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Northern Lakes Recovery Study (NLRS) – microcrustaceans

Reference conditions, acidification and biological recovery

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NATURENS TÅLEGRENSER
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Lake O.S.A., Killarney Provincial Park, Ontario, Canada (Photo: Bjørn Walseng)

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Summary

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The region in and around Killarney Provincial Park, located 40-60 km south-west of Sudbury, Ontario, Canada, was one of the first areas where widespread effects of lake acidification were documented in Canada. Since the 1970's water quality improvements have occurred in response to reductions in atmospheric pollution and some lakes have already recovered to their pre-industrial pH levels, as inferred from microfossils of diatoms preserved in lake sediments. Although numerous acidified lakes in Scandinavia are now responding to reduced atmospheric pollution levels with improvements in water quality, the lakes in Killarney Park currently provide some of the best evidence of natural chemical and biological recovery. The acidification story of Killarney is more or less parallel to what we now experience in Scandinavia, and in 1997 a Canadian/Norwegian cooperative project, the Northern Lakes Recovery Study (NLRS), was established to develop methods for characterising chemical and biological recovery.

The microcrustaceans (Cladocera and Copepoda) are generally considered as good ecological indicators and have been used to assess acidification status as well as trophic status of water bodies. Microcrustaceans have also been used in paleolimnological investigations of pre-industrial environmental conditions.

The NLRS includes studies of pelagic and littoral crustaceans from 23 lakes in Killarney Provincial Park, along a pH-gradient from 4.6 to 7.6. Sampling was conducted between 1997 and 1999. Core samples for paleolimnological studies were taken from 19 of these lakes. Also five lakes near Sudbury, which have been severely affected by acidification and heavy metal contamination, were included in the study of microcrustaceans (1997-99). Included in the Canadian studies were acidified lakes showing both slow and fast chemical recovery, as well as non-acidified reference lakes. The aim of both the Norwegian and the Canadian studies on microcrustaceans is to evaluate the acidification status and trends following improvements in water quality.

We found in total 81 microcrustacean species, including 58 cladocerans and 23 copepods, in the Killarney lakes. Three cladocerans, *Acroperus harpae*, *Chydorus piger* and *Polyphemus pediculus,* and the calanoid *Leptodiaptomus minutus* were found in all lakes. Among cyclopoid copepods, *Eucyclops serrulatus* occurred most frequently, and was found in 21 lakes. Altogether 25 species were found in more than 50 % of the lakes. The total species richness among lakes ranged from 13 in the acidic Lake Nellie to 51 in the non-acidic Lake Ishmael.

In total 41 microcrustacean species, including 25 cladocerans and 16 copepods, were found in the five Sudbury lakes. Four cladocerans, *Diaphanosoma brachyurum, Sinobosmina* sp, *Chydorus brevilabris/sphaericus* and *Polyhemus pediculus*, one calanoid, *Leptodiaptomus minutes,* and the cyclopoid copepods *Eucyclops serrulatus* and *Cyclops bicuspidatus thomasi* were found in all lakes. The highest number of species was found in Lake Swan (29), whereas the species numbers varied between 17 and 22 for the other lakes. Except for Lake Swan the Sudbury lakes have fewer species than expected compared to lakes in Killarney with similar pH. At least 15-20 additional species should be expected when these Sudbury lakes have fully recovered. Many years of metal contamination in combination with acidification may directly or indirectly have caused this reduction in diversity.

Data from Killarney are used together with data from Dorset, 300 km to the SE of Killarney Provincial Park, to evaluate the results based on qualitative and quantitative sampling respectively. The fauna of the non-acidic lakes differed between surveys using different sampling techniques. However, similar faunas were identified in the acidified lakes in both surveys, and several good indicator species were identified. For example, *Acanthocycops vernalis* was re-

stricted to lakes with pH <6. *Sinobosmina* sp. was very common but only in lakes with pH >4.8. *Tropocyclops extensus, Mesocyclops edax,* and *Sida crystallina* were commonly found but only at pH >5, and *Chydorus faviformis* only at pH >5.9. Among less common species the following seems to be acid sensitive: most daphnids like *Daphnia ambigua*, *D. mendotae*, *D. dubia, D. longiremis* and *D. retrocurva*, the calanoids *Leptodiaptomus ashlandi* and *Skiptodiaptomus oregonensis* and the cyclopoids *Cyclops bicuspidatus thomasi* and *C. varicans rubellus*.

