0.09	-0.29	0.58	0.87	0.16
TN/TP	-0.18	0.16	0.45	-0.74	0.75	0.35	0.28	0.35	-0.70	-0.36	-0.31	0.73	0.23	0.02	0.42	0.09
Winter Temp.	0.49	0.18	0.07	-0.46	0.45	-0.08	0.19	-0.46	-0.49	-0.55	-0.40	0.40	0.01	0.17	-0.16	0.05
Spring Temp.	0.47	-0.22	0.31	0.01	-0.01	-0.37	-0.06	0.08	-0.15	0.03	0.01	-0.04	-0.07	-0.37	0.00	0.23
Winter Precip.	-0.17	0.19	-0.16	-0.21	0.13	0.01	0.05	0.21	0.03	-0.06	-0.11	0.14	0.00	0.20	0.22	0.26
Spring Precip.	0.06	0.35	-0.41	0.14	-0.29	-0.32	-0.11	-0.03	0.38	-0.09	-0.17	-0.32	-0.49	0.08	-0.13	-0.24
Summer Temp.	-0.15	0.15	-0.12	0.04	-0.12	-0.18	0.11	0.19	0.12	-0.10	0.06	-0.09	0.06	-0.08	-0.01	-0.10
Fall Temp.	-0.13	0.09	0.08	-0.02	0.06	-0.19	-0.14	0.11	0.00	-0.37	-0.31	0.05	-0.04	-0.31	-0.21	0.07
Summer Precip.	-0.32	-0.03	-0.03	0.02	-0.02	-0.29	-0.22	0.31	0.06	0.25	-0.07	-0.02	-0.13	0.02	0.22	0.00
Fall Precip.	0.00	0.19	-0.33	0.06	-0.18	-0.02	-0.03	-0.12	0.31	0.16	0.01	-0.15	-0.29	0.31	-0.01	-0.47
Ice-off Date	-0.49	0.15	-0.07	0.26	-0.07	0.35	0.01	0.04	0.11	-0.06	0.07	-0.03	0.20	0.30	0.02	-0.29
Ice-on Days	-0.41	-0.07	-0.14	0.41	-0.48	0.27	-0.10	0.16	0.45	0.50	0.42	-0.44	0.15	0.03	0.12	-0.06

	TP	SiO3	SO4	TN	TN/TP	Winter Temp.	Spring Temp.	Winter Precip.	Spring Precip.	Summer Temp.	Fall Temp.	Summer Precip.	Fall Precip.	Ice-off Date	Ice-on Days
Phyto PCA Axis 1	0.05	-0.02	0.20	-0.14	-0.18	0.49	0.47	-0.17	0.06	-0.15	-0.13	-0.32	0.00	-0.49	-0.41
Phyto PCA Axis 2	0.15	0.30	0.00	0.38	0.16	0.18	-0.22	0.19	0.35	0.15	0.09	-0.03	0.19	0.15	-0.07
Alkalinity	-0.58	0.31	-0.60	-0.22	0.45	0.07	0.31	-0.16	-0.41	-0.12	0.08	-0.03	-0.33	-0.07	-0.14
Ca	0.56	-0.55	0.34	-0.09	-0.74	-0.46	0.01	-0.21	0.14	0.04	-0.02	0.02	0.06	0.26	0.41
Cl	-0.64	0.70	-0.82	0.04	0.75	0.45	-0.01	0.13	-0.29	-0.12	0.06	-0.02	-0.18	-0.07	-0.48
Cond.	-0.06	-0.18	0.08	0.33	0.35	-0.08	-0.37	0.01	-0.32	-0.18	-0.19	-0.29	-0.02	0.35	0.27
DIC	-0.35	-0.05	0.04	-0.27	0.28	0.19	-0.06	0.05	-0.11	0.11	-0.14	-0.22	-0.03	0.01	-0.10
DOC	-0.50	0.50	-0.53	0.12	0.35	-0.46	0.08	0.21	-0.03	0.19	0.11	0.31	-0.12	0.04	0.16
