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The impact of Ca-rich diamond mining effluent on downstream cladoceran communities in softwater lakes of the Northwest Territories, Canada

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Abstract

Effluent from diamond mining operations rich in calcium (Ca) has transformed softwater tundra lakes in the Northwest Territories, Canada. Lakes downstream of the Dominion Diamond Corporation Ekati Mine have experienced marked changes in water chemistry and cladoceran community composition since establishment of the mine in 1998. The greatest changes have occurred at the sites closest to the effluent discharge, with [Ca] increasing from < 1 mg L^{-1} to $>$ 30 mg L^{-1}, and corresponding increases in pH from < 7 to > 8. A split was identified in the cladoceran communities with *Holopedium glacialis* (a jelly-clad cladoceran tolerant of low [Ca]) generally dominating the cladoceran community at [Ca] < 2.5 mg L^{-1}, while in impacted lakes with [Ca] ≥ 2.5 mg L^{-1}, *Daphnia longiremis* and *D. middendorffiana* (taxa with higher [Ca] requirements) were often dominant. In contrast, the three study lakes that did not receive mining effluent maintained stable and low [Ca] (mean [Ca] = 0.66 ± 0.06 mg L^{-1} (stdev)) throughout the monitoring period, and have not experienced directional shifts in their cladoceran communities.

Introduction

The Barren Lands of the eastern Northwest Territories and Nunavut territory of Canada is mainly a rocky, undulating landscape that hosts numerous irregular-shaped lakes. The few available limnological surveys suggest that the lakes of the Barren Lands are generally oligotrophic and dilute (Pienitz et al. 1997; Rühland and Smol 1998) softwater systems, with calcium concentrations ([Ca]) < 1.5 mg L^{-1} and pH levels ranging from 5.5 to 8.6 (Pienitz et al. 1997; Rühland and Smol 1998). This remote landscape is also the location of Canada's richest producing diamond mines.

Canada's first diamond mine, the Ekati Mine, is located in the eastern Barren Lands (Figure 1). Operations began at Ekati in 1998, under BHP Billiton Canada Inc., but since 2012 it has been owned and operated by Dominion Diamond Corporation (DDC Ekati). Diamond mines in the Northwest Territories conduct Aquatic Effects Monitoring Programs (AEMP) to identify effects of the mining process and waste deposition on downstream water bodies. The effluent from DDC Ekati mining activities is characterized by elevated concentrations of the major ions SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, K^+, and HCO_3^- (Rollo and Jamieson 2006), and nitrogen (N) derived from N-based explosives used in mining activities (Bailey et al. 2013). The DDC Ekati monitoring program collects data on water quality, zooplankton communities and a variety of other parameters (e.g. metal concentrations, phytoplankton, lake benthos) from lakes downstream of the facility, as well as from several lakes both inside and outside the Koala watershed that are unaffected by diamond processing effluent. The Ca-rich nature of the effluent is of particular interest, given its transformative potential for lakes in the surrounding low alkalinity landscape.

Ca is an essential nutrient, and widespread Ca declines in other softwater regions of North America have been associated with ecologically significant changes in crustacean zooplankton communities, due to inter-specific differences in sensitivity to aqueous Ca among crustacean zooplankton (Jeziorski and Smol 2016; Jeziorski et al. 2008). For example, large-bodied species of *Daphnia* (with relatively high Ca content (Jeziorski and Yan 2006)) have decreased in regions experiencing marked Ca decline (falling below [Ca] < 1.5 mg L^{-1}) (Jeziorski et al. 2008) and at many of these sites, *Daphnia* are being replaced by jelly-clad *Holopedium glacialis* Rowe, Adamowicz & Hebert (Jeziorski et al. 2015), a similar-sized cladoceran that has a mucopolysaccharide jelly sheath instead of a heavily calcified carapace as its primary predatory defense, and thus lower Ca content (Jeziorski and Yan 2006). However, a recent study that explored the DDC Ekati monitoring dataset for potential effects of the mining effluent on the downstream lakes did not detect directional shifts in functional groups of crustacean zooplankton (the functional groups were defined based on trophic position, feeding type, and relative swimming speed) in response to the mining effluent (St-Gelais et al. 2017). Given the sensitivity of several cladoceran taxa to Ca availability, the lack of a detectable response to mining effluent among the downstream crustacean zooplankton functional groups was surprising. As St-Gelais et al. (2017) assessed biomass changes across all the crustacean zooplankton, and as copepods were by far the dominant taxonomic group in most of the monitored lakes (BHP 1994; ERM 2014; 2015; Rescan 1996, 1997a, b, 1998, 1999, 2000, 2001, 2002, 2003, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013), an analysis of biomass fluctuations due to between-site differences and inter-annual variation focused on changes within the crustacean zooplankton communities as a whole, and as such may have not identified some fundamental changes occurring among the cladoceran taxa. To explore the DDC Ekati AEMP dataset in greater detail, we used water chemistry and community species count data to calculate relative abundances (removing the effect of biomass fluctuations) of cladoceran taxa to examine the potential impacts of diamond mine effluent and to address the following questions: 1) Have the relative abundances of specific taxa within the cladoceran communities downstream of the mine changed in response to the Ca-rich effluent?; if so, 2) What are the spatial and/or temporal trends in the response?; and 3) How do the cladoceran community changes in these softwater tundra lakes compare with the impacts of [Ca] changes in other softwater lake regions?

Site Description

The Barren Lands (or Barren Grounds) is an Arctic-tundra region extending north of the treeline from the eastern Northwest Territories into Nunavut, towards the Hudson Bay coastal plains (Figure 1). The low-lying topography of the Barren Lands is characterized by thin soils with irregular bedrock outcrops. The tundra vegetation includes shrub birch (*Betula glandulosa*), alder (*Alnus* spp.), willow (*Salix* spp.), grasses, forbs, mosses, lichens and peat deposits (Huang et al. 2004).

The DDC Ekati diamond mine facilities (Figure 1) are located in the Barren Lands within the Koala watershed and include the Koala Pit, Northern Koala Pit, Panda Pit, Fox Pit, and Beartooth Pit, where kimberlite pipes are processed in both underground and open pit mines.

Effluent from the kimberlite processing is released into the Long Lake containment facility, where, following treatment, it flows through a chain of lakes including Leslie Lake, Moose Lake, Nema Lake, and Slipper Lake (listed in increasing distance from the Long Lake containment facility), which are regularly sampled as part of the DDC Ekati AEMP. The drainage ultimately discharges into the northwest arm of Lac de Gras (LDG), where the AEMP sampling sites S2 and S3 are located (Figure 1). The DDC Ekati AEMP also monitors three lakes that do not receive diamond mining effluent as reference sites: Vulture Lake (located upstream of the mine within the Koala watershed), and the more distant Nanuq Lake and Counts Lake (Figure 1). In addition to the DDC Ekati Mine operations described here, the nearby Diavik diamond mining operation is also located on Lac de Gras (Figure 1), although discharge from Diavik occurs more than 40 km east of the S2 and S3 sampling sites.

The bedrock geology of the study region is primarily composed of volcanic and meta-sedimentary geological units. The northwest arm of LDG and Vulture Lake are located on a cordorite and andalusite meta-greywacke (Kjarsgaard et al. 1994a) and Leslie Lake, Moose Lake, Nema Lake, and Slipper Lake catchments are predominately comprised of quartz diorite, a resistant silicate bedrock (Kjarsgaard et al. 1994a). Meanwhile the more remote reference sites, Counts Lake and Nanuq Lake, are situated on a muscovite-biotite granite (Kjarsgaard et al. 1994b, Kjarsgaard and Wyllie 1993). Based on the bedrock geology, it would be expected that the reference Vulture Lake and the Northwest Arm of LDG may receive a greater input of Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and HCO_3^- from the more-easily weathered calcareous bedrock, relative to the sites with catchments primarily comprised of silicate bedrock. The surficial till is generally less than 2 m thick with regular bedrock outcrops. The till is derived from granitoid rocks and the

Yellowknife Supergroup and, therefore, is not a likely source of Ca ions. The catchments of Slipper Lake and Vulture Lake contain areas of 5-30 m thick tills of the same composition (Ward et al. 1997). Reference sites Vulture, Nanuq, and Counts Lakes were oligotrophic and dilute in the most recent published AEMP data from the summer 2014 sampling season (Table 1). In contrast, the sites receiving discharge water generally had higher conductivity and nitrate concentrations than the reference sites (Table 1). Data from the DDC Ekati AEMPs were only accessible from the Wek'eezhii Land and Water Board public registry for the years 1994, 1996, 1997 (water chemistry only), and 1998-2014.

