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Impacts of Road Dust on Small Subarctic Lake Systems

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ABSTRACT. Arctic regions have been experiencing increasing pressures from multiple environmental stressors, most notably rapid climate change and human development. Previous research has demonstrated the impacts of calcareous dust from gravel roads on surrounding vegetation and permafrost, whereas aquatic systems have remained largely unstudied. Here, we explore whether 1) the chronic generation of dust from the 740 km long Dempster Highway has affected water chemistry and diatom assemblages in lakes in the Peel Plateau region of the Northwest Territories, and 2) accelerated regional warming has affected these lakes. A suite of 27 water chemistry variables was assessed from 28 lakes along a 40 m–26 km distance from the highway. Paleolimnological analyses of biological proxies (diatoms, visible reflectance spectroscopy-derived chlorophyll-*a*, and an index of chrysophyte scales to diatoms [S:D]) were undertaken on dated sediment cores from two lakes near the highway and one lake situated far from the highway, outside the expected range of dust transport. Conductivity and calcium exhibited a wide range of measurements across our 28 sites; lakes within 1 km of the highway generally exhibited higher ions and related variables than more distant lakes. Analyses of diatom assemblages indicated that the two shallower sites near the highway underwent modest compositional changes over the past approximately 100 years, whereas changes recorded at the farther site were more pronounced. The diatom records, supported by chlorophyll-*a* and S:D indices, indicated that changes in both the near and far lakes were consistent with warming, with little discernable impact from road dust. Whilst chemical changes associated with the half-century old highway corridor appear clear, they are not yet of sufficient magnitude to elicit a directional biological response in algal assemblages.

Key words: road dust; water chemistry; regional warming; paleolimnology; diatom assemblages

RÉSUMÉ. Les régions de l'Arctique subissent de plus en plus de pressions en provenance d'agresseurs environnementaux, plus particulièrement le changement climatique rapide et le développement humain. Des recherches ont permis de démontrer les incidences de la poussière calcaire émanant des routes en gravier sur la végétation et le pergélisol environnants, mais les systèmes aquatiques ont fait l'objet de très peu d'études. Ici, nous explorons : 1) si la production chronique de poussière par la route de Dempster d'une longueur de 740 km a une influence sur la chimie de l'eau et les assemblages de diatomées dans les lacs de la région du plateau Peel, dans les Territoires du Nord-Ouest; et 2) si le réchauffement régional accéléré a un effet sur ces lacs. Un ensemble de 27 variables de chimie des eaux a été évalué à partir de 28 lacs sur une distance variant entre 40 m et 26 km de la route. Des analyses paléolimnologiques de substituts biologiques (diatomées, chlorophylle-a dérivée de la spectroscopie en réflectance visible (chl-a) et indice d'échelles de chrysophytes à diatomées [S:D]) ont été effectuées sur des carottes de sédiments datées, prélevées dans deux lacs situés près de la route et dans un lac situé loin de la route, à l'extérieur de l'étendue possible du transport de la poussière. Dans les 28 sites, les taux de conductivité et de calcium enregistrés se sont répartis sur une vaste gamme de mesures. De manière générale, les lacs se trouvant à moins d'un kilomètre de distance de la route avaient une plus forte teneur en ions et en variables connexes que les lacs plus éloignés. Les analyses d'assemblages de diatomées ont permis de constater que les deux sites moins profonds à proximité de la route avaient connu des changements de composition modestes au cours des cent dernières années environ, tandis que les changements enregistrés au site plus éloigné étaient plus prononcés. Les enregistrements de diatomées, taux de chl-*a* et indices S:D à l'appui, ont permis de constater que les changements caractérisant tant les lacs situés à proximité qu'à distance coïncidaient avec le réchauffement, et que l'incidence de la poussière de route était à peine perceptible. Bien que les changements chimiques liés au corridor routier d'un

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demi-siècle semblent clairs, leur ampleur n'est toujours pas suffisante pour obtenir une réponse biologique directionnelle dans les assemblages d'algues.

Mots clés : poussière de route; chimie de l'eau; réchauffement régional; paléolimnologie; assemblages de diatomées

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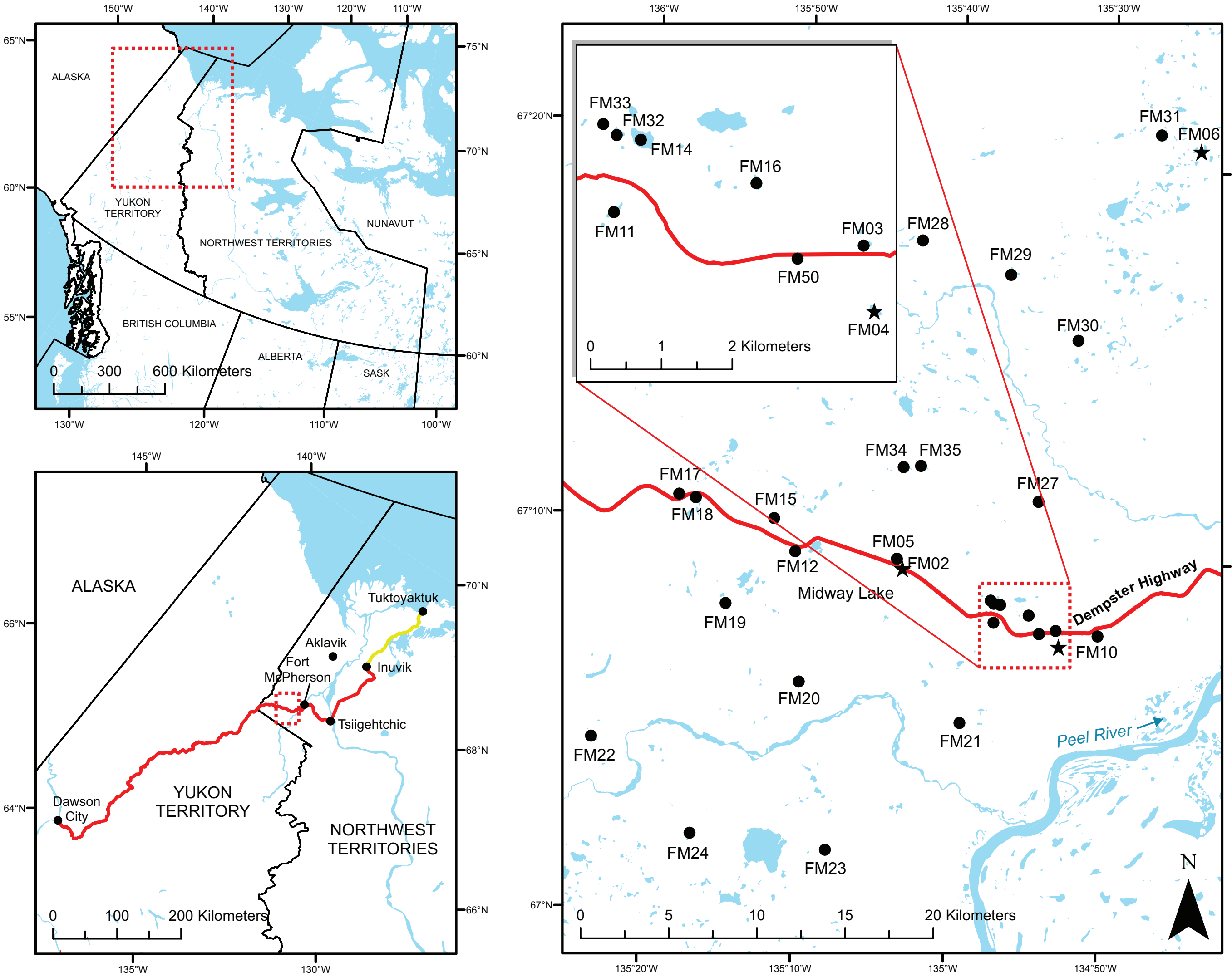
INTRODUCTION

Over the past century, Arctic ecosystems have been facing increased stress from a variety of anthropogenic disturbances during a period of rapid climate change. High-latitude lakes and ponds are important in supporting diverse aquatic communities (Vincent et al., 2013) and are highly sensitive to climate warming (Smol, 2016). Aquatic systems face numerous consequences as a result of warming and longer ice-free periods, including stronger and longer periods of thermal stratification (Schindler, 2001; Oswald and Rouse, 2004; Rühland et al., 2008, 2015), increases in ion concentrations associated with thaw-driven watershed modifications (Kokelj et al., 2005; Thienpont et al., 2013), increases in primary production (Michelutti et al., 2005), and the expansion of new aquatic habitats for biological communities (Smol et al., 2005; Smol and Douglas, 2007a, b).

In addition to rapid climate warming, high-latitude regions are also increasingly under pressure due to infrastructure expansion, such as the construction of roads and settlements (Raynolds et al., 2014). One of the most important high-latitude roads in Canada is the Dempster Highway, which connects Dawson City, Yukon to Inuvik, Northwest Territories (NT) (Fig. 1). The 740 km long gravel highway was originally conceived as a project for oil and gas exploration in the Mackenzie River Delta region, with construction occurring in two phases between 1959–61 and 1968–79 (MacLeod, 1979). A third and final phase involved the extension of the Dempster Highway to Tuktoyaktuk on the coast of the Beaufort Sea and was completed in November 2017, providing a critical link for freight and tourism traffic. Gravel road construction is commonly used in permafrost regions because it is more economical to maintain where permafrost thaw results in subsidence of the roadbed. However, the construction of gravel roads in high-latitude regions may modify the composition and structure of roadside vegetation and contribute to permafrost degradation by altering snow accumulation patterns through the release of road dust (Aurbach et al., 1997; Gill et al., 2014; Raynolds et al., 2014). For example, the environmental impacts of road dust deposition along the Dalton Highway (Alaska, USA) over a period of 35 years included elevated soil pH, increased active layer thickness, and modification of the density and height of roadside vegetation (Walker and Everett, 1987; Walker and Walker, 1991; Myers-Smith et al., 2006). More recently, Gill et al. (2014) noted similar changes occurring in the vegetation and permafrost active layer along the Dempster Highway as a result of the deposition of calcareous road dust.

The majority of studies published to date have focused on the impacts of road dust on terrestrial ecosystems, while little is known about how aquatic systems will respond. However, the release of road dust from the Dempster Highway is a chronic disturbance (Gill et al., 2014) and, together with recent warming trends, may play a combined role in modifying aquatic ecosystems. Given that lakes and ponds are key features of the Arctic landscape, an assessment of the cumulative impacts on these aquatic ecosystems informs planning, management, and regulation of future infrastructure development. In this study, we explored any putative chemical effects of calcareous-rich road dust on a suite of 28 strategically selected lakes along a range of distances (0.04–29.87 km) to the Dempster Highway in glaciated terrain of the Peel Plateau region, NT (Fig. 1). Based on the spatial distribution of our study lakes, we assessed the distance at which chemical effects could be clearly registered. In addition to the water chemistry survey, we used paleolimnological methods to determine whether the algal communities of lakes and ponds in the region have been affected by dust deposition and climate warming effects. As long-term monitoring data do not exist in this region, we selected three lakes for detailed paleolimnological analyses using diatoms (class Bacillariophyceae), spectrally inferred chlorophyll-*a* (chl-*a*) (a proxy for aquatic primary production; reviewed in Michelutti and Smol, 2016), and an index of the abundance of chrysophyte (class Chrysophyceae) scales relative to diatom valves (S:D index) to examine possible biological responses to the construction and use of the Dempster Highway and to current climate warming. We compared the nature, timing, and magnitude of proxy changes between two lakes located close to the highway (i.e., "near" sites) and one lake situated outside the expected range of road dust transport (i.e., "far" site), as referenced from Walker and Everett (1987). We explored whether calcium-rich dust deposition would result in elevated concentrations of major ions and related variables in lakes proximal to the highway and determined whether diatom assemblage composition and other paleolimnological proxies exhibited any discernible responses to calcium-rich road dust in our near-highway sites.

Diatoms are commonly used in paleolimnological studies because their siliceous cell walls are typically well preserved in sediments, their distinct cell ornamentation allows for taxonomic identification, and they respond sensitively to environmental conditions including nutrients (Hall and Smol, 2010), pH (Battarbee et al., 2010), conductivity (and related variables) (Pienitz et al., 1997a; Fallu et al., 2000; Rühland et al., 2003), and warming conditions (Smol et



Projection: Canada Lambert Conformal Conic

Map created by J.Viscek, Brock University, 2019.

FIG. 1. Map indicating the location of the 28 Fort McPherson (FM) study lakes relative to the Dempster Highway within the Peel Plateau region, Northwest Territories, Canada. Stars (FM02, FM04, FM06) denote lakes that were selected for detailed paleolimnological analysis.

al., 2005; Rühland et al., 2008, 2015). Scaled chrysophytes have also been used as a proxy for various environmental conditions, including changes in pH (Smol, 1995; Paterson et al., 2001) and climate warming (Smol, 1985, 1995; Paterson et al., 2004; Ginn et al., 2010), and were used here to support environmental inferences based on observed changes in diatom assemblage composition over time. In each sediment core, trends in spectrally inferred chl-*a* was used as a proxy for whole lake primary production. Increased chl-*a* concentrations may reflect regional warming and a longer ice-free period as well as an extended growing season (Michelutti et al., 2010). A longer and stronger stratified season can increase light availability, favouring the increased growth of algal populations and hence primary production (White et al., 2012; Nelligan et al., 2016; Paterson et al., 2017). Collectively, these biological proxies were used to determine the effects of road dust and recent warming on algal communities in lakes of the Peel Plateau.