Among littoral species the following should be considered as indicators of non-acidic lakes: *Alona costata, A. circumfimbriata/setosa, Alonella nana, Chydorus bicornutus, Camptocercus rectirostris* and *Kurzia latissima*. Five species within the genus *Pleuroxus* (*P. denticulatus, P. hastatus, P. procurvis, P. striatus* and *P. truncatus*) do also belong to the same category and are never found at pH <5.2.These indicators showed promise in gauging the early stages of recovery from acidification in three lakes that were included in a survey in 1987 as well as in our survey ten years later.

Relative occurrence of acid sensitive species varied between 0 and 50 % of total species richness. Only Lake Nellie had no acid sensitive species.

Data from the NLRS lakes were used to study the correlation between microcrustacean communities (species richness and composition) and environmental variables. Several subsets, representing cumulative species records, and yearly species records respectively were analysed separately. Microcrustacean species richness was positively correlated with fish species richness, DOC, pH, ANC, tot-P, and lake area and negatively correlated with aluminium, Secchi disk readings, and elevation. Fish species richness together with average lake depth explained up to 79% of the variance in microcrustacean richness. Fish species richness was highly correlated with acidity-related variables whereas lake depth was correlated with lake area. The results demonstrate that it is difficult to evaluate the direct and indirect effects of acidification on microcrustacean diversity.

The microcrustacean composition was strongly correlated with pH (13-16% of the total variance) and other acidity-related parameters like ANC (9-15%) and aluminium (10-16%). pH, elevation, lake size, conductivity, DOC, Al and fish species richness together accounted for about 60 % of the total variance. Stronger species-environment correlations were obtained in analyses that took into account the between-year differences compared with analyses based on the total species recorded during the study combined with the median values of chemical variables.

Altogether 33 species were observed in the paleolimnological samples. Copepods and a number of cladoceran species are not preserved in the sediment. The number of species is thus quite high compared with 58 cladoceran species in samples from the current microcrustacean fauna, the fact that some groups in sediment samples are not fully identified to species level. Two species, *Leydigia acanthocercoides* and *Pleuroxus aduncus*, were only found in core samples.

Remains of *Bosmina* spp. dominated in all but one lake (Lake Teardrop) and in all segments of the sediments. Usually more than 60% of all individuals were from these species. *Daphnia* spp. were found in all the lakes in the pre-industrial period (before 1880), as well as in 17 out of 19 lakes in the post-industrial period (1970 and later). They were not found in Lakes Clearsilver and Nellie and occurred in low numbers in Lakes Chain, Killarney and OSA. These lakes are either naturally acid or have been strongly acidified during the industrial period. Usually *Daphnia* remains are not identified to species. One of the *Daphnia* species, *D. catawba,* is not sensitive to acidification, and the remains for this taxa found during the most acid period may be this species.

We have not observed any significant changes in the cladoceran fauna from the pre-industrial period until present day, and no significant differences between the fauna at the strongest

acidified period before 1970 and the pre-industrial period based on sediment records. The main reason for this is probably that the number of segments analysed per lake is too small, especially from the period with most severe acidification.

Comparisons between the pre-industrial fauna, as indicated by core samples, and the current fauna show that differences in species numbers, percentage of acid sensitive species and composition of microcrustaceans generally is smaller for lakes that are assigned as non-acidified reference lakes or only slightly acidified lakes, as opposed to lakes that have been more severely acidified. When we define the pre-acidification situation as a goal for the lakes, there is obviously still a way to go before most lakes are fully recovered.