Methods

Methods for water quality and zooplankton sampling and analyses conducted for DDC Ekati are detailed in the annual AEMP reports (BHP 1994; ERM 2014, 2015; Rescan 1996, 1997a, b, 1998, 1999, 2000, 2001, 2002, 2003, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013), and water chemistry and cladoceran taxonomic abundance data were transcribed from these reports (the exception being 1997, as zooplankton species counts were not available). In brief, water quality samples were obtained on two occasions during the open water period in 1994 (July and August), once in 1996 (late July), once in 1997 (early Aug), on five occasions during the open water period in 1998 (once in late June, twice in July, and once in both August and September), on three occasions during the open water period from 1999 to 2009 (July, August, and September), and on one occasion from 2010 to 2014 (either late July or early August). Any modifications to sampling protocols are detailed in the annual AEMP reports (BHP 1994; ERM 2014 2015; Rescan 1996, 1997a, b, 1998, 1999, 2000, 2001, 2002, 2003, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013). On each sampling occasion, water was obtained from at least two depths, at the surface (0 m for 1994, 1996, 1997; or 1 m 1998-2014) and at a mid-depth. As the middle depths varied with lake morphometry, only water chemistry samples taken at 0-1 m depth were used in this analysis.

Zooplankton samples were collected at least once a season, in mid-summer (July-August), using a conical 0.3 m diameter, 118 µm mesh zooplankton net, pulled through the water column from approximately ~1-2 m above the lake bottom to the surface. Zooplankton samples were subsampled, enumerated, and identified to the lowest possible taxonomic level (for detailed methods see BHP 1994; ERM 2014, 2015; Rescan 1996, 1998, 1999, 2000, 2001, 2002, 2003, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013). Leslie Lake, Moose Lake, Slipper Lake, and Vulture Lake were sampled for zooplankton in 1994. Moose Lake, Nema Lake, Slipper Lake, and Vulture Lake were sampled regularly from 1996-2014, while zooplankton count data are available for the reference Counts Lake and Nanuq Lake from 1998-2014. Site S2 and Site S3 in Lac de Gras were not included in the monitoring program until 2000, and so no data are available for these sites in the early years of the mine's development. Leslie Lake was added to regular zooplankton sampling from 2003-2014.

Cladoceran relative abundances were calculated from the DDC Ekati zooplankton taxonomic data for 1994, 1996, and from 1998-2014. The primary partitions in the relative abundances of the cladoceran taxa from all lakes, including the reference sites and for all years for which data were available, were assessed as a function of mid-summer (late July-August) [Ca] and pH (for all lakes and for all available sampling years) using multivariate regression trees (MRT) and discriminant species analyses (De'Ath 2002) via the “mvpart” package (Therneau et al. 2014) and “MVPARTwrap” (Ouellette and Legendre 2013) for the R software environment (R Core Team 2013). The regression tree selected from the MRT analysis was the most parsimonious tree within one standard error of the tree with the lowest cross-validated relative error (Borcard et al. 2011). Unpaired, one-sided, 2 sample Wilcoxon tests were used to identify whether the mean relative abundances of *Holopedium* or *Daphnia* significantly differed between the groups identified in the MRT analyses.

Results

The monitoring data reveal a pronounced Ca gradient, with lakewater [Ca] from 2003-2014 decreasing as distance from the discharge location increases: from Leslie Lake (mean [Ca] ~ 21.2 mg L^{-1}), through Moose Lake (mean [Ca] ~ 19.5 mg L^{-1}), Nema Lake (mean [Ca] ~ 9.9 mg L^{-1}), Slipper Lake (mean [Ca] ~ 4.4 mg L^{-1}), to the northwest arm of LDG (sites S2, mean [Ca] ~ 2.2 mg L^{-1}; and S3, mean [Ca] ~ 1.4 mg L^{-1}) (Figure 2). In contrast, the three reference lakes had stable and low [Ca] (mean [Ca] = 0.66 ± 0.06 mg L^{-1} (stdev)) throughout the monitoring period. From 2003-2014, the mean [Ca] in the reference lakes were: Counts Lake, mean [Ca] = 0.67 ± 0.03 mg L^{-1} (stdev); Nanuq Lake, mean [Ca] = 0.69 ± 0.05 mg L^{-1} (stdev); and Vulture Lake, mean [Ca] = 0.68 mg L^{-1} ± 0.02 mg L^{-1} (stdev)) (Figure 3a). In addition to the spatial gradient, [Ca] have markedly increased over time in the lakes downstream of the effluent release (Figure 3), regularly reaching [Ca] > 25 mg L^{-1} at the two most impacted sites (Leslie Lake and Moose Lake). In contrast, prior to mine development (1994, 1996-1998), the monitored lakes receiving discharge from the Long-Lake containment facility were similar in [Ca] to the reference lakes (Figure 3a), with values typically below 1 mg L^{-1}. The pH at all sites was < 7.1 prior to 1999, and has generally increased at the impacted sites, with Leslie Lake reaching a pH of 8.05 in 2014, although there is considerable variability in the records (Figure 3b). At the reference sites pH has also increased, notably from 2012 to 2014, with pH increases from 6.4 to 7.6 in Counts Lake, 6.6 to 6.7 in Nanuq Lake, and 6.5 to 7.1 pH units in Vulture Lake (Figure 3b).

Prior to 1999, when [Ca] at the monitored downstream sites (Leslie Lake, Moose Lake, Nema Lake, and Slipper Lake) were still low and the pH was below 7, the cladoceran communities contained or were dominated by either *Holopedium glacialis* (previously *H. gibberum* Zadach) or by small-bodied *Bosmina*, with *Daphnia* spp. in generally low abundances (Figure 4). However, from 1999 onwards, after the mine development, *Holopedium glacialis* largely disappears from the downstream lakes (with *Holopedium* falling to < 5% relative abundance by 2003 (or before, as the lake was not sampled between the onset on mining in 1998 and 2002) in Leslie Lake, 2002 in Moose Lake, 2003 in Nema Lake, and 2005 in Slipper Lake). The cladoceran communities of the lakes closest to the discharge location (Leslie Lake, Moose Lake, Nema Lake, and Slipper Lake) come to be largely dominated by *Daphnia* species (large-bodied *D. middendorffiana* Fisher, and intermediate-sized *D. longiremis* Sars (Peterson et al. 1978)), while the more remote sites in LDG (Site S2, and Site S3) and reference lakes generally remain dominated by *H. glacialis* (Figure 4).

The decline in *Holopedium* is also evident in the absolute counts of Cladocera in the zooplankton net tows, as *Holopedium* populations are largely undetected in Leslie Lake, Moose

Lake, Nema Lake, and Slipper Lake after 2004-2005 (Figure 5). The response of *Daphnia* absolute counts is more complex, with some variation in magnitude and timing of the daphniid increases relative to the *Holopedium* declines across lakes (Figure 5). The *Daphnia* increases in Leslie Lake, Moose Lake and Nema Lake are largely concurrent with the *Holopedium* decline, with the exception of a large bloom of *Daphnia* in 1998-1999 in Moose Lake that pre-dated the collapse of the *Holopedium*. Slipper Lake does not appear to show any marked response in the absolute counts of *Daphnia* (Figure 5).

Multivariate regression tree analyses were applied to partition the cladoceran relative abundance data as a function of [Ca] (Figure 6a) and pH (Figure 6b). For Ca, the primary split occurred at [Ca] = 2.5 mg L^{-1}, resulting in a model with a complexity parameter (R^2) = 0.415, a cross-validated relative error = 0.62, and standard error = 0.057. *Holopedium* was identified by discriminant species analysis to be a significant ($p = 0.001$) indicator species (indicator value = 0.9321) when [Ca] < 2.5 mg L^{-1} and *Daphnia middendorffiana* was a significant ($p = 0.001$) indicator species (indicator value = 0.7069) when [Ca] ≥ 2.5 mg L^{-1}. The mean relative abundances were significantly higher ($p < 0.001$) for *Holopedium* when [Ca] < 2.5 mg L^{-1} than when [Ca] ≥ 2.5 mg L^{-1} (Figure 7a, mean *Holopedium* relative abundance where [Ca] < 2.5 mg L^{-1} is 70 ± 30 % (stdev), n = 101; mean *Holopedium* relative abundance where [Ca] ≥ 2.5 mg L^{-1} is 3 ± 12 % (stdev), n = 51). The mean relative abundances were significantly lower ($p < 0.001$) for *Daphnia* when [Ca] < 2.5 mg L^{-1} compared to when [Ca] ≥ 2.5 mg L^{-1} (Figure 7c, mean *Daphnia* relative abundance where [Ca] < 2.5 mg L^{-1} is 21 ± 26 % (stdev), n = 101; mean *Daphnia* relative abundance where [Ca] ≥ 2.5 mg L^{-1} is 78 ± 34 % (stdev), n = 51).