SITE DESCRIPTION

The Peel Plateau in northwestern NT, Canada, is situated on the eastern slopes of the Richardson and Mackenzie Mountains (Fig. 1). The bedrock geology of the Peel Plateau region consists mainly of Mesozoic-aged mudstone and sandstone (Norris, 1997; Hadlari, 2006) overlain by ice-rich moraine, glaciofluvial, and glaciolacustrine materials deposited during the maximum westward extent of the Laurentide Ice Sheet (Kokelj et al., 2017). In the Peel Plateau, these calcium-rich glacial deposits have been the main source of material used in the construction and maintenance of the Dempster Highway (MacLeod, 1979). The region is underlain by continuous permafrost, hosting ice-rich sediments that are enriched in soluble ions such as Ca^{2+} and Mg^{2+} relative to the active layer (Malone et al., 2013; Kokelj et al., 2017; Zolkos et al., 2018). The soluble ion-rich permafrost material is quarried from borrow pits along the highway, stockpiled and thawed for construction

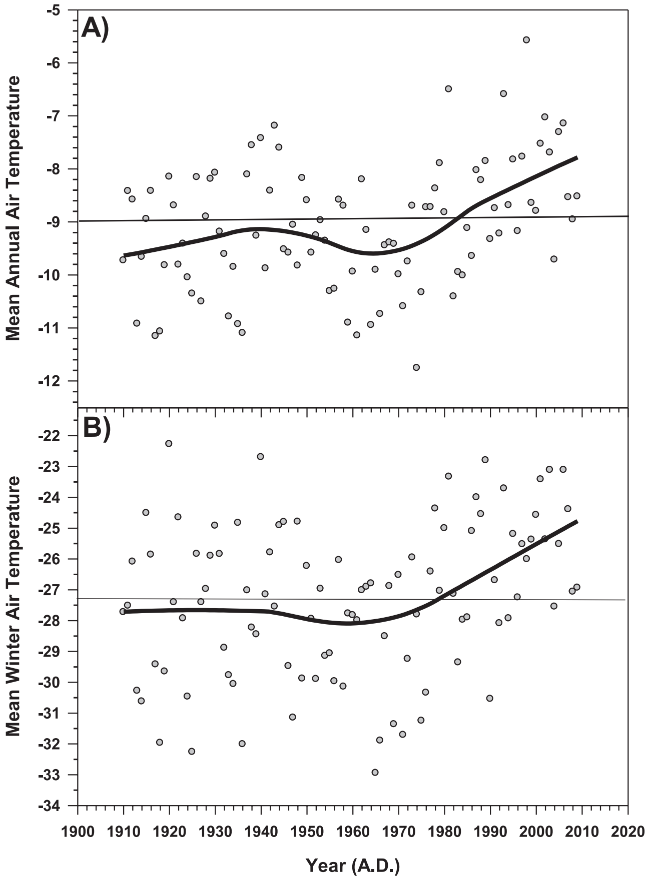


FIG. 2. Composite air temperature data (Porter et al., 2013) from the Peel Plateau region (Northwest Territories, Canada) based on data collected from three weather stations since 1910 (Fort McPherson, Inuvik, and Aklavik) showing (A) mean annual air temperature (MAAT) and (B) mean winter air temperature (MWAT) data, with the increase in temperature over the period of the record (~ 100 years) given at the top of each plot. Data are from the Historical Adjusted Climate Database of Canada, Environment Canada (http://www.cccma.ec.gc.ca/hccd/). To highlight the trends over time, a LOESS smoother with a cross-validated span (thick black lines) was applied to both MAAT (span = 0.49) and MWAT (span = 0.65). The mean temperature of the full record is depicted by thin horizontal lines.

activities. Recent warming trends and influences from the road have led to localized permafrost thawing, as noted by Gill et al. (2014). Large, natural disturbances, accelerated by climate-driven permafrost thaw and referred to as "mega-slumps," are transforming the landscape and have impacted aquatic chemistry and biota in streams throughout this region (Kokelj et al., 2013; Chin et al., 2016). The landscape and vegetation varies with topography as the Peel Plateau ranges from 150 to 600 m above sea level; coniferous forest dominates the lower elevations of the plateau, while higher elevations where our study lakes are concentrated are represented by shrub tundra.

The Peel Plateau experiences a Subarctic climate with long, cold winters and relatively short summers. The average annual air temperature recorded at the Fort McPherson weather station between 1981 and 2010 was −7.3˚C, and monthly mean air temperatures from the same time period ranged from −27.5˚C in January to 15.2˚C in July, with a daily maximum not exceeding 20˚C (Environment Canada, 2019). Receiving on average 310 mm of precipitation per year, the Peel Plateau is considered a semi-arid region (Burn and Kokelj, 2009; Environment Canada, 2019). The predominant wind directions in the Peel Plateau region are from the north-northwest and northwest between June and August, and from the east-southeast and southeast during the remaining months (online Appendix Fig. S1; Meteoblue, 2016; Gunter, 2017).

The main anthropogenic activities along the Dempster Highway are freight and tourism traffic and road maintenance activities. Material for the initial construction of the highway and maintenance of gravel embankments were obtained from nearby quarries (MacLeod, 1979) at locations along the highway throughout the Peel Plateau. Historical oil and gas exploration has left a legacy of seismic lines and several drilling-mud sumps in the region. Although there are no settlements on the Peel Plateau, the region is in the heart of Gwich'in lands (Slobodin, 1981) and hosts traditional trails, camps, and subsistence harvesting activities of the Tetl'it Gwich'in. The nearest town is Fort McPherson (pop. 776), located on the Peel River northeast of the study region (Fig. 1).

METHODS

Regional Temperature Trends

Instrumental air temperature records from three separate climate stations (Fort McPherson, Inuvik, and Aklavik) were combined to form a composite temperature record (Porter et al., 2013). The composite dataset consists of mean annual air temperatures (MAAT) as well as seasonal air temperature data collected since 1910. To visually highlight trends in air temperatures, a LOESS smoother was applied after determining an appropriate span width using generalized cross validation (using the fANVCOVA R package; Wang, 2010). Temperature trends for MAAT and mean winter air temperature (MWAT) were compared to the mean temperature of the full instrumental record (1910–2009) (Fig. 2).

Study Lakes

Twenty-eight lakes and ponds were strategically selected to assess the impact of the Dempster Highway on water chemistry, and three of those lakes were chosen to assess impacts on aquatic biota (Fig. 1). With the exception of the lakes that are proximal to the highway, the study lakes are largely unaffected by other human watershed activities. All lakes sampled for this study are relatively small (lake areas range from 0.23–9.0 ha) and shallow (maximum depth ranges from 0.8–9.8 m), with relatively small catchment areas (1.1–12.7 km^2) (Table 1).

Lakes span a distance of 40 m–26 km from the highway, making it possible to test the assumption that those nearest the road (from here on referred to as "near" lakes) would be the most heavily affected by calcareous-rich road dust, while lakes farther from the highway (from here on referred to as "far" lakes) would experience lesser impacts. The Dempster Highway from Fort McPherson to the Northwest Territories – Yukon border crosses the altitudinal treeline. However, all lakes in this study are located above the treeline at elevations ranging from 283 – 494 m above sea level, and sampling was therefore restricted to an intermediate range of the full elevation gradient for the Peel Plateau (i.e., 150 – 600 m above sea level). To eliminate potential confounding effects of differences in vegetation and elevation on water chemistry across sampling sites, all of the lakes sampled were from regions dominated by shrub tundra. When trees were present, they were scattered individuals or occurred as small clumps along drainage tracts. In general, shrubs surrounding lakes near the highway were taller than shrubs around lakes farther from the highway (Gill et al., 2014). Not all sampled lakes have official names and so were numbered within the suite of FM (Fort McPherson) lakes (e.g., FM01, FM02).

Chemical Data Collection and Analysis

Water samples and field measurements were initially collected on 19 August 2014; these measurements were repeated on 20 August 2015. The lakes were accessed by helicopter, and water chemistry samples were taken from the center of each lake, which was assumed to be the deepest part of these remote, small, shallow, and simple lakes (i.e., bathymetry not available). For each lake, a 1 L polyethylene bottle was rinsed three times with lake water before collecting water from a depth of approximately 50 cm below the water surface. Sample bottles were placed in a cooler with ice packs and delivered to Taiga Environmental Laboratory in Yellowknife, NT for analyses.

For each lake, 27 chemical and 9 physical and geographical variables were measured. Chemical variables included ammonia (NH_3), nitrate (NO_3^-), nitrite (NO_2^-), nitrate + nitrite (NO_3^-/NO_2^-), dissolved nitrogen (DN), total nitrogen (TN), dissolved organic carbon (DOC), total organic carbon (TOC), orthophosphate (OP), dissolved phosphorus (DP), total phosphorus (TP), total dissolved solids (TDS), total suspended solids (TSS), apparent colour (COL), reactive silica (Si), alkalinity (ALK), conductivity (COND), hardness (HARD), turbidity (TURB), pH, major ions (calcium [Ca], chloride [Cl], fluoride [F], magnesium [Mg], potassium [K], sodium [Na], and sulphate [SO_4^{2-}]). Water chemistry data were collected in mid-August each year, but were analysed as a single sample per lake by using an average of the 2014 and 2015 values (Table 1). To assess whether the lakes were phosphorus or nitrogen limited, mass ratios of total nitrogen (TN) to total phosphorus (TP) were calculated (Table 1).

The physical and geographical variables consisted of maximum lake depth (DEPTH), distance to the Dempster Highway (DIST), elevation (ELEV), lake surface area (AREA), catchment area (CATCH), the ratio of catchment area to lake area (CA:LA), the length of road within the catchment area (organized into three nominal categories: NO-Rd = lakes with no road in catchment, LOW-Rd = lakes with less than 1.0 km of road within the catchment, and MOD-Rd = lakes with greater than 1.0 km of road within the catchment), latitude (LAT), and longitude (LONG). Catchment sizes and the lengths of road passing through each catchment were calculated in ArcMap version 10.4, using the ArcHydro Toolset and the Canadian Digital Elevation Model (CDEM) from Natural Resources Canada. The tiled dataset was combined with a mosaic tool, and gaps were filled to generate a continuous drainage network.

Chemical Data Screening

Six of the original 27 chemical variables (Cl, F, OP, DP, TSS, NO_2^-) had concentration values below the level of detection for many of our lakes and were therefore eliminated from further analyses. Continuous variables including the remaining chemical variables, as well as DIST, DEPTH, ELEV, AREA, CATCH, LAT and LONG, were tested for normality using the Shapiro-Wilk Normality test. Variables that were found to have normal distributions, and therefore did not require a transformation, included DN, DOC, TOC, ELEV, CATCH, LAT, and LONG (and pH which is already measured on a logarithmic scale). For several variables (NH_3, Mg, NO_3^-, NO_3^-/NO_2^-, Na, and TDS), a transformation did not correct skewness; thus, these variables were run passively (i.e., as supplementary data) in subsequent numerical analyses. The remaining variables were corrected for non-normal distributions by transformations, including log x (TP, ALK, COND, TURB, Ca, K, SO_4^{2-}, DIST) and log (x + 1) (TN, COL, Si, DEPTH, AREA). The final summarized environmental dataset is given in Table 1 and consisted of 19 chemical and 9 physical and geographical variables. The complete dataset can be found in the supplementary materials (online Appendix Table S2).

At one site (FM29), located ~ 18.5 km from the Dempster Highway, a small retrogressive thaw slump was observed on its shoreline after sampling had been completed. This lake was not included in the analyses as thaw slumps can significantly affect lake water chemistry (Thienpont et al., 2013), therefore overriding potential relationships to the Dempster Highway. For this reason, FM29 was not included when calculating the mean of the full dataset, as well as the mean of the far sites, and was treated as a passive variable in our ordination analysis.

Numerical Analyses

Principal component analysis (PCA) performed with Canoco version 5.0 (ter Braak and Šmilauer, 2012) was used to examine the major patterns of variation in the environmental data. One of the aims of this ordination analysis was to explore the interrelationships among environmental variables and to examine if there were chemical trends related to distance to the Dempster

TABLE 1. Summary of physical and geographical variables and general water chemistry variables[1] measured in the 28 lakes (19 August 2014 and 20 August 2015). Chemical measurements were averaged over two years for each lake unless specified. Calculations of the mean, median, minimum, and maximum chemical variables for FM29 (thaw slump lake) were excluded.