Comparisons between the crustacean zooplankton fauna during the period with most severe acidification (1972-73) and the current zooplankton fauna show that most Killarney lakes are in the process of biological recovery. An exceptions include lakes that have not been acidified, or only slightly acidified, as well as lakes that have been severely acidified and have not recovered above pH 5.0. Lakes Lumsden and Terry, with fast chemical recovery and with current pH >5.0, also show slow biological recovery. All other lakes are in the process of biological recovery. However, based on the zooplankton data alone it is not possible to estimate the rate of biological recovery for the Killarney lakes with a high precision. Therefore, information from historical data on crustacean zooplankton, pre-industrial fauna based on paleolimnological reconstructions and regional reference lakes was combined in the assessment of biological recovery. Our results indicate that the microcrustacean fauna of some lakes may be very close to its biological end-points for recovery; these lakes have probably never been severely acidified. The overall biotic response to chemical recovery remains modest and several reasons may account for this: 1) some lakes have still too toxic water to allow further biological recovery, 2) many lakes in Killarney have been severely acidified for a long period, and the biological recovery is therefore mainly dependant on external dispersion, 3) species interactions which may delay or prevent recovery, 4) confounding factors like climate-induced changes and invasions of exotic species may influence recovery from acidification.

Re-sampling of the lakes, now 10 years after the start of the NLRS, including both pelagic and littoral samples, should be considered and paleolimnological analyses of more core samples conducted. With these new data the assessment of recovery processes (recovery rates and delays) is expected to be greatly improved.

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Sammendrag

Schartau, A.K., Halvorsen, G. & Walseng, B. 2007. Northern Lakes Recovery Study (NLRS) – småkreps. Referansetilstand, forsuring og biologisk gjenhenting. - NINA Report 235: 66 s.

Killarney Provincial Park med omkringliggende områder, beliggende 40-60 km sørvest for Sudbury i provinsen Ontario var av de første områdene i Kanada hvor omfattende effekter av innsjøforsuring ble dokumentert. Siden 1970-tallet har det vært en bedring av vannkvaliteten som en følge av utslippsreduksjoner. Paleolimnologiske undersøkelser av kiselalger viser at noen av innsjøene allerede har oppnådd en fullstendig kjemisk gjenhenting, dvs. at disse innsjøene nå har en vannkjemi tilsvarende forholdene før forsuring. Selv om en rekke innsjøer i Skandinavia nå responderer på reduksjoner i luftforurensingene med forbedring av vannkvaliteten, så representerer innsjøene i Killarney så langt det beste eksemplet på naturlig kjemisk og biologisk gjenhenting. Forsuringen av Killarney er mer eller mindre en parallell til forsuringshistorien i Skandinavia. I 1997 ble det kanadisk-norske forskningsprosjektet ”Northern Lakes Recovery Study” (NLRS) etablert for å utvikle metoder for karakterisering av kjemisk og biologisk gjenhenting.

Småkreps (vannlopper og hoppekreps) er generelt vurdert som gode økologiske indikatorer og har blitt benyttet både i vurdering av forsurings- og trofitilstand i vannforekomster. Småkreps har også blitt brukt i paleolimnologiske studier av referansetilstand, dvs. av miljøforholdene før industriell påvirkning.

NLRS inkluderer studier av pelagiske og littorale småkreps fra 23 innsjøer i Killarney Provincial Park. Innsjøene, som dekker en pH-gradient fra 4.6 til 7.6, ble undersøkt i perioden 1997-1999. Kjerneprøver for paleolimnologiske undersøkelser ble tatt fra 19 av innsjøene. Dagens fauna av småkreps ble også undersøkt i fem sjøer nær Sudbury. Disse sjøene har tidligere vært svært skadet av forsuring og tungmetaller. De kanadiske sjøene omfatter både forsurede sjøer som viser en langsom kjemisk gjenhenting, forsurede sjøer med rask kjemisk gjenhenting og dessuten referansesjøer som har vært lite påvirket av forsuring. Målsettingen med både de norske og de kanadiske studiene av småkreps er å evaluere forsuringstilstand og –utvikling som en følge av vannkjemiske forbedringer.