The cladoceran relative abundance data was also partitioned into 2 groups as a function of pH by a MRT analysis (Figure 6b), with the primary split occurring at pH = 7.1, with a complexity parameter (R^2) = 0.344, a cross-validated relative error = 0.73, and standard error = 0.062. *Holopedium* was identified by discriminant species analysis to be a significant ($p = 0.001$) indicator species (indicator value = 0.8908) for the sites where the pH < 7.1 and *Daphnia middendorffiana* was a significant ($p = 0.001$) indicator species (indicator value = 0.7007) in the sites where pH ≥ 7.1. The mean relative abundances were significantly higher ($p < 0.001$) for *Holopedium* when pH < 7.1 than when pH ≥ 7.1 (Figure 7b, mean *Holopedium* relative abundance where pH < 7.1 is 66 ± 33 % (stdev), n = 107; mean *Holopedium* relative abundance where pH ≥ 7.1 is 4 ± 16 % (stdev), n = 45). The mean relative abundances were significantly lower ($p < 0.001$) for *Daphnia* when pH < 7.1 compared to when pH ≥ 7.1 (Figure 7d, mean *Daphnia* relative abundance where pH < 7.1 is 24 ± 29 % (stdev), n = 107; mean *Daphnia* relative abundance where pH ≥ 7.1 is 78 ± 34 % (stdev), n = 45).

Throughout the monitoring dataset, pH and Ca concentrations were significantly ($p < 0.001$) positively correlated ($r = 0.89$), with *Holopedium* primarily found at a pH < 7.1 and at [Ca] < 2.5 mg L^{-1} (Figure 8). Due to this strong correlation, only one datum point (Counts Lake in 2014), had both high pH and low Ca, where pH was 7.6 and [Ca] = 0.70 mg L^{-1}. *Holopedium* were present at a relative abundance of 61%, with *Daphnia* at a relative abundance of 28%.

Discussion

Effluent from the DDC Ekati mines has had a striking influence on the water quality of downstream lakes, evident in Ca and pH gradients positively related to proximity to the Long Lake containment facility (Figure 2), and the increase in Ca and pH since mine development at all the study sites receiving effluent (Figure 3). In contrast to the muted response to the diamond mining activity across the entire crustacean zooplankton community (St-Gelais et al. 2017), we identified a marked shift in cladoceran relative abundances within the crustacean zooplankton species assemblage. Prior to mining activities (1994-1998), downstream cladoceran communities closest to the containment facility were generally dominated by *Holopedium glacialis*, but have since experienced increases in the relative abundance of *Daphnia* spp. (Figure 4) concurrent with increasing pH and [Ca] (Figure 3) from the mining effluent.

A strong spatial trend is evident in the composition of the cladoceran assemblages, with *Holopedium* virtually absent (Figure 4 and Figure 5) from those lakes closest to the effluent discharge, while the reference lakes and the monitoring sites within the northwest arm of Lac de Gras (sites S2 and S3) that have maintained relatively low and stable [Ca] (Figure 2, Figure 3), continue to be dominated by *Holopedium* (Figure 4). The monitoring data from prior to the development of the DDC Ekati diamond mine (in 1998) suggest that Leslie Lake, Moose Lake, Nema Lake, and Slipper Lake all had similar water chemistry to that of the reference sites (i.e. [Ca] < 1 mg L^{-1} and pH < 7; Figure 3). The monitoring records also indicate that the cladoceran communities in these lakes have markedly changed, at the species level, since the early years of mine development when the communities were dominated by taxa with low Ca content (*Holopedium glacialis* and *Bosmina* spp.; Jeziorski and Yan 2006). *Holopedium glacialis* is now largely absent from recent monitoring surveys of the four lakes closest to the containment facility, with corresponding increases in the proportions of *Daphnia longiremis* and *D. middendorffiana* (Figure 4), and with marked (Leslie Lake) or moderate (Moose Lake and Nema Lake) increases in *Daphina* absolute abundances (Figure 5).

The general replacement of *Holopedium* by *Daphnia* spp. is likely a response to the alteration of limnological conditions by mine effluent (particularly increases in Ca and pH). *Holopedium* and *Daphnia* spp. are both filter-feeders that graze on an overlapping range of particle sizes (Hessen et al. 1989), with *Daphnia* spp. generally being the more efficient grazers (Allan 1973; Tessier 1986). However, *Holopedium* can outcompete some *Daphnia* spp. at low-nutrient, low-Ca sites, when the pH is below 8 (Hessen et al. 1995), conditions present in the early years of mine development, as well as in the LDG sites and reference lakes. Under these conditions, *Holopedium* may have been better able than the *Daphnia* spp. to exploit the available resources, and dominate the assemblages.

The dominance of *Holopedium* relative to *Daphnia* prior to mine development is likely due to the relatively low Ca requirements of *Holopedium* (Jeziorski and Yan 2006), and their ability thrive in the low Ca conditions (Jeziorski and Smol 2016; Jeziorski et al. 2015; Wærvågen et al. 2002). In contrast, at the start of the monitoring record, Ca levels were generally < 1 mg L^{-1}, below the requirements of many daphniid taxa including *D. longiremis* (that has a field-identified lower Ca threshold of 1.26 mg L^{-1} ; (Cairns 2010). The high Ca requirements of the daphniids are largely due to their Ca-rich carapace, and low aqueous [Ca] can limit their growth, reproduction, and fecundity (Ashforth and Yan 2008). In contrast, *Holopedium* has a much lower Ca burden than some larger daphniid species (Jeziorski and Yan 2006), as rather than a carapace, its principal defense from predators is an enveloping mucopolysaccharide jelly sheath. Low Ca demands and high fecundity relative to daphniids (supplementary material; Jeziorski et al. 2015), allows *Holopedium* to rapidly exploit food resources when daphniid populations are low.

Increased production at the DDC Ekati mines after 1999 resulted in elevated Ca and higher pH levels in the downstream lakes (Figure 3), with a corresponding increase in the proportion of *Daphnia* spp. (primarily *D. longiremis* and *D. middendorffiana* (Figure 4)) in the lakes closest to the discharge location. The marked, negative relationship between [Ca] and *Holopedium* relative abundances (Figure 7a) is most likely an indirect relationship, resulting from increased competition between *Holopedium* and *Daphnia*, with *Daphni*a species able to exploit the new high-Ca environment due to the input of Ca-rich effluent. A structural equation model analyzing long-term monitoring data from lakes in south-central Ontario spanning a similar range of [Ca] indicated that *Holopedium* did not directly respond to changes in lakewater Ca (Jeziorski et al. 2015). Instead, members of *Daphnia* spp. were highly sensitive to falling Ca, and as concentrations fell below threshold values their populations declined, freeing up food resources for *Holopedium* (Jeziorski et al. 2015). The Barren Lands' lakes downstream of the diamond mines have experienced similar changes, but in reverse, with *Daphnia* spp. increasing in relative abundances (Figure 4) and in many cases in absolute abundances (Figure 5), as [Ca] increased, with a corresponding decline in *Holopedium*. In Moose Lake, the disappearance of *Holopedium* was preceded by a large spike in *Daphnia* concentrations in 1998-1999 (Figure 5), which, given their competition for food resources, may have accelerated the virtual elimination of *Holopedium* from the lake. In addition to the increasing [Ca], concurrent changes in the phytoplankton community may have also contributed to the cladoceran community shift in the impacted lakes. Recent increases in the biomass of edible planktonic diatoms within the effluent-receiving lakes (St-Gelais et al. 2017) may also have favoured daphniids over *Holopedium*, as they are generally more efficient algal grazers (Allan 1973, Tessier 1986).

The split identified in the regression tree analysis at [Ca] ~ 2.5 mg L^{-1}, between samples with high relative abundances of *Holopedium* and those with little to no *Holopedium* (Figure 6a, Figure 7a), is slightly above the Ca requirements of *D. longiremis* (1.26 mg L-1; Cairns 2010). Although we are unaware whether the Ca optimum of *D. middendorffiana* has been identified, the general increase in daphniid relative abundances as [Ca] increased above ~ 2.5 mg L^{-1} (Figure 7c) suggests that conditions have become more favorable for both *D. longiremis* and *D. middendorffiana*, allowing these efficient grazers (Allan 1973, Tessier 1986) to outcompete *Holopedium* for resources.