Fe	0.54	-0.68	0.79	-0.13	-0.70	-0.49	-0.15	0.03	0.38	0.12	0.00	0.06	0.31	0.11	0.45
K	0.27	-0.49	0.74	0.09	-0.36	-0.55	0.03	-0.06	-0.09	-0.10	-0.37	0.25	0.16	-0.06	0.50
Mg	0.18	-0.74	0.61	-0.08	-0.31	-0.40	0.01	-0.11	-0.17	0.06	-0.31	-0.07	0.01	0.07	0.42
Na	-0.61	0.68	-0.78	0.09	0.73	0.40	-0.04	0.14	-0.32	-0.09	0.05	-0.02	-0.15	-0.03	-0.44
NH3 + NH4	-0.39	0.00	-0.43	-0.29	0.23	0.01	-0.07	0.00	-0.49	0.06	-0.04	-0.13	-0.29	0.20	0.15
NO2 + NO3	0.42	0.03	0.43	0.58	0.02	0.17	-0.37	0.20	0.08	-0.08	-0.31	0.02	0.31	0.30	0.03
TKN	0.15	0.11	0.07	0.87	0.42	-0.16	0.00	0.22	-0.13	-0.01	-0.21	0.22	-0.01	0.02	0.12
pH	0.05	0.16	-0.10	0.16	0.09	0.05	0.23	0.26	-0.24	-0.10	0.07	0.00	-0.47	-0.29	-0.06
TP	1.00	-0.36	0.77	0.34	-0.77	-0.10	-0.01	-0.15	0.24	-0.02	-0.07	-0.04	0.28	-0.06	0.10
SiO3	-0.36	1.00	-0.81	0.10	0.43	0.30	0.08	0.14	0.02	-0.04	0.20	0.36	-0.02	-0.17	-0.53
SO4	0.77	-0.81	1.00	0.27	-0.57	-0.18	-0.13	-0.05	0.11	-0.03	-0.22	-0.23	0.25	-0.07	0.35
TN	0.34	0.10	0.27	1.00	0.33	-0.05	-0.19	0.28	-0.07	-0.05	-0.33	0.19	0.14	0.17	0.12
TN/TP	-0.77	0.43	-0.57	0.33	1.00	0.17	-0.20	0.33	-0.32	-0.01	-0.08	0.07	-0.24	0.19	-0.11
Winter Temp.	-0.10	0.30	-0.18	-0.05	0.17	1.00	0.18	0.04	0.12	-0.06	0.32	-0.38	-0.07	-0.31	-0.71
Spring Temp.	-0.01	0.08	-0.13	-0.19	-0.20	0.18	1.00	-0.37	-0.24	-0.18	-0.05	-0.02	-0.30	-0.69	-0.33
Winter Precip.	-0.15	0.14	-0.05	0.28	0.33	0.04	-0.37	1.00	0.16	0.17	0.21	0.09	-0.18	0.17	0.02
Spring Precip.	0.24	0.02	0.11	-0.07	-0.32	0.12	-0.24	0.16	1.00	0.18	0.25	0.08	0.39	0.15	0.02
Summer Temp.	-0.02	-0.04	-0.03	-0.05	-0.01	-0.06	-0.18	0.17	0.18	1.00	0.26	-0.08	0.18	0.09	0.10
Fall Temp.	-0.07	0.20	-0.22	-0.33	-0.08	0.32	-0.05	0.21	0.25	0.26	1.00	-0.28	-0.15	-0.12	-0.37
Summer Precip.	-0.04	0.36	-0.23	0.19	0.07	-0.38	-0.02	0.09	0.08	-0.08	-0.28	1.00	0.22	-0.06	0.04
Fall Precip.	0.28	-0.02	0.25	0.14	-0.24	-0.07	-0.30	-0.18	0.39	0.18	-0.15	0.22	1.00	0.19	0.08
Ice-off Date	-0.06	-0.17	-0.07	0.17	0.19	-0.31	-0.69	0.17	0.15	0.09	-0.12	-0.06	0.19	1.00	0.63
Ice-on Days	0.10	-0.53	0.35	0.12	-0.11	-0.71	-0.33	0.02	0.02	0.10	-0.37	0.04	0.08	0.63	1.00