Totalt ble det registrert 81 arter småkreps, 58 arter vannlopper og 23 arter hoppekreps, fra innsjøene i Killarney. Tre vannlopper, *Acroperus harpae*, *Chydorus piger* og *Polyphemus pediculus,* og calanoiden *Leptodiaptomus minutus* ble funnet i alle innsjøene. Blant de cyclopoide hoppekrepsene var *Eucyclops serrulatus* mest vanlig; denne ble funnet i 21 innsjøer. Totalt 25 arter ble funnet i mer enn 50 % av innsjøene. Artsantallet varierte fra 13 i den sure innsjøen Nellie til 51 i den ikke-forsurede Ishmael.

Totalt 41 arter, 25 arter vannlopper og 16 arter hoppepkreps, ble funnet I sjøene nær Sudbury. Fire vannlopper, *Diaphanosoma brachyurum, Sinobosmina* sp., *Chydorus brevilabris/ sphaericus* and *Polyhemus pediculus*, en calanoid hoppekreps, *Leptodiaptomus minutus,* og to cyclopoide hoppekreps, *Eucyclops serrulatus* og *Cyclops bicuspidatus thomasi*, ble funnet i alle innsjøene. Høyest artstantall ble funnet i Swan med totalt 29 arter, mens artsantallet varierte mellom 17 og 22 for de andre sjøene. Bortsett fra Swan så hadde innsjøene i Sudbury-området lavere artsantall enn forventet sammenlignet med innsjøer i Killarney med tilsvarende forsuringsgrad. Minst 15-20 arter mangler i disse innsjøene før disse kan anses å ha oppnådd full biologisk restituering. Mange år med tungmetallforurensning i kombinasjon med forsuring har direkte eller indirekte ført til redusert diversitet av småkreps i Sudbury-sjøene.

Data fra Killarney ble sammen med data fra Dorset, 300 km sørøst for Killarney Provincial Park, brukt til å evaluere resultater basert på kvalitative og kvantitative innsamlingsmetoder. Faunaen i ikke-forsurede innsjøer varierte med innsamlingsmetoden, mens faunaen i de sure sjøene var tilsvarende i begge undersøkelsene. Flere gode indikatorarter ble identifisert gjennom denne undersøkelsen. For eksempel, *Acanthocycops vernalis* ble kun funnet i innsjøer

med pH <6. *Sinobosmina* sp. var svært vanlig, men kun i innsjøer med pH >4.8. *Tropocyclops extensus, Mesocyclops edax* og *Sida crystallina* var også vanlig forekommende men kun ved pH >5, og *Chydorus faviformis* kun ved pH >5.9. Blant de mindre vanlige artene synes følgende å være følsomme for forsuring: de fleste dafnier som *Daphnia ambigua*, *D. mendotae*, *D. dubia, D. longiremis* og *D. retrocurva*, de calanoide hoppekrepsene *Leptodiaptomus ashlandi* og *Skiptodiaptomus oregonensis* samt de cyclopoide hoppekrepsene *Cyclops bicuspidatus thomasi* og *C. varicans rubellus*.

Blant de litorale småkrepsene kan følgende vurderes som forsuringsfølsomme: *Alona costata, A. circumfimbriata/setosa, Alonella nana, Chydorus bicornutus, Camptocercus rectirostris* og *Kurzia latissima*. Fem arter innen slekten *Pleuroxus* (*P. denticulatus, P. hastatus, P. procurvis, P. striatus* og *P. truncatus*) hører også til denne kategorien og er aldri funnet ved pH <5.2. Disse artene indikerer begynnende biologisk gjenhenting i tre innsjøer som ble undersøkt både i 1987 og i 1997-99.

Relativ forekomst av forsuringsfølsomme arter varierte mellom 0 og 50 % av total artsrikdom. Kun Nellie hadde ingen sensitive arter.

Data fra Killarney ble benyttet for å studere korrelasjon mellom småkrepsfaunaen (artsantall og –sammensetning) og miljøvariable. Ulike datasett, som representerer henholdsvis kumulative artslister og årlige artsregistreringer, ble analysert. Artsrikdom av småkreps var positivt korrelasjon med antall arter av fisk, DOC, pH, ANC, tot-P og innsjøareal, og negativt korrelert med aluminium, siktedyp og høyde over havet. Artsrikdom av fisk samt gjennomsnittlig innsjødyp forklarte 79 % av variasjonen i artsrikdom av småkreps. Fiskediversiteten viste høy positivt korrelert med pH, mens innsjødypet var korrelert med innsjøareal. Resultatene viser at det kan være vanskelig å evaluere indirekte og direkte effekter av forsuring på diversiteten av småkreps.