The decrease in *Holopedium* in the impacted lakes was often, but not always accompanied by an increase in the absolute counts of *Daphnia* (e.g. Slipper Lake; Figure 5) suggesting that not only competition from daphniids, but physiological stress from the novel limnological conditions created by the diamond mining effluent may be impacting the *Holopedium*. *Holopedium* populations may be stressed as a result of pH increases concurrent with the [Ca] increases. High pH (pH > 8) conditions can result in increased mortality and reduced fecundity in *Holopedium* (Hessen et al. 1995), and at the DDC Ekati sites *Holopedium* were found at significantly lower relative abundances when pH ≥ 7.1 (Figure 7b). Given the significant correlation (Figure 8) between increasing [Ca] and lakewater pH (Figure 3), it is difficult to distinguish the relative impact of each factor in the study lakes, as the diamond mining effluent has contributed Ca^{2+}, other major ions, and alkalinity to the softwater lakes (Rollo and Jamieson 2006). However, the pH of the lakes is unlikely having direct effects on the *Daphnia* spp., as daphniids are commonly found in circumneutral pH waters similar to that of the downstream lakes prior to the onset of mining. Increasing relative abundance and absolute abundances of daphniids over the monitoring record is most likely due to [Ca] increasing above threshold concentrations. However, the decline in *Holopedium* in these lakes is likely due to a combination of increased competition for food resources with daphniids and increased physiological stress from higher pH and altered limnological conditions.

The changes in [Ca] experienced by the Barren Lands' lakes downstream of DDC Ekati mines are particularly interesting, as they are the opposite to those occurring in many previously-acidified softwater lakes in eastern Canada and the United States (e.g. Jeziorski et al. 2008; Leys et al. 2016) and Scandinavia (e.g. Hessen et al. 2017). During acidification, lakes can lose acid-sensitive *Daphnia* taxa (Malley and Chang 1986; Walton et al. 1982), but even after recovery, the long-term decline in exchangeable cations may still hinder biological recovery (e.g. Keller et al. 2001). Many softwater lakes are experiencing substantial decreases in lakewater [Ca], as a legacy of acid deposition with corresponding decreases in Ca-sensitive daphniids (Jeziorski and Smol 2016) and their replacement by *Holopedium* (Jeziorski et al. 2015; Korosi and Smol 2012). In contrast, the lakes in the Northwest Territories receiving diamond mine effluent are exhibiting the reverse, in a process that mirrors trends associated with liming (Labaj et al. 2014) or an influx of Ca-rich road dust suppressant (Shapiera et al. 2012). The sites downstream of the DDC Ekati mines offer an opportunity to examine the impacts of Ca additions in otherwise undamaged ecosystems (i.e. elimination of fish communities etc. as a result of acidification is not a factor affecting the cladoceran community changes at these sites).

The potential impacts of the cladoceran community shift on other trophic levels are not clear. *Daphnia* typically contain more phosphorus (as percent dry weight) than *Holopedium* (Andersen and Hessen 1991), and furthermore, *Holopedium* and *Daphnia* differ in their composition of polyunsaturated fatty acids (Persson and Vrede 2006). Thus, changes in their relative dominance may alter nutrient transfer throughout food webs. However, selective predation (Arts and Sprules 1988), the vulnerability of *Daphnia* relative to *Holopedium* to invertebrate predation (Vinyard and Menger 1980), and gap-limited predation (Tessier 1986) will also affect how the cladoceran community may influence higher trophic levels. To assess the effects on upper trophic levels within the effluent receiving lakes, continued monitoring of the fish and invertebrate predators will be required. The diamond mining AEMPs in the Barren Lands provide a multi-decadal monitoring record of remote northern lakes, and are a valuable dataset for further work examining lake ecosystems in the Canadian North. The unique circumstances of the naturally dilute and softwater lakes of the eastern Barren Lands receiving Ca-rich effluent, coupled with the regular monitoring conducted by the DDC Ekati Mine, create important records of whole lake manipulation of Ca (and other major ion) inputs, which have implications for the restoration of acidified lakes, and the impacts of cladoceran community changes on foodweb structure and function.

The changes in the cladoceran species composition of lakes downstream of Ekati mines highlight the importance of considering high-level taxonomic data in aquatic monitoring programs. The monitoring record of Lac de Gras (sites S2 and S3, as well as others in the main basin monitored by the Diavik Diamond Mining AEMP (Golder 2016), suggest that, at least within its embayments, this large lake may be approaching [Ca] of 2.5 mg L^{-1} identified in this study as the threshold concentration for *Holopedium* in the upstream lakes closer to the mine. Continued robust monitoring may capture a transition from *Holopedium* to daphniid dominance of the cladoceran community within Lac de Gras, and on a regional level will be important for providing insights on the zooplankton community response to an unusual environmental stress, and provide the data necessary for the development of informed mitigation plans.

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Table 1: Lake parameters and water chemistry data from August 2014, collected by the DDC Ekati AEMP for lakes downstream of mining operations (Leslie, Moose, Nema, Slipper, and both Site S2 and Site S3 in Lac de Gras), as well as the reference lakes (Counts Nanuq, and Vulture).

Site	Latitude (°N)	Longitude (°W)	Surface area (ha)	Max depth (m)	Conductivity (µS cm^{-1})	pH	Nitrate (mg L^{-1})	Total Phosphate (mg L^{-1})	Total Calcium (mg L^{-1})
Leslie Lake	64.6820	110.6969	61	12	830	8.05	2.14	0.0040	22.25
Moose Lake	64.6799	110.6512	43	9.5	526	7.92	0.996	0.0058	14.70
Nema Lake	64.6651	110.7127	78	9.5	408	7.70	0.130	0.0070	12.20
Slipper Lake	64.6121	110.8547	183	14.7	194	7.51	0.0083	0.0056	6.78
Site S2	64.6044	110.8419	56900	5.1	56.4	7.05	0.0117	0.0023	4.45
Site S3	64.6028	110.8731	56900	13.2	49.3	7.05	<0.0050	0.0024	1.90
Counts Lake	64.6510	110.2891	114	10.8	14.1	7.65	<0.0050	0.0090	0.699
Nanuq Lake	64.9146	110.2751	305	28.4	12.1	6.73	<0.0050	0.0053	0.749
Vulture Lake	64.7525	110.5519	174	38.9	13.1	7.18	<0.0050	0.0027	0.718

Figure 1: Map of the study region in the southern Northwest Territories (red box) with yellow stars representing towns and cities around Great Slave Lake, NWT. Inset A shows the Lac De Gras region of the Barren Lands with the location of reference lakes Counts and Nanuq. Inset B shows the primary DDC Ekati diamond mine operation with the study lakes in the Koala watershed, showing the generalized path of flow from the Long Lake Containment Facility (LLCF) marked with an orange line and arrows. Basemap data from Natural Resources Canada Canvec database. Satellite underlay for Inset B from Google Earth imagery.

Figure 2: Open water (June, July and August) Ca concentrations (A) and pH (B) from 2003 (when all sites were regularly monitored) to 2014 for the effluent-receiving lakes Leslie, Moose, Nema, Slipper lakes, Site S2 and Site S3 in Lac de Gras, and reference Counts Lake, Nanuq Lake, and Vulture Lake, from the DDC Ekati AEMP. The whiskers represent 1.5 x the interquartile range (from the 25th to 75th percentiles), while data beyond the end of the whiskers are outliers and plotted as points.

Figure 3: Mid-summer (late July / early August) Ca concentrations (A) and pH (B) over the sampling record for which we have data (1994, 1996-2014) for potentially impacted Leslie, Moose, Nema, Slipper lakes, Site S2 in and Site S3 in Lac de Gras, and reference Counts Lake, Nanuq Lake, and Vulture Lake, from the DDC Ekati AEMP. The markers for Vulture Lake and Nanuq Lake [Ca] are obscured by those for Counts Lake due to the similarity of the three lake's calcium records.

Figure 4: Mean relative abundance of genera and species of Cladocera for Leslie (closest to the mine discharge), Moose, Nema, Slipper lakes, Lac de Gras sites S2 and S3 (farthest from the mine discharge), and reference Counts Lake, Nanuq Lake, and Vulture Lake, from date of first sampling (1994, 1996, 1998 or 2000 depending on the site) to 2014. Samples from 1994 in Leslie Lake, 1994 and 1996 from Moose Lake and Slipper Lake, and 1996 from Nema Lake represent the pre-impact communities as the DDC Ekati mine was established in 1998.