	Alk mg/L	Area Sq km	Ca mg/L	Catch Sq km	CA:LA	CA-Road km	Col (2014) CU	Cond µS/cm	Depth m	Dist km	DN (2014) mg/L	DOC mg/L	Elev m asl	Mg mg/L
Impacted lakes within 1 km from the Dempster Highway (n = 15):														
Detection Limit		0.4		0.1				5	0.4			0.06	0.5	
Mean	31.8	0.0223	24.7	2.6	267.4	1.0	200.1	203.0	2.41	0.45	0.41	12.8	398.3	8.3
Median	15.4	0.0170	13.2	2.3	150.0	0.8	139.0	118.5	2.00	0.43	0.40	14.2	384.0	5.4
Min	0.5	0.0023	1.1	1.4	25.0	0.0	14.0	11.3	0.80	0.04	0.25	6.7	326.0	0.6
Max	117.0	0.0680	91.2	4.5	1395.7	2.5	1150.0	598.0	7.00	0.95	0.64	17.5	494.0	22.2
Reference lakes greater than 1 km from the Dempster Highway (n = 13):														
Mean	4.9	0.0364	3.9	3.9	143.7	0.000	218.3	31.4	4.23	13.45	0.42	15.7	328.5	1.3
Median	4.7	0.0315	4.0	2.9	150.5	0.0	193.5	26.4	3.60	11.90	0.41	15.7	327.0	1.1
Min	0.5	0.0090	1.5	1.1	13.5	0.0	102.0	14.1	1.70	4.82	0.30	12.2	238.0	0.6
Max	10.0	0.0860	8.2	12.7	397.8	0.0	388.0	70.9	9.80	29.87	0.54	20.0	444.0	2.9
Summary statistics for all lakes, excluding FM-29 (n = 27):														
Mean	19.9	0.0286	15.5	3.2	209.99	0.56	208.2	126.7	3.2	6.2	0.4	14.1	365.9	5.2
Median	7.6	0.0190	5.0	2.5	150.26	0.00	153.0	50.9	2.6	0.9	0.4	14.6	356.0	1.9
Min	0.5	0.0023	1.1	1.1	13.49	0.00	14.0	11.3	0.8	0.0	0.3	6.7	238.0	0.6
Max	117.0	0.0860	91.2	12.7	1395.65	2.50	1150.0	598.0	9.8	29.9	0.6	20.0	494.0	22.2

	Na mg/L	NH_3 mg/L	NO_3 mg/L	NO_3/NO_2 mg/L	pH pH units	K mg/L	Si (2015) mg/L	TOC mg/L	Turb NTU	SO_4 mg/L	TN µg/L	TP µg/L	TN:TP
Impacted lakes within 1 km from the Dempster Highway (n = 15):													
Detection Limit	0.1	0.1	0.005	0.01	0.01		0.1	0.025	0.5	0.05	1	60	2
Mean	3.8	0.026	0.23	0.24	6.98	0.6	1.793	14.1	7.74	67	489	36	13.4
Median	2.3	0.007	0.06	0.07	7.16	0.5	1.520	15.5	2.73	42	435	17	25.6
Min	0.3	0.005	0.03	0.03	5.31	0.1	0.185	6.8	0.37	1	255	4	63.8
Max	13.7	0.210	2.54	2.54	8.15	2.0	4.990	19.0	52.37	212	995	127	7.8
Reference lakes greater than 1 km from the Dempster Highway (n = 13):													
Mean	0.5	0.008	0.03	0.04	6.33	0.3	1.533	17.8	5.09	6	512	34	15.0
Median	0.4	0.007	0.03	0.04	6.45	0.2	1.365	17.7	4.16	3	500	30	16.7
Min	0.3	0.005	0.03	0.03	5.15	0.1	0.279	13.2	0.86	1	380	16	23.8
Max	1.5	0.019	0.05	0.05	6.98	0.5	2.780	22.0	15.88	19	790	97	8.1
Summary statistics for all lakes, excluding FM-29 (n = 27):													
Mean	2.3	0.018	0.14	0.15	6.69	0.5	1.677	15.8	6.56	40	499	35	24.2
Median	0.7	0.007	0.04	0.04	6.68	0.3	1.400	16.8	2.78	12	475	22	17.6
Min	0.3	0.005	0.03	0.03	5.15	0.1	0.185	6.8	0.37	1	255	4	5.8
Max	13.7	0.210	2.54	2.54	8.15	2.0	4.990	22.0	52.37	212	995	127	83.8

[1] Alk = total alkalinity as $CaCO_3$, Area = lake surface area, Ca = calcium, Catch = catchment area, CA:LA = catchment area: lake area, %CA-Road = the percentage of the catchment area occupied by the road ((road area/catchment area) × 100), Col = apparent colour, Cond = specific conductivity at 25°C, Depth = coring depth, Dist = distance to Dempster Highway, DN = dissolved nitrogen, DOC = dissolved organic carbon, Elev = elevation, Hard = hardness, Lat = Latitude, Long = Longitude, Mg = magnesium, NH_3 = ammonia as nitrogen, NO_3 = nitrate as nitrogen, NO_3/NO_2 = nitrate/nitrite, K = potassium, Si = reactive silica, TDS = total dissolved solids, TN = total nitrogen, TOC = total organic carbon, TP = total phosphorus, Turb = turbidity, SO_4 = sulphate, TN:TP mass ratios: < 9 - N-limitation (Guildford and Hecky, 2000).

Highway. Nominal variables were converted into binary data (i.e., 0, 1) before including them as dummy variables in the ordination (Lepš and Šmilauer, 2003). Data were centred and standardized to mean zero and unit variance so that all environmental variables were comparable. Geographical, physical, and nominal variables were treated as supplementary (passive) variables in the ordination space. A Pearson correlation matrix was used to identify highly correlated variables (excluding nominal variables) using Bonferroni-adjusted probabilities with significant correlations determined at both $p \leq 0.05$ and $p \leq 0.01$. Ten representative variables were run actively in the ordination (ALK, Ca, COND, COL, DOC, pH, Si, TN, TP, TURB), whereas the remaining variables were included as supplementary data. These variables were included passively as it was of interest to inspect their position in the PCA ordination relative to other variables and how they relate to the positioning of the study sites. The correlation matrix can be found in online Appendix Table S1.

To assess the potential influence of distance to the Dempster Highway on lake water chemistry, we examined the distribution of calcium and other ion-related variables (e.g., COND, ALK, pH) along a range of distances (from 0.04 – 29.87 km) to the highway, as the gravel used for road construction, and thus road dust, is rich in calcium. In addition to variables related to major ions, we also examined the relationship between other chemical variables that were found to be important to the main direction of variation in PCA axis 1 and axis 2. In addition, other factors that may affect the delivery of dust to the lakes and the concentration of solutes in the lake were explored. These included catchment area, ratio of catchment area to lake area, the length of road that crosses a lake's catchment, and elevation.

Sediment Coring for Detailed Paleolimnological Analyses

Based on distance from the highway and trends in conductivity, three sites (FM02, FM04, and FM06) were chosen for detailed paleolimnological analyses (Fig. 1) to examine the potential biological effects that road dust and climate change impose on lakes in the region. We chose two sites situated within 1 km of the highway and a third site located ~ 24 km from the highway. FM02 (67˚14′30.49″ N, 135˚19′34.77″ W) is located 50 m north the Dempster Highway. It is a shallow lake (maximum depth ~ 2.15 m) covering an area of two hectares with a catchment area of 4.54 km^2 and is characterized by slightly alkaline pH (7.34) and higher conductivity (155.5 µS/cm) relative to more distant sites. FM04 (67˚15′7.06″ N, 135˚5′57.31″ W) is located 670 m south of the highway. It is also a shallow lake (maximum depth ~ 2.95 m) with a surface area of 1.5 hectares, a catchment area of 1.38 km^2, and is characterized by higher conductivity (92.9 µS/cm) relative to more distant lakes. Compared to other near lakes in this dataset, FM04 has lower pH (6.13) and alkalinity (1.5 mg/L) levels than lakes farther from the highway, including our far lake, FM06 (3.6 mg/L). FM06 (67˚30′20.23″ N, 135˚18′35.33″ W) is located ~ 24 km from the highway, and based on its water chemistry, was anticipated to be outside the range of road dust deposition. In comparison to the two near lakes (FM02 and FM04), the far lake has lower conductivity levels (16.5 µS/cm) and is smaller and deeper, with a surface area of 0.91 hectares, a maximum depth of ~ 9.8 m, and a catchment area of 1.71 km^2.

A sediment core was collected from each of the three study lakes in April 2014 using a Uwitec gravity corer with an inner core tube diameter of 86 mm. Sediment cores were retrieved through ~ 1.5 m of ice near the centre of each lake. The cores retrieved from FM02, FM04, and FM06 were 52 cm, 57 cm, and 58 cm in length, respectively. To obtain a high-resolution paleolimnological profile, each core was sectioned on site into 0.5 cm contiguous intervals for the upper 20 cm of the core and 1.0 cm contiguous intervals for the remainder of the core.

Radioisotopic Dating

Sediment subsamples from each core were dated using gamma spectroscopy to establish chronologies within the past approximately 150 years. For each core, a selection of 12 – 20 sedimentary intervals was analysed following Schelske et al. (1994). Approximately 1.5 g of freeze-dried sediment were placed into plastic tubes and sealed with 2-ton epoxy® to ensure equilibrium between ^{226}Ra and ^{214}Bi (Schelske et al., 1994). Total ^{210}Pb activity was measured throughout the core and the supported ^{210}Pb (in situ component that is in equilibrium with the parent material) was estimated based on when total ^{210}Pb counts deep in the core no longer changed. In addition, ^{214}Bi was measured for each interval analysed and the average of these activities was used as a proxy for supported ^{210}Pb (i.e., background or equilibrium activity). The unsupported ^{210}Pb per gram dry weight was calculated by subtracting supported ^{210}Pb from the total ^{210}Pb activities. Unsupported ^{210}Pb activity was used to estimate dates using the constant rate of supply (CRS) model (Binford, 1990; Appleby, 2002). ^{137}Cs was used in addition to ^{210}Pb to corroborate the radiometric dates, where a peak in ^{137}Cs activity corresponded to the 1963 global ban on atmospheric nuclear testing (Appleby, 2002). Samples were analysed at the Paleoecological Environmental Assessment and Research Laboratory (PEARL), Queen's University, Kingston, Ontario, Canada. Dates for sedimentary intervals not analysed by gamma spectroscopy were estimated using straight-line interpolation between each successive pair of dated intervals (Campbell, 1996), thereby providing an estimated CRS date for each available sedimentary interval.

Sedimentary Chl-a

Visible reflectance spectroscopy was used to infer sedimentary chl-*a* trends based on procedures described by Michelutti et al. (2010) and reviewed in Michelutti and Smol (2016). Approximately 1 g of freeze-dried sediment selected from ~ 30 intervals from each core was sieved through a 125 µm screen to remove large particles and equalize the grain size. Each sample was processed through a FOSS NIRSystem Model 6500 Rapid Content Analyzer using the reflectance spectra at wavelengths between 650 and 700 nm to infer trends in chl-*a* with the published algorithm from Michelutti et al. (2010). This method quantifies trends in both chl-*a* concentrations and its main derivatives (pheophytin and pheophorbide) and therefore accounts for the major diagenetic products while tracking changes in primary production through time (Michelutti et al., 2010; Michelutti and Smol, 2016).

Diatom Analysis

Sediment subsamples from FM02, FM04, and FM06 were prepared for diatom analysis following standard protocols (e.g., Rühland and Smol, 2002). For each interval analysed, approximately 0.1 g of wet sediment was digested using 15 ml of a 1:1 molar ratio of HNO_3 and H_2SO_4, then placed in a hot water bath heated to 80˚C for two hours. The digested sediment was allowed to settle for ~ 24 hours prior to being aspirated and rinsed with deionized water. This process was repeated with a 24-hour settling period between each aspiration until a neutral pH was reached. The resulting diatom slurry was strewn onto cover slips in four different dilutions, allowed to evaporate, and mounted onto microscope slides using Naphrax®. For one of the near lakes (FM02), the prepared diatom samples contained an excess amount of siliciclastic material and low numbers of diatom valves in sedimentary intervals below ~ 6.5 cm. In these samples, efforts were made to attain sufficient diatom valves for analyses by applying a density gradient separation technique using sodium polytungstate (SPT) at a density of 2.3 g/cm^3 to both concentrate the diatoms and remove excessive siliciclastic material (Tapia and Harwood, 2002).

Microscope slides were examined using a Leica DMR microscope fitted with differential interference contrast optics at 1000× magnification. For each slide, a minimum of 300 diatom valves was counted. When possible, diatom valves were identified to the levels of species and variety using taxonomic sources including Krammer and Lange-Bertalot (1986 – 91) and Fallu et al. (2000). Diatom data were expressed as percent relative abundances. For display purposes only, diatoms with similar trends and ecological preferences were grouped to better highlight assemblage compositional changes. For example, small, benthic fragilarioid taxa (*Staurosirella pinnata*, *S. pinnata* var. *intercedens*, *S. pinnata* var. *lancettula*, *S. pinnata* var. *acuminata*) were grouped together as they have similar life strategies and showed similar trends in the downcore assemblages. Similarly, planktonic fragilarioid diatoms (*Fragilaria nanana* and *F. tenera*) were combined, as were *Tabellaria* taxa (*Tabellaria flocculosa* and *T. fenestrata*). However, all statistical analyses were conducted on the ungrouped, full diatom dataset. Diatom diversity was calculated for each sedimentary sample using the Hill's N2 statistic (Hill, 1973). These diversity numbers are measured in units of effective taxa where each taxon is weighted by its abundance (Hill, 1973), with N2 diversity being the number of very abundant taxa in a sample (Birks, 2010). Siliceous scales of scaled chrysophytes (mainly *Mallomonas* spp.) were counted alongside diatom valves, although not identified taxonomically. The relative number of chrysophyte scales was expressed as a percentage relative to the total number of diatom valves counted (Scale:Diatom or S:D), and was calculated for each sedimentary interval using the formula:

$$S{:}D = (\#\ of\ scales\ /\ (\#\ of\ diatom\ valves)) \times 100$$

(Smol, 1985; Cumming et al., 1993).