Artssammensetningen av småkreps viste høy korrelasjon med pH, som forklarte13-16 % av totalvariasjonen, og andre forsuringsrelaterte parametre som ANC (9-15 %) og aluminium (10-16 %). pH, høyde over havet, innsjøareal, ledningsevne, DOC, aluminium og antall fiskearter forklarte totalt 60 % av variasjonen i småkrepsfaunaen. En sterkere korrelasjon mellom artssammensetning og miljøforhold ble funnet ved å ta hensyn til mellom-årsvariasjon enn ved analyse av akkumulerte artslister.

I kjerneprøvene for paleolimnologiske undersøkelser ble det totalt registrert 33 arter. Hoppekrepsene samt en rekke vannlopper blir ikke bevart i sedimentet, og flere grupper av vannlopper lar seg ikke bestemme til artsnivå. Artsantallet er derfor relativt høyt sammenlignet med de 58 artene av vannlopper som ble funnet i dagens fauna i de samme innsjøene. To arter, *Leydigia acanthocercoides* og *Pleuroxus aduncus*, ble kun funnet i kjerneprøver.

Rester av *Bosmina* spp. dominerte totalt i alle innsjøer med unntak av Teardrop, og i alle sedimentlag. Vanligvis utgjorde *Bosmina* spp. mer enn 60 % av alle individer i prøven. *Daphnia* spp. ble funnet i alle innsjøer i segmenter som representerte den før-industrielle perioden (før 1880) så vel som i 17 av 19 innsjøer i den post-industrielle perioden (1970 og senere). Dafnier ble ikke funnet i innsjøene Clearsilver og Nellie og ble funnet kun i mindre mengder i Chain, Killarney og OSA. Disse innsjøene er naturlig sure eller har vært svært forsuret med langsom kjemisk gjenhenting. Vanligvis er rester av dafnier ikke mulig å bestemme til art. En av dafniene, *D. catawba*, er ikke følsom for forsuring, og det kan være denne arten som er funnet i sedimentlag som representerer den mest forsurede perioden.

Vi har ikke funnet noen signifikante endringer i faunaen av vannlopper fra før-industriell periode fram til den mest forsurede periode og videre til dagens fauna basert på kjerneprøvene. Hovedårsaken til dette er antagelig at få prøver er analysert fra hver sjø. Spesielt fra forsuringsperioden er antallet for lavt til at det er mulig å registrere forskjeller over tid.

Sammenligning mellom før-industriell fauna, gitt ved kjerneprøver, og dagens fauna viser at det er forskjeller i artsantall, andel forsuringsfølsomme arter og artssammensetning av småkreps. Forskjellene er generelt mindre for ikke-forsurede referansesjøer og sjøer som er vurdert å være lite forsuret sammenlignet med sjøer som har vært mer påvirket av forsuring. Dersom vi definerer den før-industrielle faunaen som et gjenhentingsmål for innsjøene, så vil de fleste innsjøene være et godt stykke fra full biologisk restituering.