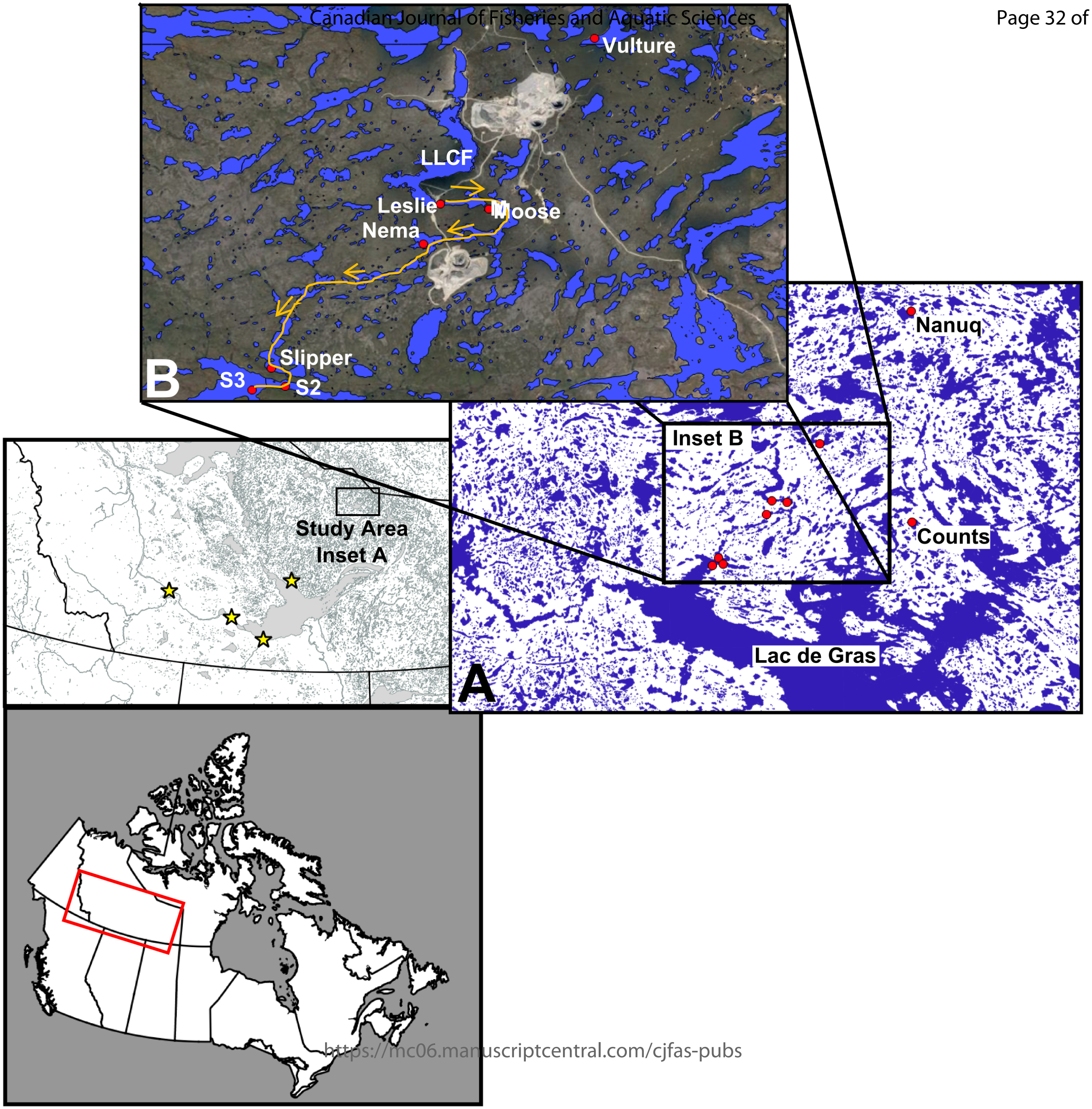
Figure 5: Species counts from water column sampling of *Daphnia* (sum of *Daphnia middendorffiana*, *D. longispina* and *Daphnia* spp.) and *Holopedium glacialis* for all monitored lakes receiving mining effluent (Leslie, Moose, Nema, Slipper lakes, Lac de Gras sites S2 and S3 - from closest to farthest from the mine discharge) from the date of first sampling (1994, 1996, 1998 or 2000 depending on the site) to 2014. Moose Lake is plotted on a log+1 axis to account for a large peak in *Daphnia* abundance in 1998.

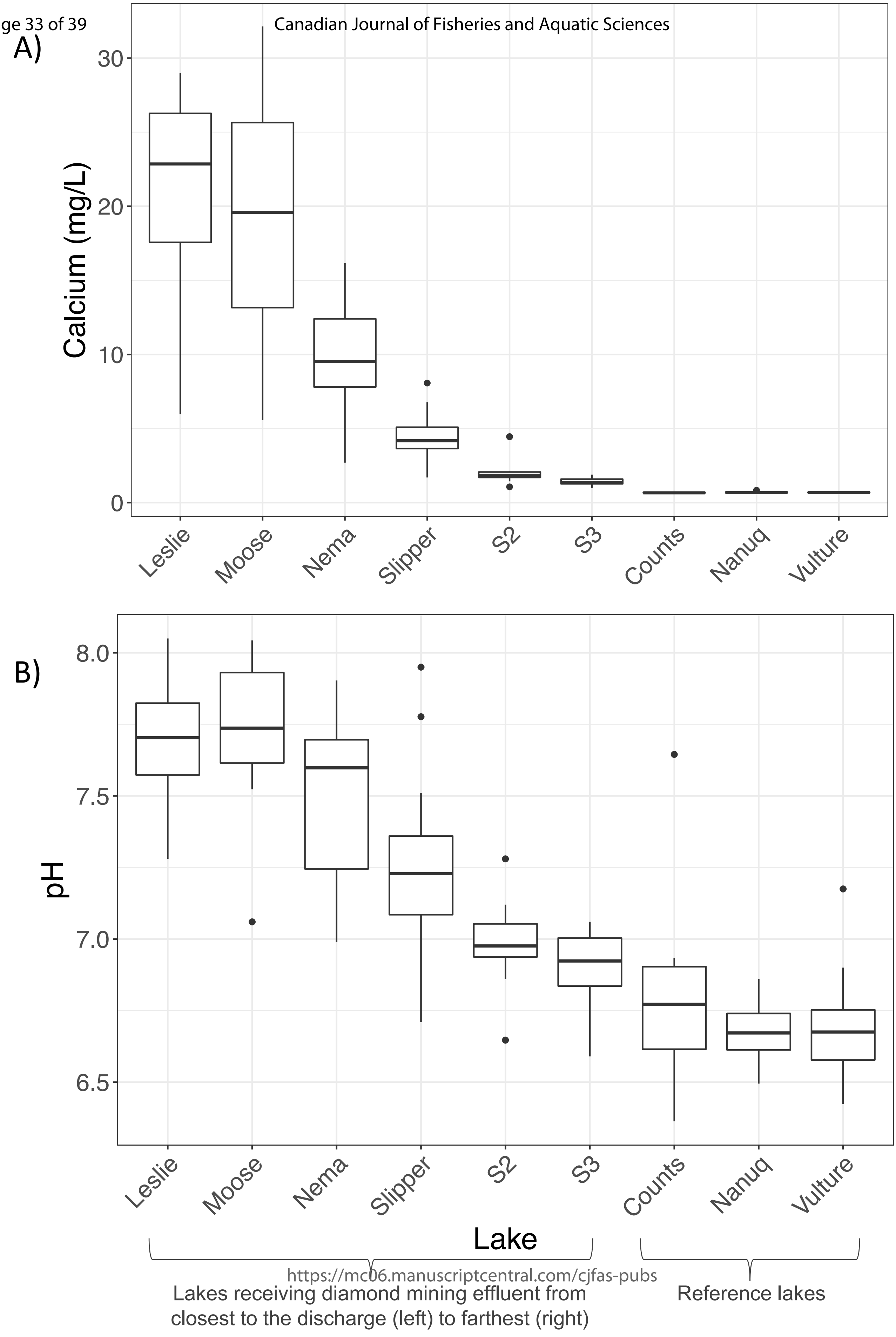
Figure 6: Multivariate regression trees (MRT) partitioning the full species dataset by mid-summer Ca concentrations (A) and pH (B). The MRTs each have one division splitting the sites into two leaves. Box plots show the *Daphnia* and *Holopedium* relative abundances for the sites that fall under each leaf of the MRT. The complexity parameter (R^2), cross-validated error (CV Error) and standard error (SE) are shown for each MRT.