In samples where the number of chrysophyte scales greatly outnumbered diatom valves, the ratio was based on the number of scales observed in the first 50 diatom valves counted.

RESULTS

Regional Temperature Trends

MAAT and MWAT increased by 1.3˚C and 2.3˚C, respectively, over the 100-year composite climate record (Fig. 2A, B). LOESS smoothers were applied to the temperature data (cross-validated span widths of 0.49 for MAAT and 0.65 for MWAT) to visually highlight the trends. Prior to the past few decades, both annual and winter temperature trends remained close to or below the record mean (1910 – 2009), with a period of cooler temperatures between 1955 and 1975. Both MAAT and MWAT show a positive warming trend from the late 1970s (winter) and early 1980s (annual) to the present, during which time temperature trends were consistently above the mean of the record (Fig. 2A, B).

Water Chemistry Data

Major ions and related variables exhibited a relatively wide range of values across our 28 sites (Table 1). In general, lakes within 1 km of the Dempster Highway had significantly higher (t-test, $p < 0.01$) concentrations of major ions and related variables, such as conductivity and calcium (e.g., mean conductivity = 204 µS/cm; mean Ca = 24.7 mg/L), compared to study lakes that were greater than 1 km away from the highway (e.g., mean conductivity = 31.4 µS/cm; mean Ca = 3.9 mg/L) (Table 1; Fig. 3A, B). There were, however, a few exceptions to this general trend; three near lakes had some of the lowest measures of conductivity and calcium of the 28 study lakes, and fell below the mean for far lakes (> 1 km) (Fig. 3A, B).

One of the far lakes (FM29, ~ 18.5 km from highway) had a small, but active, retrogressive thaw slump along its shoreline at the time of sampling, which likely resulted in anomalously high conductivity (439 µS/cm; Fig. 3B) and ionic composition, particularly Na, Mg, and SO_4 (online Appendix Table S2). Similar results were noted in a nearby study of thaw slumps by Thienpont et al. (2013). However, in spite of anomalously high concentrations in major ions and elevated conductivity, alkalinity and pH values were moderately low in this lake (online Appendix Table S2), as were TP and TN values. Given that the chemistry in lake FM29 differs from the other far lakes, likely due to the occurrence of thaw slumping, this site was not actively included in the analyses.

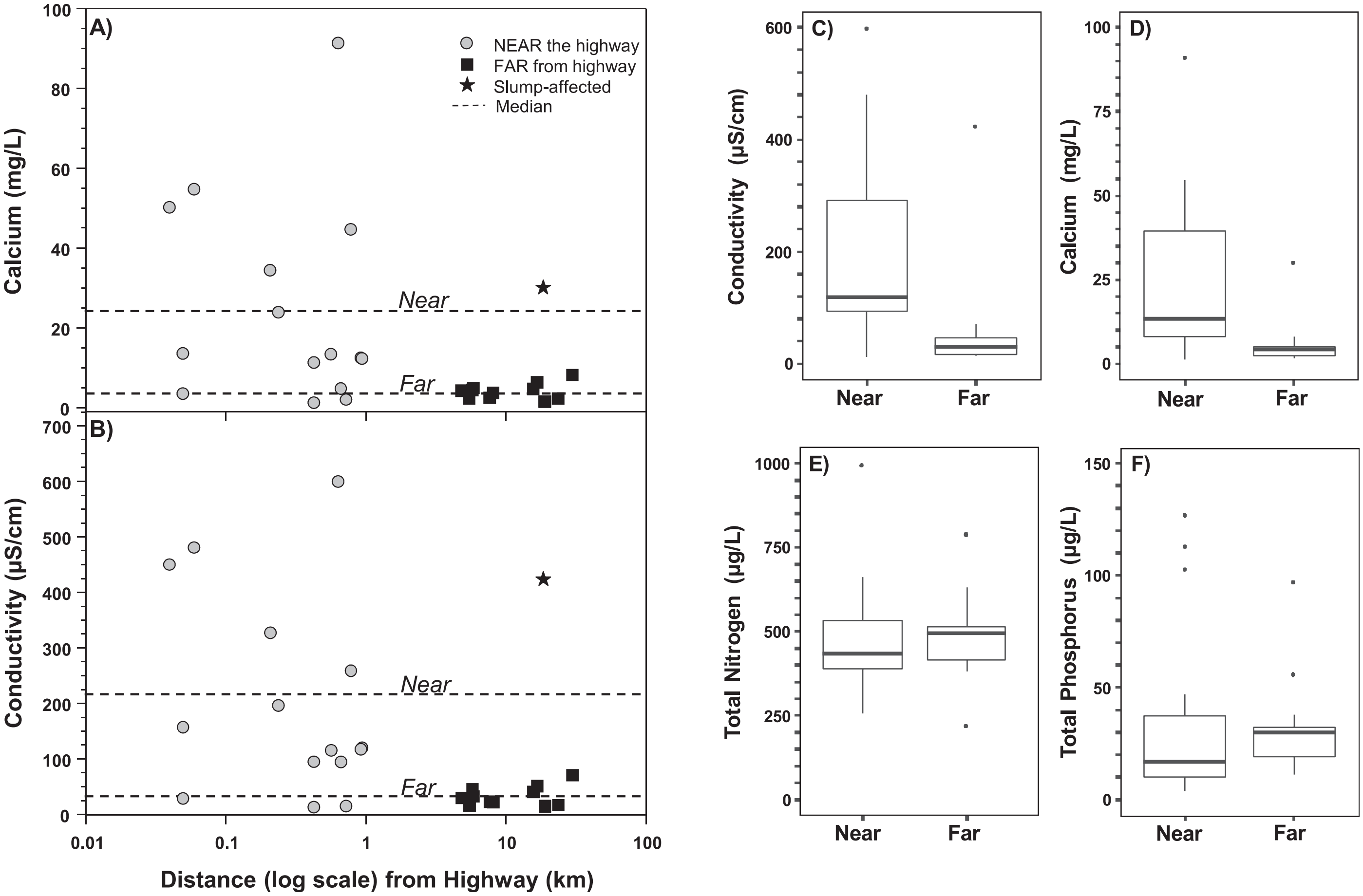


FIG. 3. Relationship between distance of lake to the Dempster Highway and (A) lake water calcium concentrations and (B) conductivity measurements for the 28 Peel Plateau (Northwest Territories, Canada) study sites. Distance is depicted on a log scale. Near lakes (within 1 km of the highway) are denoted by grey circles and far lakes (greater than 1 km from the highway) are denoted by black squares. The star depicts one lake that was affected by a retrogressive thaw slump and therefore has anomalously high calcium and conductivity levels for a far lake. Dashed lines indicate the median values of the near and far sites. Boxplots reveal differences in (C) conductivity levels and (D) calcium concentrations between near and far lakes, while (E) total nitrogen levels and (F) total phosphorus were comparable between the two lake groups.

Lakes in our Peel Plateau study were moderately to highly enriched in nutrients compared to lakes studied in other parts of the Canadian Subarctic (e.g., Pienitz et al., 1997a, b; Rühland et al., 2003). While many sites proximal to the highway had TP concentrations that were well above the mean for the dataset (35 µg/L), near lakes (mean = 34 µg/L) did not significantly differ (t-test, p = 0.85) from far lakes (Fig. 3F, mean = 36 µg/L). Likewise, TN concentrations in the Peel Plateau lakes near the highway (mean = 489 µg/L) did not significantly differ (t-test, p = 0.68) from lakes farther away (Fig. 3E, mean = 512 µg/L). Mass ratios of TN:TP were highly variable across lakes ranging from 6 to 84 (mean: 24), with the majority of lakes (86%) considered to be phosphorus-limited at the time of sampling (based on Downing and McCauley, 1992; Guildford and Hecky, 2000). All N-limited lakes (four lakes) had high TP concentrations ranging from 97 to 127 µg/L and well above the mean TP of the full dataset (35.4 µg/L) (online Appendix Table S2).

Principal Component Analysis

The distribution of sites and environmental variables in the PCA ordination generally tracked the spatial gradient in water chemistry in relation to distance to the Dempster Highway (Fig. 4). PCA revealed two main directions of variation with axis 1 explaining 51% of the total variance and axis 2 explaining an additional 25% (Fig. 4). The strongest direction of variation (PCA axis 1) was primarily a gradient of conductivity, Ca- and pH-related variables that showed a negative relationship (i.e., arrows in opposite directions in PCA plot) with COL, DOC, TP, and the supplementary variable, DIST. The second gradient was characterized by strong positive correlations of TN, TP, and TURB to PCA axis 2 (Fig. 4).

The 28 sites were broadly separated within the PCA ordination based on their relationship to major ions on the first axis and nutrients along the second axis (Fig. 4). Most of the lakes within 1 km of the highway were characterized by relatively higher conductivity and related variables, and plotted on the right-hand side of the PCA ordination (Fig. 4). Exceptions to this trend include lakes FM10, FM05, and

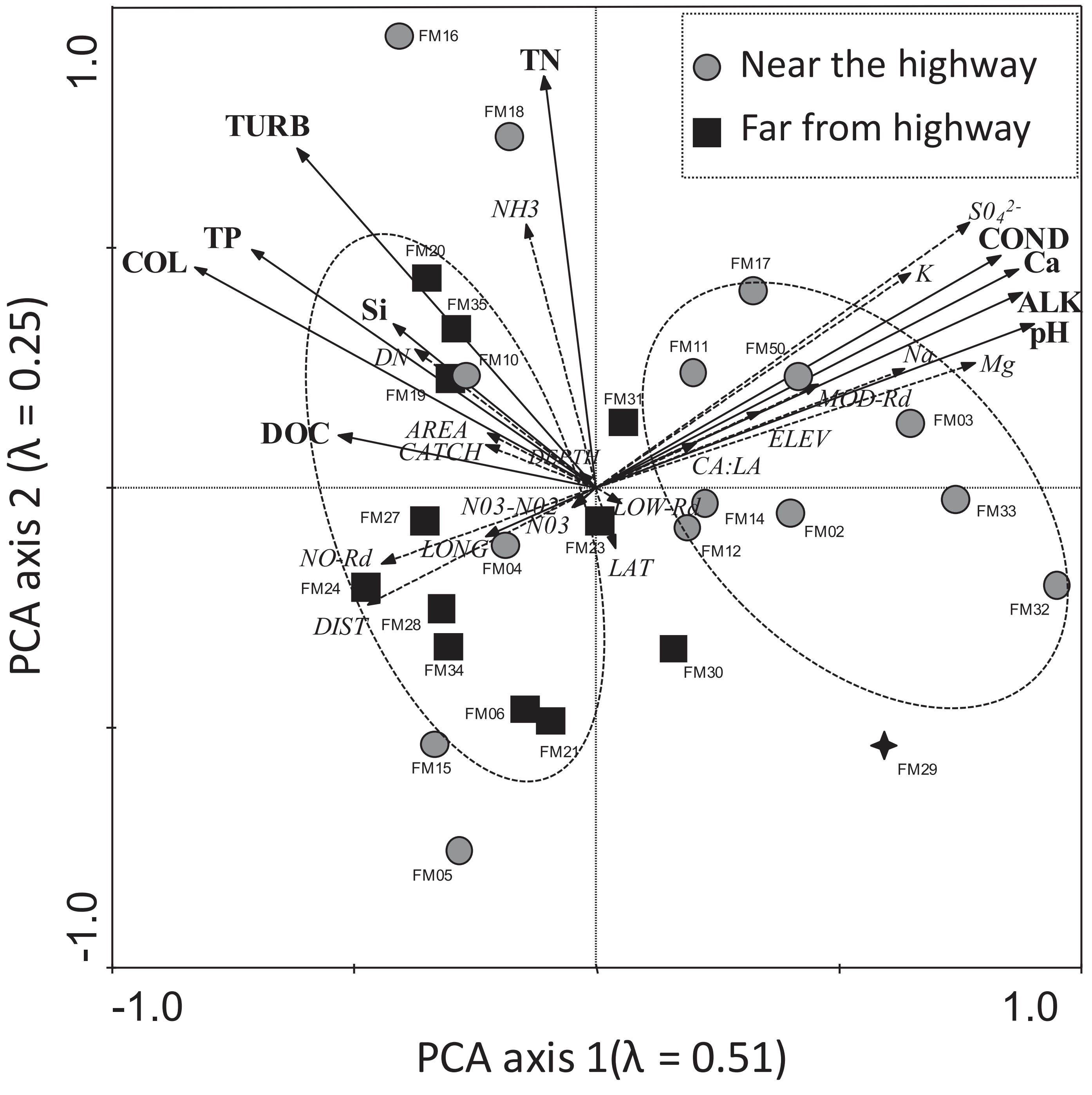


FIG. 4. Principal component analysis (PCA) of the physical and chemical variables from the 28 Peel Plateau study lakes near the Dempster Highway (Northwest Territories, Canada). The ordination was generated using 10 active variables (shown with solid arrows and bold font). All other variables were run passively in the analysis (dashed arrows and italicized font). Grey circles represent near lakes that are within 1 km of the highway. Black squares represent far lakes located greater than 1 km from the highway. FM29, represented by a star, experienced a retrogressive thaw slump resulting in anomalously high concentrations of conductivity and related variables that were independent of the effects of the highway and was run passively in the ordination. Ovals were drawn to help visualize the clustering of near and far lakes within the ordination space. The variable abbreviations are as follows: ALK = total alkalinity as $CaCO_3$, AREA = lake surface area, Ca = calcium, CATCH = catchment area, CA:LA = the ratio of catchment area to lake area, NO-Rd = no road in catchment, LOW-Rd = less than 1.0 km of road within the catchment, MOD-Rd = greater than 1.0 km of road within the catchment, COL = apparent colour, COND = specific conductivity at 25˚C, DEPTH = coring depth, DIST = distance to Dempster Highway, DN = dissolved nitrogen, DOC = dissolved organic carbon, ELEV = elevation, LAT = latitude, LONG = longitude, Mg = magnesium, NH_3 = ammonia as nitrogen, NO_3 = nitrate as nitrogen, NO_3-NO_2= nitrate/nitrite, K= potassium, Si = reactive silica, TN = total nitrogen, TP = total phosphorus, TURB = turbidity, SO_4^{2-} = sulphate, TN:TP mass ratios = <9 - N-limitation (Guildford and Hecky, 2000).