Sammenligning av pelagiske småkreps fra perioden med mest omfattende forsuring (1972-73) og dagens fauna av pelagiske småkreps viser at de fleste Killarney-innsjøene er under biologisk gjenhenting. Et unntak er innsjøene som aldri har vært forsuret eller kun svakt forsuret, samt enkelte sjøer som har vært alvorlig forsuret og som viser svak vannkjemisk gjenhenting. Også to av sjøene (Lumsden, Terry) med rask kjemisk gjenhenting som i dag har pH >5,0 viser svak biologisk gjenhenting. Basert på dyreplanktonet alene er det ikke mulig å estimere hastigheten av biologisk gjenhenting med stor presisjon. I den videre vurderingen av biologisk gjenhenting ble derfor informasjon fra historiske data på dyreplankton kombinert med informasjon om før-industriell fauna basert på paleo-prøver og informasjon fra regionale referansesjøer. For noen av sjøene kan faunaen av småkreps vurderes å være nærmest fullt restituert; disse sjøene har sannsynligvis aldri vært alvorlig forsuret. Generelt må imidlertid den biologiske gjenhentingen vurderes som moderat, og det er vist at det kan være flere årsaker til dette: 1) noen sjøer har en vannkjemi som fremdeles er for giftig til å tillate videre biologisk gjenhenting, 2) mange sjøer i Killarney har vært alvorlig forsuret i en lang periode, og biologisk gjenhenting vil i hovedsak være avhengig av naturlig innvandring fra omkringliggende vannsystemer, 3) interaksjon (konkurranse, predasjon) mellom allerede etablerte arter og arter som forsøker å reetablere seg i innsjøen vil kunne forsinke eller forhindre gjenhenting av en naturlig fauna, 4) andre miljøfaktorer som klimainduserte endringer og innvandring av fremmede arter vil kunne hindre en full biologisk gjenhenting.

Det bør vurderes nye undersøkelser av innsjøene, nå 10 år etter oppstart av NLRS. Både litorale og pelagiske småkreps bør inngå i undersøkelsene. Sammen med analyse av flere kjerneprøver fra hver innsjø forventes dette å gi et mye bedre grunnlag for estimering av gjenhentingsprosesser.

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Contents

Foreword

The acidification story of Killarney is more or less parallel to what we now experience in Scandinavia, and in 1997 a Canadian/Norwegian cooperative project, the Northern Lakes Recovery Study (NLRS), was established to develop methods for characterising chemical and biological recovery. Sampling of microcrustaceans from lakes within Killarney Provincial Park, as well as lakes near Sudbury, were conducted during the years 1997-1999.

Phase I of the NLRS was finalised by a special issue of Ambio in May 2003. Results from NLRS have also been presented at several seminars (Sudbury, Canada in January 1998 and February 2002, Grimstad, Norway in June 2001 and September 2002) and conferences (for instance the Acid Rain conference in Japan, December 2000). However, analyses of microcrustacean samples from sediment cores (Killarney lakes) and of the current fauna (Sudbury lakes) have continued up to the present. Therefore, no complete presentation of the microcrustacean data has been given so far.

This report presents an overview of the main results on microcrustaceans from the NLRS study with special emphasis on reference conditions, effects of acidification and recovery of the microcrustacean fauna.

Sampling of microcrustaceans and sediment samples for paleolimnological analysis has been conducted by the Cooperative Freshwater Ecology Unit, Biology Department, Laurentian University, Sudbury, Canada (CFEU) which also has provided us with physico-chemical data and information on fish communities. John Gunn, CFEU, has coordinated the work in Canada and also commented on this report. The Norwegian Institute for Water Research (contact person Atle Hindar) and the University of Bergen (contact person Gunnar Raddum) have been our Norwegian partners in NLRS, responsible for studies on respectively critical loads and profundal macroinvertebrates.

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Oslo, February 2007

Ann Kristin Schartau
(project coordinator)

1 Introduction

Acidification of rivers and lakes has for a long time been a major ecological problem in the Scandinavian countries, parts of Wales and Scotland, Central Europe and in Russian Kola (Raddum et al. 2001) as well as parts of North America (Jeffries 1997, Driscoll et al. 2001). In 1995 the critical load for sulphur (S) was exceeded in 9 % of the Finnish lakes (3000 lakes), 9 % of the Swedish lakes (6000 lakes) and 27 % of Norwegian lakes (10000 lakes) (Skjelkvåle et al. 2001). The emission of S has been reduced by 66 % from 1980 to 2003 in Europe (EMEP 2005) and this has lead to a marked decrease in S deposition in larger parts of Europe (Kulmala et al. 1998, Skjelkvåle et al. 2003). Although natural recovery of water chemistry has been documented in a number of lake ecosystems across Europe (Wilander 1997, Stoddard et al. 1999, Skjelkvåle et al. 2003), and recent studies have attributed recovery of lake biology to decreased deposition of acidifying compounds (e.g. Raddum et al. 2004), acidification is still considered as a serious threat to the biodiversity and functioning of inland surface waters in Northern parts of Europe.