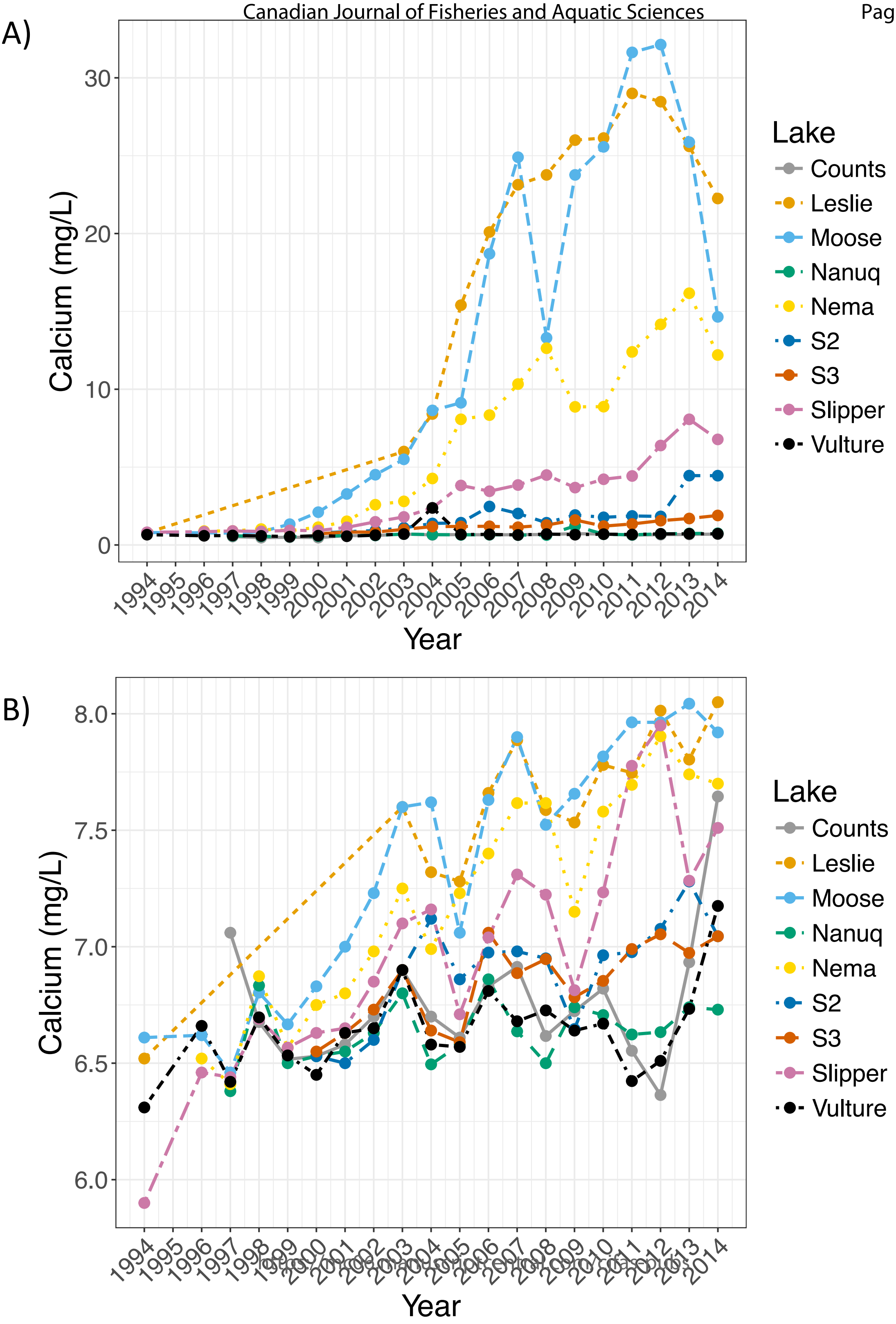
Figure 7: *Holopedium* (A and B) and *Daphnia* (C and D) relative abundance data for all sampling occasions for which we have data (1994, 1996, 1998-2014) as a function of the

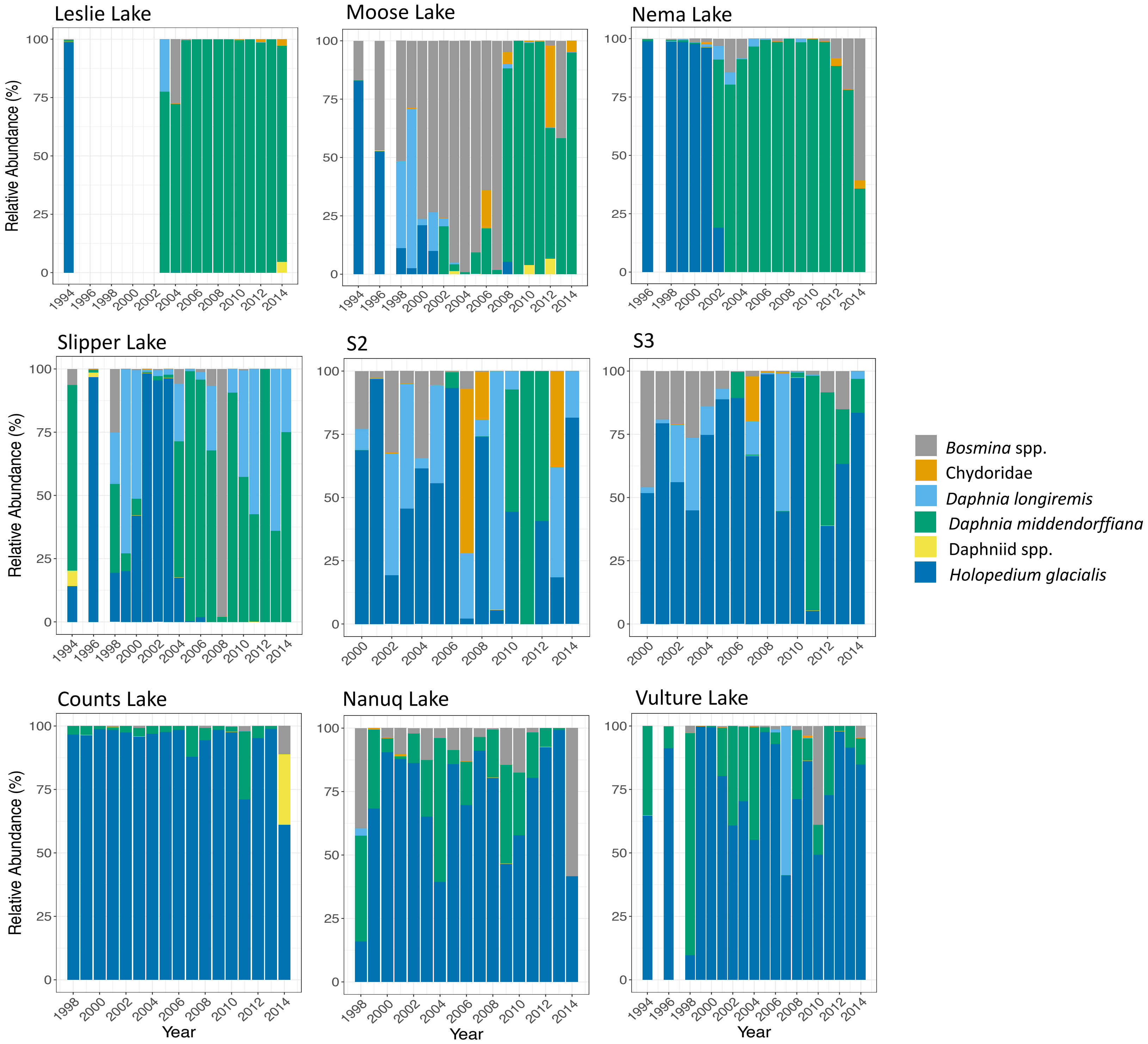
measured mid-summer Ca concentrations (A and C) and pH (B and D). The dashed line represents the first significant split identified by MRT analyses.