FM15, which are located within 1 km of the road, but had relatively low levels of conductivity, pH, alkalinity, and related variables compared to other lakes located near the highway (online Appendix Table S2). Study site FM04, situated within 1 km of the road, had high levels of conductivity relative to sites farther away from the

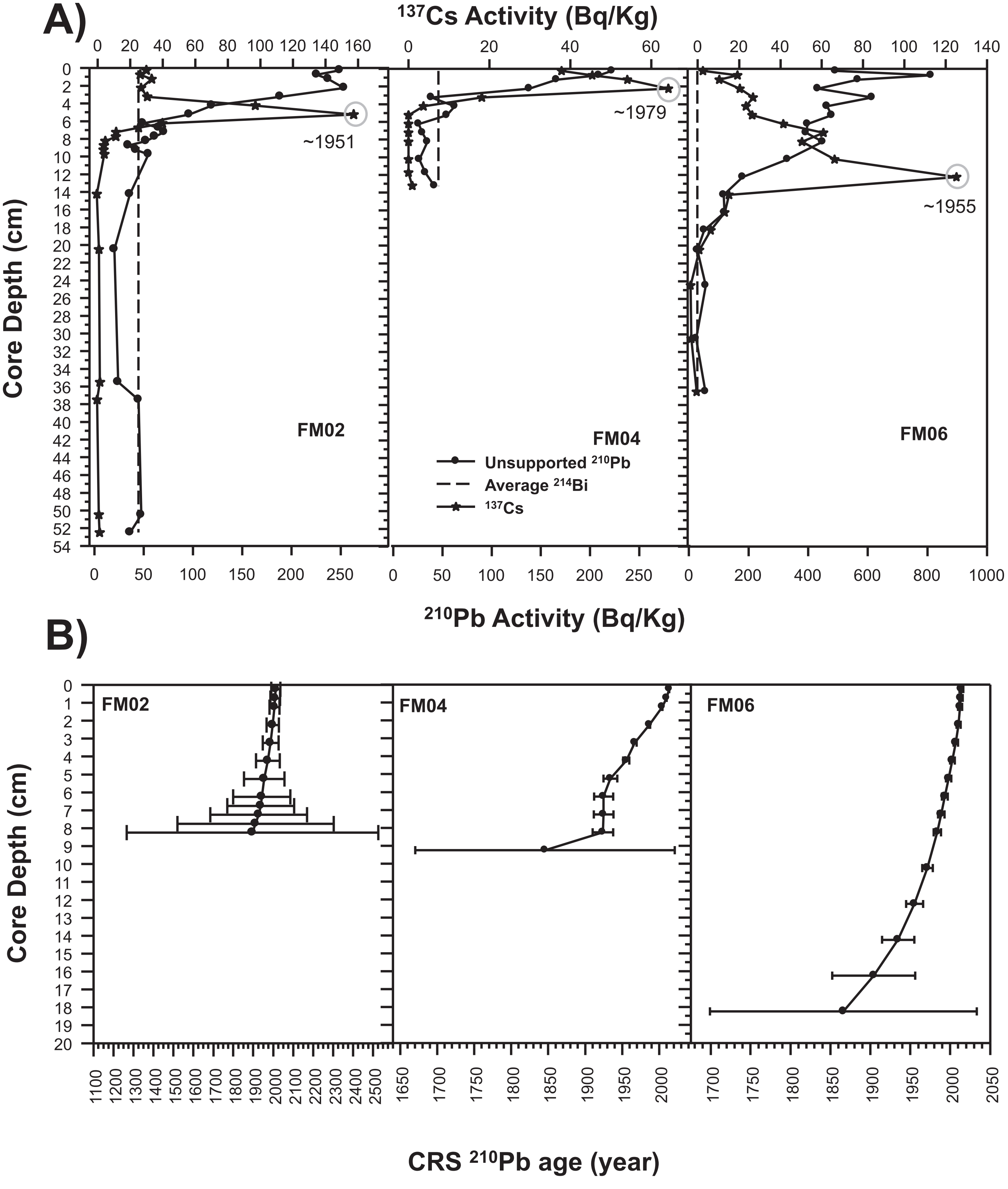


FIG. 5. Radiometric dating results using gamma spectroscopy showing (A) ^{210}Pb, ^{137}Cs, and ^{214}Bi activities in becquerels per kilogram (Bq/kg) dried sediment, plotted against core depth for the three Peel Plateau (Northwest Territories, Canada) lakes, where detailed paleolimnological analyses were undertaken, and (B) corresponding dates estimated from the constant rate of supply (CRS) model plotted against core depth and associated standard errors. The dashed vertical line in (A) is the mean of all sample-specific ^{214}Bi activities and is a proxy for supported (background) ^{210}Pb levels. CRS dates corresponding to the interval of highest ^{137}Cs activity are denoted in (A) and are associated with the height of nuclear fallout following the 1963 moratorium on weapons testing. Note the change in x-axes scale in (A).

highway, but low measurements of pH, Ca, and alkalinity, and therefore plotted on the left-hand side of the ordination plot. Lakes that were greater than 1 km from the highway plotted on the left-hand side of the PCA ordination and also displayed a greater dispersal in ordination space indicating that these lakes had generally lower conductivity (and related variables) and a greater variability in lake water chemistry than lakes proximal to the highway.

Variation in lake nutrients (TP and TN) characterizing PCA axis 2 was not clearly related to distance to the Dempster Highway (Fig. 4). Lakes that were high in nutrients, particularly FM10, FM16, FM18, FM20, and FM35, had measured TP concentrations exceeding 50 µg/L and TN concentrations above 565 µg/L; these plotted in the upper left quadrat of the PCA ordination (online Appendix Table S2; Fig. 4). Many of these high nutrient lakes also had high turbidity and colour that exceeded the dataset mean. Unlike the majority of lakes located within 1 km of the highway, high-nutrient far lakes generally had lower concentrations of alkalinity and lower pH (online Appendix Table S2).

Although the majority of lakes located within 1 km of the highway were elevated in major ions, there was a relatively high degree of variability in the chemistry of these lakes (Fig. 3A). To explore possible explanations for this variability, a suite of physical variables that could potentially affect the concentration of solutes entering a lake (e.g., catchment area, lake area, proportion of highway in catchment) were included in the analyses. CA:LA was represented by a short arrow in the PCA ordination with a positive relationship to major ions and related variables (Fig. 4). No clear trends were observed between CA:LA and COND, TP, and TN; lakes with low CA:LA were represented by both high and low COND levels; there was no distinction between near and far lakes (data not shown). Lakes that have no highway in their catchments (NO-Rd) showed a negative relationship to major ions in the PCA ordination; lakes with a moderate length of the highway in the catchment (MOD-Rd) showed a positive relationship to major ions (Fig. 4). However, a plot of amount of road in the catchment versus COND suggested that this relationship is not clear (data not shown). The arrow for elevation (ELEV) plotted in the same direction as major ions in the PCA, suggesting a positive relationship (Fig. 4). The highway is situated at higher elevations than farther sites, and nearby lakes had higher conductivity levels than sites at the lower end of the elevation gradient (i.e., lakes farther than 1 km from highway).

Radioisotopic Dating of Sediment Cores

Unsupported ^{210}Pb was contained in the upper 7.75 cm and 8.75 cm of near-highway lakes FM02 and FM04 (Fig. 5A) respectively, which is typical of high-latitude lakes and ponds characterized by low sedimentation rates (Douglas and Smol, 2000). Sedimentation rates based on the CRS dating model for the three Peel Plateau sites were generally low with the far site (FM06) showing no notable change over time (online Appendix Fig. S2). FM02 and FM04 showed increases in sedimentation rates over time, for example, FM04 exhibited a large increase in sedimentation around the time the highway was constructed in 1955. However, large errors and low temporal resolution precluded more in-depth analyses (online Appendix Fig. S2). Despite low initial ^{210}Pb activities and low temporal resolution in the sediment cores from the two lakes, exponential decay curves were observed and CRS dates circa 1963 were associated with clear ^{137}Cs peaks, thus providing greater confidence in our dating chronology (Fig. 5A). The far lake (FM06) had higher initial ^{210}Pb activity than the two sites near the highway, with the unsupported ^{210}Pb inventory contained within the top ~ 20 cm of the sediment core, yielding a relatively high temporal resolution for this tundra lake. Similar to FM02 and FM04, dates derived from the CRS model for FM06 were corroborated with a distinct ^{137}Cs peak (Fig. 5A). ^{210}Pb dates estimated from the CRS model and standard errors associated with each estimated date are given in Figure 5B.

Diatom and Chl-a Trends in Dated Sediment Cores

FM02 (Near site): Diatom valves, although well preserved in all sediment intervals, were too scarce to count below a core depth of 6.5 cm (ca. 1915). Treatment of these sedimentary intervals with a heavy liquid separation technique (SPT) did not succeed in concentrating the diatom valves sufficiently for enumeration in lower sedimentary intervals. For this reason, diatom analysis for all cores focused on the past approximately 100 years (ca. 1900 to present), which covers the time period of interest for this study.

A total of 95 diatom taxa were identified in the upper 6.5 cm of the FM02 core. Diatom assemblages throughout the core were dominated by an epipsammic *Staurosirella pinnata* complex (~ 70% mean relative abundance) composed of *Staurosirella pinnata*, *S. pinnata* var. *acuminata*, *S. pinnata* var. *intercedens*, and *S. pinnata* var. *lancettula* (Fig. 6). In addition to the *S. pinnata* complex, a *Pseudostaurosira brevistriata* complex (*P. brevistriata* and *P. brevistriata* var. *papillosa*), *Staurosira construens* var. *venter*, *S. construens* var. *pumila*, and a small *Navicula* (sensu lato [s.l.]) complex (*Sellaphora seminulum*, *S. absoluta*, *S. kuelbsii*, *Nupela vitiosa*) were also important components of the diatom assemblages in the upper 6.5 cm of the core (Fig. 6). Hill's N2 species diversity showed a slight increase from 8 to 11 very abundant taxa post circa 1980 (Fig. 6).

Changes in diatom assemblage composition in the FM02 record were modest, but decreases in the relative abundance of the *Staurosirella pinnata* complex from approximately 85% circa 1968 to 60% circa 2014 were notable. *Nitzschia* and *Diploneis* taxa, absent in the earlier sediments, had increased to ~ 3%–5% relative abundance since their first appearance circa 1968 (Fig. 6).