The region in and around Killarney Provincial Park, located 40-60 km south-west of Sudbury, Ontario, Canada, was one of the first areas where widespread effects of lake acidification were documented in Canada (Beamish and Harvey 1972, Neary et al. 1990). Since the 1970's water quality improvements have occurred in response to reductions in atmospheric pollution and some lakes have already recovered to their pre-industrial pH levels, as inferred from microfossils preserved in lake sediments (Snucins et al. 2000, Keller et al. 2003). Although numerous acidified lakes in Scandinavia are now responding to reduced atmospheric pollution levels with improvements in water quality (Skjelkvåle et al. 2001, 2005), the lakes in Killarney Park currently provide the best evidence of natural chemical and biological recovery.

The acidification story of Killarney is more or less parallel to what we now experience in Scandinavia. In 1997 a Canadian/Norwegian cooperative project, the Northern Lakes Recovery Study (NLRS), was established to develop methods for characterising chemical and biological recovery. Phase I of the NLRS was conducted during the period 1997-2002 and included lakes within Killarney Provincial Park as well as lakes near Sudbury.

Killarney lakes are interesting from a Norwegian point of view. They resemble Norwegian lakes due to the slowly weathering bedrock and have also been exposed to long term acidification. Acid deposition may be regarded as uniform in this area of about 500 km^2. However, the lakes are quite different from Norwegian acidified lakes in terms of critical load (Hindar & Henriksen 1998), meaning that their sulphur deposition and rate of deposition reductions have been higher than in Norway. This is probably also true for the rate of reversibility and recovery. Reintroduction of lost species may be greater due to the vicinity of less affected lakes in some of the park area. Also, the biodiversity is different compared to acidified Norwegian lakes due to the many fish species.

A central part of the NLRS program is to establish biological datasets that may document changes in biota given changes in the deposition of sulphur and nitrogen in the Killarney Provincial Park. This is also the aim of the Norwegian monitoring program on long-range transported air pollutants. Surveys of planktonic and littoral crustaceans have revealed valuable information for the environmental surveillance of lakes and ponds, because these groups:

1) include species with specific environmental requirements and restricted distributions as well as species which occur in a wide range of standing waters over a large geographical area;
2) are well known with regards to geographical distribution and environmental demands;
3) have a generally high capacity for dispersal which should facilitate quick responses to remedial actions; and
4) their sampling requires only modest expenditure of time and equipment.

Given the similarities and differences in lake characteristics between the Killarney and acidified Norwegian lakes, examination of the rate of recovery in Killarney may give Norwegian authorities knowledge regarding what might be expected in Norwegian lakes in the future. In this study we use results from Canada to evaluate which metrics and methods that could be used in the assessment of acidification status and trends in Norway.

For implementation of the EU's Water Framework Directive (WFD; 2000/60/EC) there is a general need for more information on reference conditions for various chemical and biological quality elements. In many respects the lakes included in the NLRS are comparable to acid sensitive lakes in Norway. Although there are biological differences we consider these lakes to represent ecological features which may be of interest also in the Norwegian work on establishment of reference conditions and classification systems with regard to the WFD.

Lake sediments may act as archives of past lake conditions, containing information about chemical, physical and biological processes in the lake and in its watershed (Frey 1958, Berglund 1986, Smol et al. 2001). Remains of cladocerans, and especially the chydorides, are well preserved in the sediment and have among others been used to reconstruct the past environmental changes caused by acidification and eutrophication (Sandøy & Nilssen 1986, Whiteside 1970, Jeppesen et al. 2001, Smol et al. 2001). Following the implementation of the WFD there has been more focus on the use of paleolimnological studies to establish reference values for water types for which historical data or regional reference sites are missing. Paleolimnological studies were included as a part of the NLRS to establish reference values and follow the acidification history (including acidification period and recovery period) through sediment records of diatoms, chydorides and chironomids.