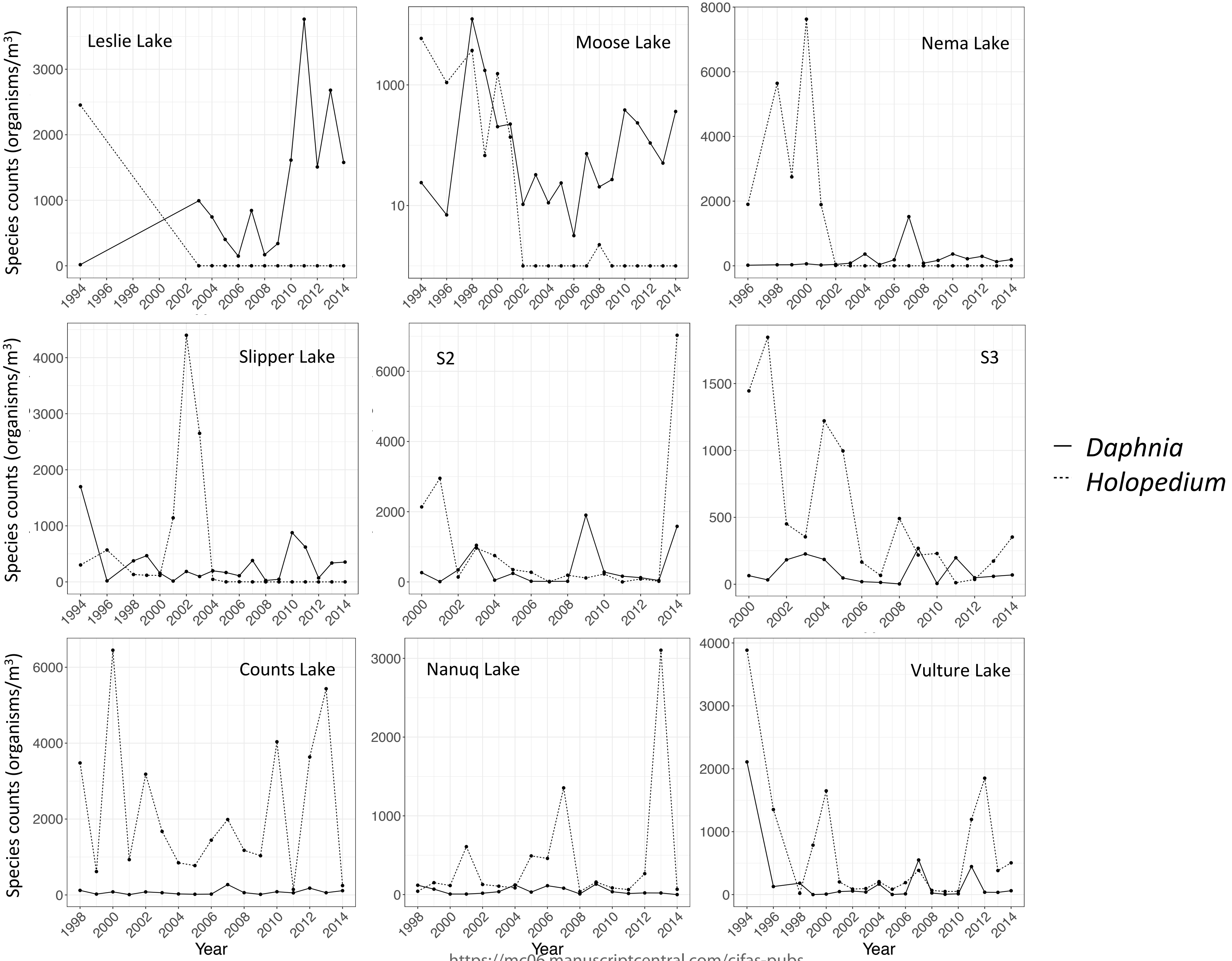
Figure 8: Mid-summer pH as a function of the measured Ca concentrations for all sampling occasions for which we have data (1998, 1999, 2004-2014) with points coloured according to the *Holopedium* relative abundance, with darker points reflecting higher relative abundances and light grey points reflecting sites without *Holopedium*. A logarithmic regression line (blue) with the equation pH=0.7393 log([Ca]) + 6.7671 indicates a significant ($p < 0.001$) positive relationship between pH and Ca concentrations with an adjusted $R^2_{adj} = 0.7975$.

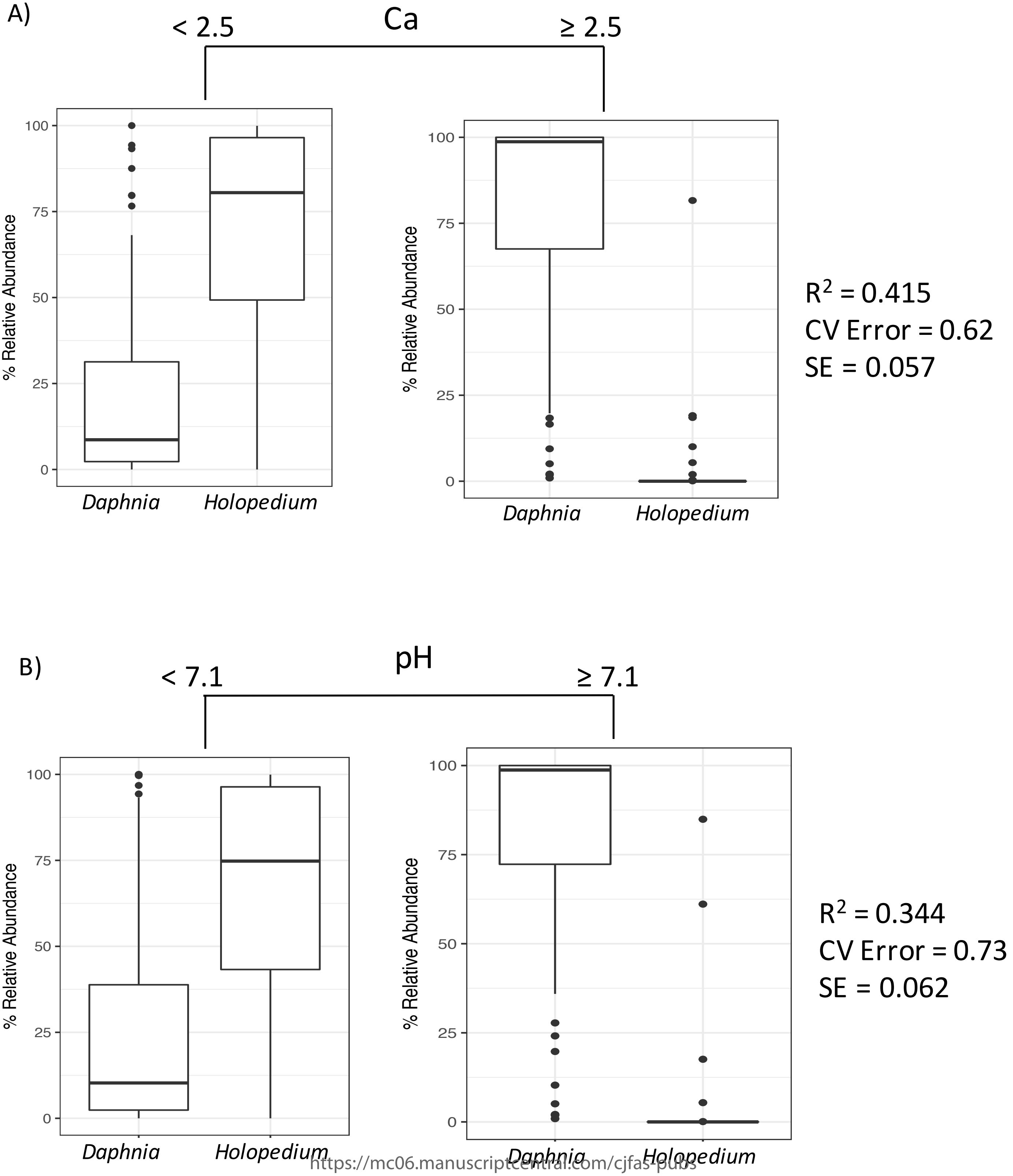

Vulture
LLCF
Leslie
Moose
Nema
Slipper
S3
S2
B
Nanuq
Inset B
Counts
Lac de Gras
A
Study Area
Inset A