Chrysophyte scales were not observed in sufficient numbers to count in the FM02 core. Prior to the mid-1970s,

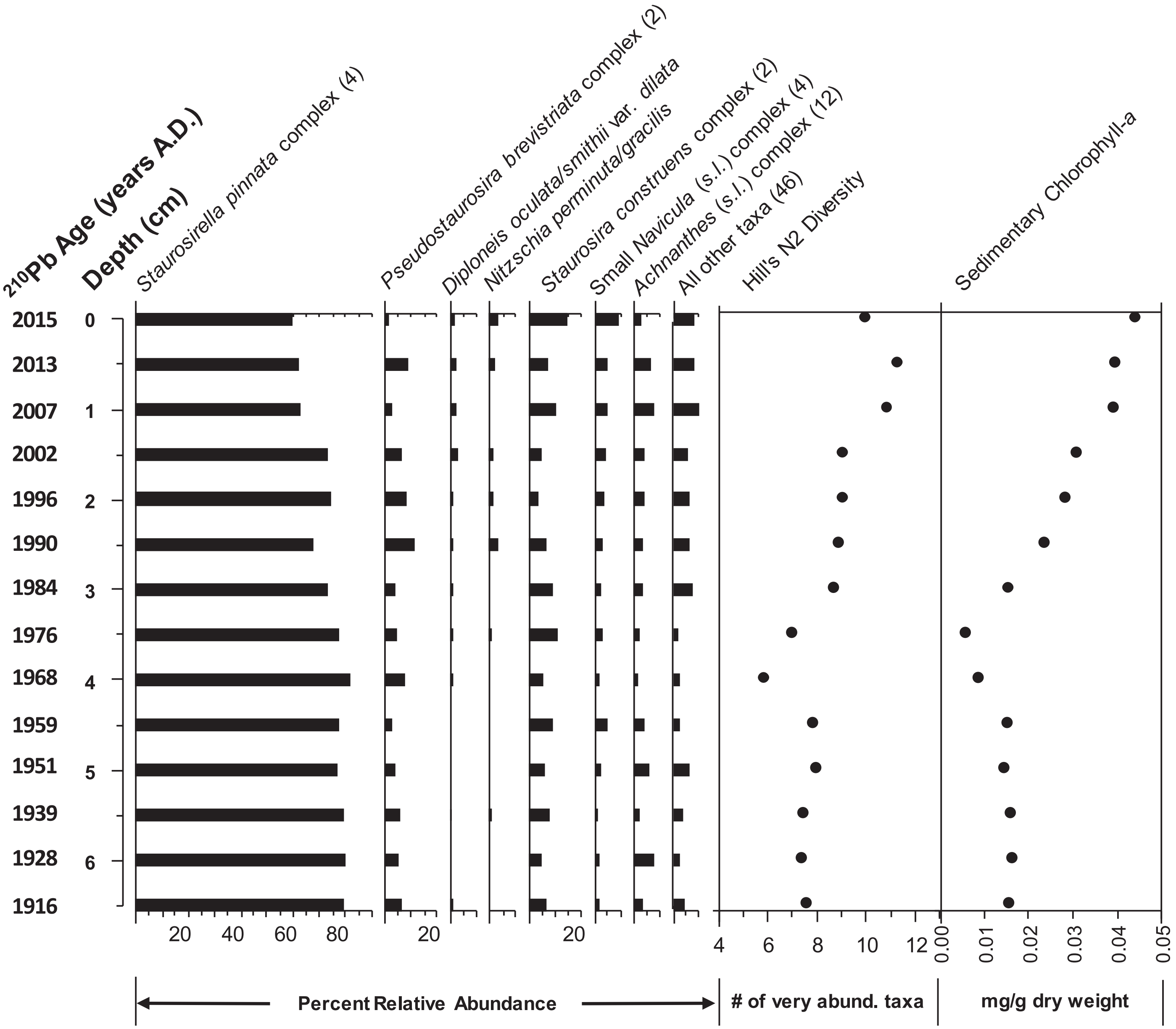


FIG. 6. Stratigraphical sequences for near lake FM02 showing the percent relative abundances of the most common diatom taxa, the number of very abundant taxa identified via Hill's N2 statistic, and sedimentary chlorophyll-*a* concentrations plotted against core depth and ^{210}Pb-estimated dates. To better visualize compositional trends in the figure, diatom taxa with similar ecological characteristics and temporal trends were grouped into complexes with the number of taxa within each grouping given in brackets following the taxon label. s.l. = sensu lato.

the sedimentary chl-*a* values for FM02 were relatively stable and generally low, after which there was an approximate four-fold increase to the top of the core (Fig. 6).

FM04 (Near Site): A total of 66 diatom taxa were identified in the upper 6 cm of the FM04 core, which represents approximately 100 years. No distinct changes in the diatom assemblage composition were observed during this roughly 100-year period. The assemblages were dominated throughout the core by small benthic fragilarioid taxa (*Staurosirella pinnata* complex, *Staurosira construens* f. *exigua*, *S. construens* var. *venter*) in addition to moderate relative abundances of *Aulacoseira ambigua*, *Psammothidium subatomoides*, *P. carissima*, *P. curtissimum*, and small *Navicula* s.l. taxa (*Navicula digitulis*, *N. maceria*, *Sellaphora minima*, *S. seminulum*, *Fallacia egregia*) (Fig. 7). The Hill's N2 diversity index changed little over the approximate 100-year record, ranging from 23 to 27 very abundant taxa (Fig. 7).

Unlike the other near-highway site FM02, chrysophyte scales were observed in FM04; the S:D ratios showed a steady increase in scale abundance since circa 1980 (~ 5%) and reached a maximum percentage (~ 21%) in the top-most interval of the core (circa 2014) (Fig. 7). The chl-*a* concentration trend in FM04 was generally low, but began a gradual increase around 1930, which continued to the present day when it reached maximum concentrations (Fig. 7).

FM06 (Far Site): A total of 96 diatom taxa were identified in the far site FM06, which shared similarities

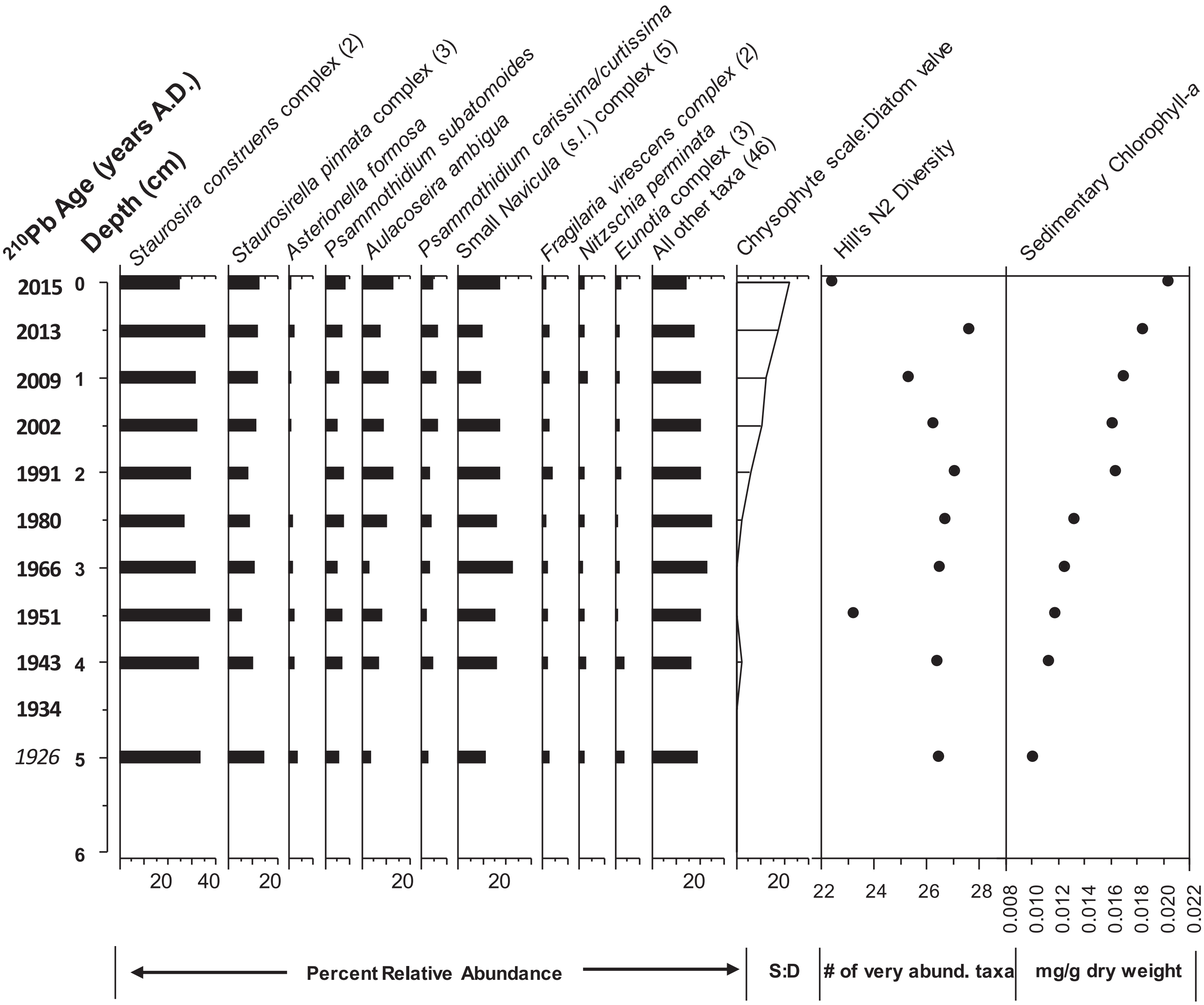


FIG. 7. Stratigraphical sequences for near lake FM04 showing the percent relative abundances of the most common diatom taxa, chrysophyte scale to diatom valve index, the number of very abundant taxa identified via Hill's N2 statistic, and trends in sedimentary chlorophyll-*a* concentrations plotted against core depth and ^{210}Pb-estimated dates. To better visualize compositional trends in the figure, diatom taxa with similar ecological characteristics and temporal trends were grouped into complexes with the number of taxa within each grouping given in brackets following the taxon label. An extrapolated ^{210}Pb date is indicated in italics and should be viewed with caution. s.l. = sensu lato.

in taxa with both of the near sites. However, one notable difference in the diatom assemblage composition in the deeper far site was the greater number and higher relative abundances of planktonic diatom taxa throughout the approximate 100-year record (Fig. 8). Diatom taxa that were present throughout the FM06 core in notable abundances included benthic fragilarioid taxa (*Staurosirella pinnata*, *S. pinnata* var. *intercedens*, *Staurosira construens* var. *venter*, *S. construens* var. *pumila*), small *Achnanthes* s.l. species (*Psammothidium curtissimum*, *P. subatomoides*, and *Achnanthidium minutissimum* among others) and small *Navicula* s.l. species (including *Sellaphora minima*, *Sellaphora seminulum, Nupela vitiosa*) (Fig. 8). Planktonic *Cyclotella ocellata* occurred in low abundances (< 5%) throughout the core, with the exception of a distinct peak from circa 1905 to circa 1935, during which it dominated the assemblage (maximum ~ 35% relative abundance). At a core depth of 12 cm (circa 1950), there was a clear change in assemblage composition with increases in the relative abundance of pennate planktonic taxa such as *Asterionella formosa*, *Fragilaria nanana*, *F. tenera*, *Tabellaria fenestrata*, and *T. flocculosa* (Fig. 8). *Asterionella formosa*, a colonial planktonic diatom, was present in trace abundances prior to circa 1985 after which its relative abundance increased, reaching a maximum abundance of 23% circa 2012 (Fig.8.) The other pennate planktonic taxa in the assemblage exhibited a similar trend, almost tripling in relative abundance from an average of ~ 4% to ~ 11% relative abundance post-1950. Although greater than the two sites near the highway, there was no clear trend in Hill's

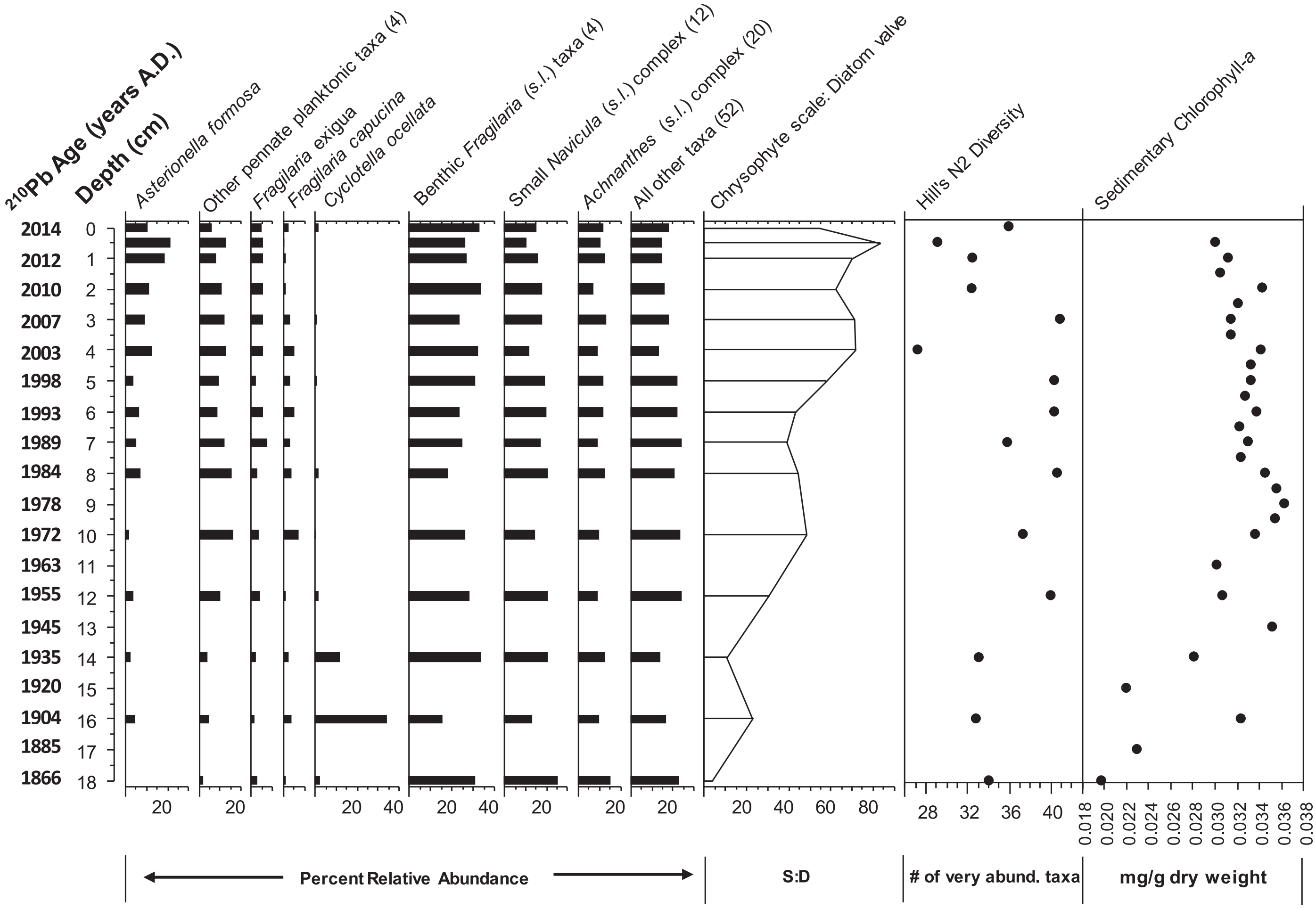


FIG. 8. Stratigraphical sequences for far lake FM06 showing the percent relative abundances of the most common diatom taxa, chrysophyte scale to diatom valve index, the number of very abundant taxa identified via Hill's N2 statistic, and trends in sedimentary chlorophyll-*a* concentrations plotted against core depth and ^{210}Pb-estimated dates. To better visualize compositional trends in the figure, diatom taxa with similar ecological characteristics and temporal trends were grouped into complexes with the number of taxa within each grouping given in brackets following the taxon label. s.l. = sensu lato.

N2 diversity, which underwent modest changes throughout the sediment record where the number of very abundant taxa varied between 30 and 40 (Fig. 8).

Chrysophyte scales were recorded throughout the sediment record of FM06, but were most abundant in the upper 10 cm of the core (Fig. 8). The S:D index exhibited an increasing trend since circa 1866, followed by a more rapid increase between circa 1935 and circa 1972, a period during which scales were present in approximately the same abundance as valves (S:D ratio = ~ 50%). Chrysophyte scale abundances continued to increase towards the top of the core and peaked circa 2012 (S:D index = ~ 85%), at which time they were the dominant siliceous microfossil (Fig. 8). Sedimentary chl-*a* concentrations in FM06 were generally higher than in the two near sites. In the early sediments of FM06, chl-*a* started to increase by the end of the 19th century, peaking circa 1940, reaching a two-fold increase over the circa 1850 concentrations (Fig. 8). From circa 1980 to the top of the core, chl-*a* concentrations become more stabilized and remained relatively high over the past approximate 25 years.

DISCUSSION

Chemical Characterization of Lakes in the Peel Plateau

Our chemical survey of 28 lakes indicated that, with a few exceptions, sites within 1 km of the Dempster Highway were significantly higher in major ion concentrations (e.g., Ca) and related variables (e.g., conductivity) than lakes farther from the highway. While there was a relatively high degree of variability in water chemistry among our near-sites, these results suggest that calcium-rich road dust from the Dempster Highway is affecting water chemistry variables related to major ion concentrations of small (0.23 – 9.0 ha) and relatively shallow (0.8 – 9.8 m) lakes in the region. PCA results highlight that lakes near the highway were chemically distinct from the far lakes, particularly in terms of higher levels of conductivity and related variables (Fig. 4). With the exception of three near-sites with lower concentrations of major ions, the most notable chemical response was observed in lakes located within 1 km of the highway, where specific conductivity levels (mean = 203 μS/cm) were clearly above those measured in the far lakes (all below ~ 70 µS/cm) (Fig. 3B). This pattern is consistent with the predicted impact of dust deposition and is in agreement with what was observed along the Dalton Highway (Alaska, USA), where most of the dust was deposited within 300 m of the road (Everett, 1980). In the Peel Plateau, materials are likely transported over greater distances, since the mudstone-derived tills are composed of much finer fractions of clay and silt (Kokelj et al., 2017) that tend to remain longer in aerial suspension (Gill et al., 2014). Although dust likely did not travel much farther than 1 km from the highway, it was not possible to determine the distance at which dust delivery ceased to affect lake water chemistry in the Peel Plateau study as no lakes between 1 and 5 km from the highway were sampled.

Our Peel Plateau far lakes had conductivity measurements (and related variables) that were comparable to undisturbed lakes from the nearby Mackenzie Delta region (Thienpont et al. (2013), and moderately elevated conductivity levels relative to undisturbed tundra lakes in other regions of the Canadian Arctic that are located on Precambrian Shield bedrock (e.g., Pienitz et al., 1997b; Rühland et al., 2003). For example, the mean conductivity measured at far lakes (31.4 µS/cm) was ~ 2.3 times higher than the mean conductivity of remote tundra lakes in the central Canadian Subarctic (mean conductivity = 13.9 µS/cm of 31 tundra lakes combined from Pienitz et al., 1997b and Rühland et al., 2003). Conductivity values of the far lakes were somewhat lower but comparable to undisturbed tundra lakes in the Mackenzie Delta region (n = 21; mean conductivity = 87.6 µS/cm: Kokelj et al., 2005; Thienpont et al., 2013). Although the far lakes were generally deeper than the near lakes (Table 1), conductivity and calcium levels were similar for both the shallow and deeper far lakes; a short arrow denoting depth in the PCA suggests that this variable is weakly associated with water chemistry trends of the Peel Plateau lakes (Fig. 4). Differences in conductivity levels among Subarctic regions are not surprising given differences in geology, where lakes in the central Canadian Subarctic are situated on Precambrian Shield bedrock and therefore naturally low in base cations. In contrast, till deposits derived from calcium-rich sandstone and Cretaceous marine shale and siltstone confer higher levels of cations in the Peel Plateau and Mackenzie Delta region lakes (Norris, 1984). Although conductivity levels were higher in lakes in the Peel Plateau relative to Arctic regions on the Precambrian Shield, these values are still considered to be relatively low. The generally low levels of conductivity in surface waters of high latitude sites (including the Peel Plateau) can be attributed to the presence of continuous permafrost, which limits surface water interaction to a thin, seasonally thawed active layer. The anomalously high conductivity (439 µS/cm) and ionic composition, particularly Na, Mg, and SO_4 measured in one of the far lakes (FM29, ~ 18.5 km from the highway), can be explained by the occurrence of a small, but active retrogressive thaw slump along its shoreline at the time of sampling (online Appendix Table S2; Fig. 3A, B). The water chemistry of this thaw slump-affected lake is comparable to the elevated conductivity and major ion levels recorded in the slump-affected Mackenzie Delta lakes studied by Thienpont et al. (2013).

In contrast to the far lakes, some of the highest levels of conductivity (maximum ~ 600 µS/cm) and calcium (maximum 91.2 mg/L) were recorded in lakes located within 1 km of the Dempster Highway (Fig. 3A, B; online Appendix Table S2). Gravel used to construct and maintain the Dempster Highway is derived from a series of local borrow pits excavated in permafrost. These materials are similar in origin to those thawed by lakeside slumps and may account for the higher conductivity levels of near-highway lakes, which approach the high values of lakes disturbed by retrogressive thaw slumps reported by Thienpont et al. (2013). While not all lakes sampled within 1 km of the Dempster Highway had exceptionally high conductivity levels (range 11.3 to 598 µS/cm) and calcium concentrations (range 1.1 to 91.2 mg/L), the mean for near lakes was ~ 6.5 times above the mean measured in far lakes for this region (Table 1). These significant differences in water chemistry suggest that the construction and use of the Dempster Highway has had a measurable impact on the near-highway lakes (Fig. 3C, D).

Although most of the near lakes followed a general pattern of elevated conductivity (and related variables), there existed a high degree of variability in water chemistry within the lakes near the road (Fig. 3A, B). For example, three lakes (FM10 [0.05 km], FM05 [0.43 km], and FM15 [0.73 km]) had conductivity measurements (27.3, 11.3, and 13.7 µS/cm, respectively) and calcium concentrations (3.3, 1.1, and 1.8 mg/L, respectively) that were well below the mean of lakes within 1 km of the highway (203 µS/cm and 24.7 mg/L, respectively) and even below the mean of the far lakes (31.4 µS/cm and 3.9 mg/L, respectively). Given the assumption that all of the near sites would be exposed to the same effects from the highway, the low measurements of soluble ion-related variables at these few sites warranted further exploration. Several catchment characteristics were examined to better understand this variability (catchment area relative to lake area and length of highway within catchments). The amount of solutes entering a lake may be affected by the size of the lake in relation to its catchment area (CA:LA), with lakes having higher CA:LA expected to have a higher input of solutes due to a larger impacted catchment area (Kortelainen, 1993). However, the small lakes that were studied on the Peel Plateau do not follow this trend, with some of the highest conductivity levels recorded in lakes with the smallest CA:LA, and vice-versa (online Appendix Table S2). The short length of the PCA arrow for this supplementary variable (Fig. 4) suggested that CA:LA had a weak association with the water chemistry in our study lakes. We also explored the possibility that the length of the highway that transects a lake's catchment may have an effect on water chemistry (Fig. 4). Although the length of highway within a lake's catchment was quite small for this set of lakes (0 to 2.5 km), the PCA ordination suggested that this catchment factor might have exerted some effect on water chemistry. Lakes with the highway in their catchments may receive additional solutes from road runoff passing through slow-flowing wetlands, even though we actively avoided sampling sites with well-defined drainage tracts leading from the highway. However, plots of highway length in lake catchments and ion-related variables (conductivity, pH, alkalinity, Ca) did not reveal a strong pattern (data not shown). For example, two lakes with the greatest length of road occupying its catchments (FM03 and FM10 = 1.32 km) showed very different levels of conductivity, and FM03 showed substantially greater levels (448.5 µS/cm) than FM10 (27.3 µS/cm) (online Appendix Table S2). Although there was a general positive relationship, the length of highway occupying the catchment did not clearly account for the variability in water chemistry observed in the near lakes.

Other factors that could account for some of the variability observed in conductivity and related measurements among near lakes include differences in vegetation stature (e.g., tall shrubs and trees versus low-lying shrubs) and soil development. For example, it is possible that a higher density of trees and more prolific shrub growth surrounding the study lakes can lead to the development of thicker organic soils, resulting in less interaction with underlying mineral soils (and therefore lower major ion concentrations in the lake) than more poorly developed soils of the shrub tundra sites present throughout the Peel Plateau. Additionally, the presence of the Dempster Highway may have contributed to the proliferation of shrub tundra vegetation of much greater stature than is typical elsewhere on the Peel Plateau (Gill et al., 2014). The presence of taller vegetation such as trees and tall shrubs within a lake's catchment may trap airborne dust away from the lake, initially decreasing the amount of material entering the lake. Dust trapped in this manner could eventually be washed into the lake, although likely at a reduced rate as it filters through the low-lying marshes of the region. While our sampling strategy was designed to minimize the potential confounding effects of different vegetation types, there were a few near lakes at lower elevations that had trees surrounding parts of the lake catchments (FM10 and FM11, in particular). However, these two near-highway lakes had conductivity values that were distinctly different from each other. FM10 (conductivity = 27.3 µS/cm) was surrounded by tall shrubs and was also one of the few sites where numerous coniferous trees occurred around the lake. FM11 was also noted for the presence of large shrubs in its catchment, but in contrast, had a higher conductivity value (194.5 µS/cm) that was comparable to the near-highway lake mean (203 µS/cm). The contrast in water chemistry of these two sites makes it unclear whether the presence of tall vegetation surrounding the lake has any affect on the delivery of road dust. It would be beneficial for future studies to assess the rate of dust deposition at sites with varying vegetation coverage.

Lakes near the highway in the study site also generally had higher elevations than the far lakes. However, vegetation cover, underlying geology, and permafrost development did not vary greatly with this small elevation gradient in this region. Therefore, the clear positive relationship between conductivity and elevation was likely because of the proximity of these lakes to the highway rather than elevation-driven variability. These results suggest that, for the small lakes sampled on the Peel Plateau, the relationship between catchment characteristics and lake water chemistry is not straightforward. Although we can eliminate several potential explanations related to catchment characteristics, it remains difficult to identify mechanisms that could explain why the chemistry of a few of the lakes proximal to the road do not follow the expected pattern of exposure to calcium-rich road dust that the majority of the near lakes experienced.