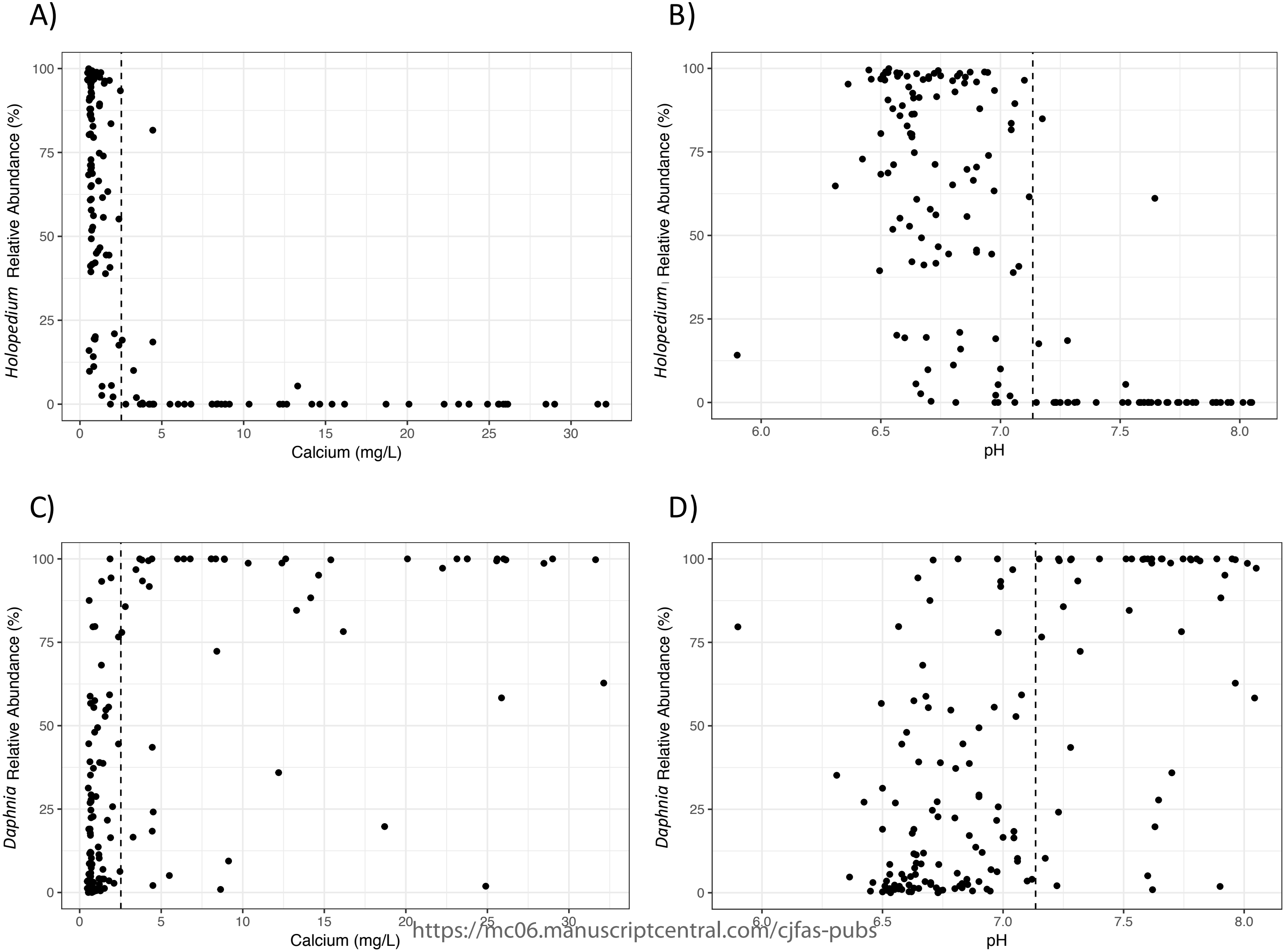

A)
Calcium (mg/L)
30
20
10
0
Leslie
Moose
Nema
Slipper
S2
S3
Counts
Nanuq
Vulture
B)
pH
8.0
7.5
7.0
6.5
Leslie
Moose
Nema
Slipper
S2
S3
Counts
Nanuq
Vulture
Lake
Lakes receiving diamond mining effluent from closest to the discharge (left) to farthest (right)
Reference lakes

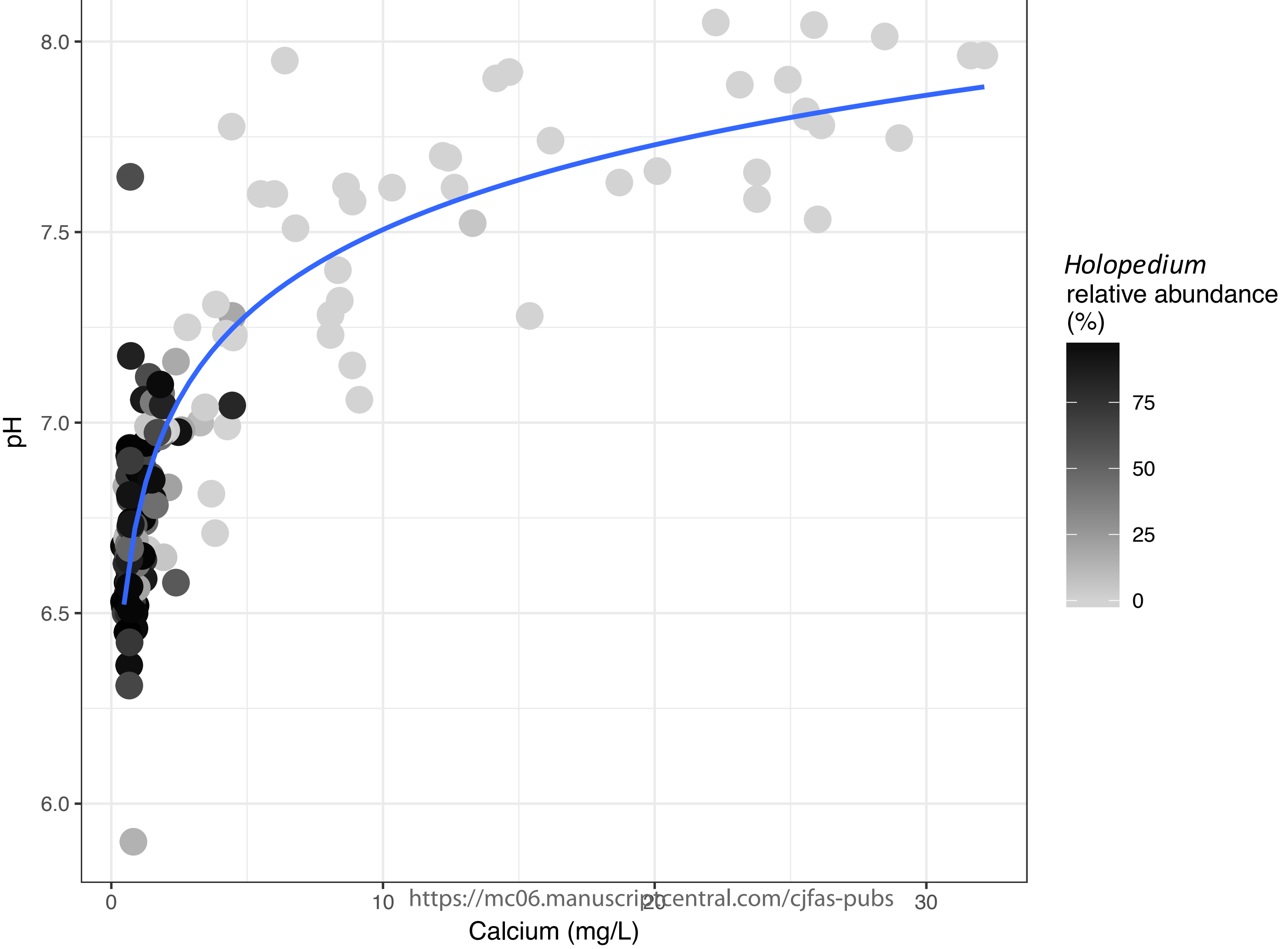

A)
Calcium (mg/L)
0
10
20
30
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year
Lake
Counts
Leslie
Moose
Nanuq
Nema
S2
S3
Slipper
Vulture
B)
Calcium (mg/L)
6.0
6.5
7.0
7.5
8.0
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year
Lake
Counts
Leslie
Moose
Nanuq
Nema
S2
S3
Slipper
Vulture


Leslie Lake
Moose Lake
Nema Lake
Slipper Lake
S2
S3
Counts Lake
Nanuq Lake
Vulture Lake
Relative Abundance (%)
0
25
50
75
100
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
Year
Bosmina spp.
Chydoridae
Daphnia longiremis
Daphnia middendorffiana
Daphniid spp.
Holopedium glacialis


Leslie Lake
Moose Lake
Nema Lake
Slipper Lake
S2
S3
Counts Lake
Nanuq Lake
Vulture Lake
Species counts (organisms/m³)
Year
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
0
1000
2000
3000
4000
6000
8000
10
500
1500
— Daphnia
--- Holopedium


A)
Ca
< 2.5
≥ 2.5
% Relative Abundance
0
25
50
75
100
Daphnia
Holopedium
R^2 = 0.415
CV Error = 0.62
SE = 0.057
B)
pH
< 7.1
≥ 7.1
% Relative Abundance
0
25
50
75
100
Daphnia
Holopedium
R^2 = 0.344
CV Error = 0.73
SE = 0.062


A)
Holopedium Relative Abundance (%)
100
75
50
25
0
Calcium (mg/L)
0
5
10
15
20
25
30
B)
Holopedium Relative Abundance (%)
pH
6.0
6.5
7.0
7.5
8.0
C)
Daphnia Relative Abundance (%)
Calcium (mg/L)
D)
Daphnia Relative Abundance (%)
pH


8.0
7.5
7.0
6.5
6.0
pH
0
10
20
30
Calcium (mg/L)
Holopedium relative abundance (%)
75
50
25
0