Downcore Trends in Diatoms and Primary Production

Prior to the construction of the Dempster Highway in our study region (pre-1960), diatom assemblages in the three lakes chosen for paleolimnological analyses were dominated by small, benthic fragilarioid taxa. These taxa are often considered to be "pioneering" species that are capable of becoming established and proliferating under a wide variety of environmental conditions (i.e., generalists). When dominant in Arctic and alpine systems, they have been associated with periods of colder temperatures and longer seasonal ice cover (Smol, 1988; Lotter and Bigler, 2000). The absence of notable trends in diatom assemblages, the S:D index, and chl-*a* concentration trends in the pre-1960 record for the two shallow near-highway sites suggest that prior to the onset of accelerated regional warming and road construction, these Subarctic lakes experienced little ecological disturbance and remained relatively stable. In contrast, the somewhat deeper FM06 site records an increase in *Cyclotella ocellata* abundance (maximum ~ 35%) relative to the small benthic fragilarioid and naviculoid taxa between circa 1905 and circa 1935. Together with a brief increase in sedimentary chl-*a* circa 1905, this trend suggests a change in the aquatic environment over this relatively short time period. The arrival and increase in abundance of small, cyclotelloid taxa are often associated with warming, decreasing ice cover, and enhanced thermal stability of the water column, partly because their high surface area to volume ratio provides competitive advantages by reducing sinking velocity and enhancing their ability to harvest light and acquire nutrients (Pannard et al., 2008; Winder et al., 2009). However, regional paleoclimatic reconstructions (Porter et al., 2013) and instrumental records from the Mackenzie Delta region (Fig. 2A, B) show no evidence that this was a particularly warm period in the region, and the available meteorological data cannot explain the brief rise in *C. ocellata* in FM06 between circa 1905 and circa 1935.

As both the construction of the Dempster Highway in our study region and the onset of rapid regional warming occurred around the late-1970s, one might expect that the most notable responses in our biological proxies would begin shortly after that time. However, diatom assemblage compositions at the two shallow sites near the road have remained remarkably stable throughout the sedimentary record, and only minimal diatom assemblage changes were noted (Figs. 6, 7). Although the two sites chosen for detailed diatom analyses had conductivity levels (155.5 and 92.9 µS/cm) that were higher than any of the far sites, these levels are still low compared to conductivity changes that elicit a response in diatom assemblages (Fritz et al., 2010) and therefore were likely not high enough to elicit a threshold-type response by the diatoms, as has been noted in other high-latitude lakes as a response to regional warming (Rühland et al., 2008; Thienpont et al., 2013). These types of responses are often characterized by gradual trends initially, followed by much greater rates of change as an ecological threshold is crossed. The dominant benthic taxa that comprise the assemblages of the shallow FM02 and FM04 sites are generalists in nature, particularly the *Fragilaria* s.l. taxa, and are able to thrive in a wide range of environmental conditions. Given the relatively low modern-day levels of conductivity and major ion concentrations measured at these sites, the impact of the highway may not have yet reached a magnitude large enough to elicit a change in these opportunistic, benthic taxa that dominate the assemblages of these near sites.

Despite the relatively muted diatom compositional changes recorded in the two near sites, there were some changes that are nevertheless worth noting. For example, diatom assemblages in FM02 became more species-rich after circa 1968, with subtle changes among the various dominant fragilarioid taxa (Fig. 6). It is unlikely that these diatom compositional changes were in response to increased conductivity levels (currently ~ 156 µS/cm at FM02) resulting from calcareous road dust deposition, as taxa representing the most recent assemblages do not have substantially higher optima for conductivity than the pre-highway assemblages. For example, based on a calibration set of 70 lakes in the central Canadian Subarctic (Rühland, 1996), the declining taxon of FM02, *S. pinnata*, was estimated to have a relatively low conductivity optimum of 47.1 µS/cm that was comparable to optima for taxa that were increasing in abundance such as *Staurosira construens* var. *venter*, *Sellaphora seminulum*, and *Diploneis oculata* (estimated conductivity optima of 56.9, 13.4, and 32.1 µS/cm, respectively). It is unlikely that the subtle increases in the abundances of the new arrivals were the result of modest increases in conductivity from road dust at this site.

Instead, the pronounced diatom compositional changes in the deeper and farther lake (FM06) and the more muted changes in the shallow FM02 site were more consistent with previous studies assessing warming-related changes to lake properties and increased aquatic habitat availability (Smol and Douglas, 2007a; Rühland et al., 2015). In high-latitude lakes, shorter periods of ice cover and longer and warmer growing seasons can have profound effects on diatom communities. In deeper Subarctic lakes for example, these changes can result in increased thermal stability and associated water column changes that have been shown to result in a shift in diatom life strategy from benthic or tychoplanktonic to planktonic taxa (Rühland et al., 2003; Thienpont et al., 2013), as we observe in our far site, FM06. In shallow lakes and ponds of the Arctic, reduced ice cover and a longer growing season can promote aquatic vegetation growth, providing more diverse aquatic habitats that result in an increase in the complexity and richness of diatom assemblages (Smol et al., 2005, Smol and Douglas, 2007a), as we observe in FM02.

The diatom assemblage shift in FM06 was marked by increases in pennate planktonic taxa such as *Asterionella formosa*, *Fragilaria nanana*, *F. tenera*, *Tabellaria fenestra,* and *T. flocculosa* (Fig. 8). Many deeper lakes in northern latitudes often exhibit a shift in diatom life strategy from benthic or tychoplanktonic to planktonic taxa that is indicative of a threshold-type response to amplified warming (Smol et al., 2005; Axford et al., 2009). The increase in the relative abundance of planktonic *A. formosa* above trace levels circa 1984, with further increases in the early 2000s to above 20%, is similar to diatom assemblage shifts observed in deep, undisturbed lakes from the nearby Mackenzie Delta region, where 20th century regional warming has been identified as the main driver of this assemblage shift (Thienpont et al., 2013). Comparable trends were noted in these reference lakes where a slow initial increase in pennate planktonic diatom abundance beginning circa 1900 was followed by more abrupt shifts as regional temperatures increased starting circa 1970 (Thienpont et al., 2013).

Asterionella formosa has previously been linked to increased nutrient concentrations and is considered to be sensitive to increased nitrogen inputs (Wolfe et al., 2003; Hundey et al., 2014). Where recent and widespread occurrences of *A. formosa* elsewhere can often be explained by increased nutrients (Hobbs et al., 2010; Hundey et al., 2014), recent work throughout Ontario (Hadley et al., 2013; Sivarajah et al., 2016) and the Northwest Territories (Thienpont et al., 2013) has reported notable increases in this taxon in the absence of nutrient increases and was instead more closely linked to periods of amplified regional warming. This is particularly underscored in lakes of remote Subarctic regions, such as FM06 and other reference lakes in the Mackenzie Delta region (Thienpont et al., 2013) that do not experience human development within their catchments. Undisturbed lakes in this region are naturally relatively rich in nutrients (FM06: TP = 22.0 µg/L; Thienpont et al. (2013) reference lake 7a: TP = 40.1 µg/L) and may therefore be predisposed to favour nutrient-sensitive *A. formosa* in response to recent warming (Rühland et al., 2015). Warmer temperatures, the lengthening of the growing season, and subsequent changes in water column properties such as increased thermal stability tend to favour diatom taxa that have high surface area to volume ratios and relatively low sinking velocities (such as *A. formosa*), providing them with a more efficient means of light harvesting and nutrient uptake (Litchman et al., 2007; Winder et al., 2009). Even though the shallow, near-highway sites (particularly FM02) recorded only a muted diatom response, the nature of these changes were nevertheless consistent with a shift towards a more complex diatom assemblage that has been reported as a warming response throughout the circumarctic (Smol et al., 2005). For example, the appearance of new taxa to the FM02 diatom record included *Diploneis* as well as *Nitzschia perminuta*, the latter being a taxon that has undergone recent increases and has been referred to as one of the most ubiquitous diatoms recorded in the modern sediments of the Canadian Arctic (Antoniades et al., 2005; Keatley et al., 2008).

An increase in the number of periphytic diatom species that exhibit more complex life habits (e.g., attached to a variety of different substrates) has been attributed to an increase in the ice-free period, which allows for the establishment and proliferation of aquatic mosses and macrophytes (Smol et al., 2005; Smol and Douglas, 2007a). As expected, the diatom responses to regional warming exhibited in our shallow Peel Plateau sites (particularly FM02) were not as pronounced as the clear shifts observed in High Arctic shallow lakes and ponds. The lower latitude near lakes of our study region have likely long experienced extended and complete ice-free periods during the summer and therefore have supported pre-warming diatom assemblages that were more complex and diverse (e.g., small *Navicula* s.l. and *Achnanthes* s.l. taxa in FM02 and FM04) than pre-warming assemblages from shallow lakes in the High Arctic (as reviewed in Rühland et al., 2015). While there was no discernable diatom trend in FM04, the subtle increase in species diversity observed in FM02 suggests an ongoing assemblage response to regional warming (Smol and Douglas, 2007a).

The chl-*a* trends recorded in the sediment cores support our interpretation that regional warming has played a role in the subtle diatom compositional changes observed in FM02. Increases in chl-*a* levels have been used to track increased aquatic primary production linked to warming and reductions in ice-cover (Michelutti et al., 2010; Michelutti and Smol, 2016), as longer growing seasons may allow more time for the growth of algal populations, resulting in higher concentrations of chl-*a* in the sedimentary record (Nelligan et al., 2016; Paterson et al., 2017). The increase in the trend in chl-*a* in FM02 corresponds to the onset of increases in Hill's N2, beginning circa 1984, as FM04 displayed a more gradual increase over the record with a small acceleration of this trend post-1980s (Fig. 7).

Similar to trends reported by Thienpont et al. (2013), further evidence to support a biological response to regional warming was the increase in the S:D index for the far lake FM06, where the S:D index exceeded 50% after circa 1998 and chrysophyte scales remained dominant throughout the top of the core (Fig. 8). Increases in the relative abundance of scaled chrysophytes have been linked to declines in vertical water column mixing and periods of greater thermal stratification (Paterson et al., 2004; Ginn et al., 2010; Michelutti et al., 2015) because the limited mobility provided by their flagella allow certain chrysophyte taxa to migrate towards areas of greater nutrient and light availability in the stratified water column (Raven, 1995). Trends in the S:D index add to the narrative for climate change effects in the reference lake, as increases in scale abundance followed similar timing to the onset of accelerated regional warming. Meanwhile, the near-highway lake FM04 also marked a steady increase in chrysophyte scales post-circa 1980 with the S:D index reaching ~ 20% in the uppermost interval (Fig. 7). While the S:D index trend in FM06, a relatively deep lake, is likely related to the development of thermal stratification, FM04 is a shallow lake (~ 2.95 m) and was not expected to develop strong thermal stratification. Instead, the increase in chrysophyte scale abundance (composed predominantly of *Mallamonas crassisquama*) may be in response to increasing conductivity levels, as this taxon has a relatively high conductivity optimum of approximately 121 µS/cm (Siver, 1993). While chrysophytes have been used to reconstruct past conductivity levels in lake sediment records, the detailed enumeration of chrysophte scales was not a priority of this study, and it was difficult to determine whether the main driver of this trend was an increasing trend in conductivity.

CONCLUSIONS

While water chemistry from the 28 lakes studied in the Peel Plateau region exhibited a relatively high degree of variability, the majority of lakes within 1 km of the Dempster Highway were chemically distinct from lakes farther from the highway. With the exception of three sites, lakes within 1 km of the highway had significantly higher levels of calcium and conductivity (and related variables) than lakes farther from the highway, which suggests that calcareous road dust from the highway impacts the chemistry of these shallow lakes. The effect of catchment characteristics (e.g., ratio of catchment area to lake area and amount of catchment occupied by road) were not found to be important variables in explaining the trends in water chemistry in these small lakes or the variability in ionic strength at sites near the highway. The general trend for our Peel Plateau sites is in agreement with what was observed in earlier studies along the Dalton Highway in Alaska. However, because of gaps in lake sampling between 1 and 5 km from the highway, we cannot accurately determine the distance at which the delivery of dust to the lakes ceases to be important in our Peel Plateau study (in Alaska, this was found to be within 300 m of the highway).

We found no evidence for a clear algal response to dust deposition from the Dempster Highway using our paleolimnological approaches, even though conductivity levels in near-highway lakes FM02 and FM04 were distinctly higher than lakes located farther away from the Dempster Highway. We suggest that road dust did not result in a large enough increase in conductivity levels to have elicited a notable response in these shallow lakes that were dominated by generalist benthic diatom taxa. The subtle changes in the diatom assemblages of the near sites over time do not appear to be linked to water chemistry changes from road dust deposition. Instead, the collective trends in the diatoms, chl-*a*, and S:D index values from our three sedimentary records provide evidence that regional warming has affected these lakes in the past few decades. Although the diatom responses to warming are muted in our shallow near-highway lakes, the nature of these changes is consistent with longer open-water periods and the associated development of new shallow lake habitats. The diatom response to warming was most clearly expressed in our deeper site farther from the highway and is consistent with weaker mixing and increased thermal stability of the lake. An increase in primary production in all lakes and the appearance and increase in scaled chrysophytes in the reference lake supports the premise that warming has had an affect on these lakes post-circa 1980.

APPENDIX 1

The following supplementary materials are available online:

FIG. S1. Wind rose generated from a weather station situated on the Peel Plateau.

FIG. S2. Sedimentation rates and associated errors derived from the CRS model for the study lakes FM02, FM04, and FM06 plotted against the ^{210}Pb-estimated CRS dates.

TABLE S1. Pearson's correlation matrix of measured environmental variables for 28 study lakes.

TABLE S2. Summary of physical and geographical variables and general water chemistry variables measured in the 28 lakes (19 August 2014 and 20 August 2015).

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