The objectives of the present study are 1) to describe the relationship between the biological metrics, describing microcrustacean species richness and composition, and environmental variables in a set of lakes spanning a wide pH gradient, 2) to evaluate which of the acidification related variables (pH, Al, ANC) most strongly correlated with the variations in the microcrustacean communities, 3) to evaluate methods for establishment of reference conditions and departure from such conditions, 4) to describe reference conditions for metrics relevant for assessment of acidification status.

2 Study area

2.1 Killarney Provincial Park

2.1.1 Geographical position and physical characteristics

The Killarney Park watershed (55,980 ha) contains over 600 water bodies spanning a broad range of physical and chemical characteristics (Snucins et al., 2000). The 23 lakes in our study (**Figure 1, Table 1**) were chosen to include the main environmental gradients. One of the lakes, Lake Tyson, is situated just outside the park area. Thirteen lakes were sampled in 1997, and ten more were added in 1998 and 1999. One of the original lakes, Burke Lake, was taken out of the survey in 1998. These 23 lakes represent three main conditions with reference to acidification: reference lakes and lakes that have never been severely acidified (pH always >6) (N=4), lakes that did acidify but show a relatively fast chemical recovery with pH >5 (N=13), and those that did acidify, remain acidic today (pH <5) and show a slow chemical recovery (N=6). Characterization of acidification status is based on comparison of historical data on water chemistry (Sprules 1975, Loche & Sprules 1994), diatom inferred pH (Gunn & Sandøy 2001) and current water chemistry. There is no information on historical pH for Lake Burke. In some lakes (e.g. Bell, Chain, Terry, Tyson) natural acidity may interfere with anthropogenic acidification.

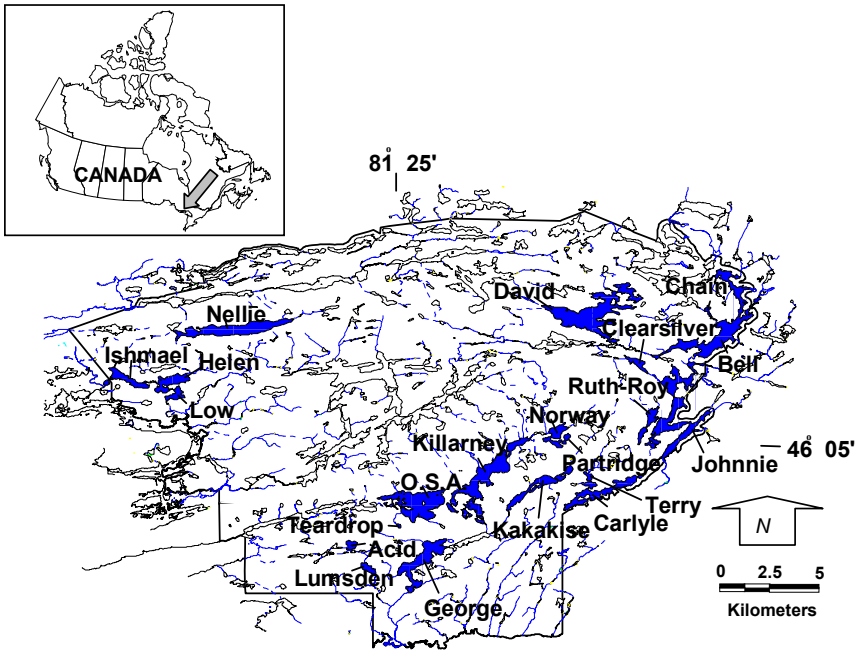

Figure 1. *NLRS study lakes in Killarney Provincial Park, Ontario, Canada. Lake Tyson is located outside the park and therefore not shown on the map.*

The studied lakes vary relatively little in elevation (range: 182 – 325 m a.s.l), but differ substantially in lake size (0.03 – 11.42 km^2) and maximum depth (8 – 61 m).

Fish communities in the studied lakes are very different compared to acidified Norwegian lakes, due to the many fish species. In total 21 fish species are recorded from 22 Killarney lakes (no data from Lake Burke) (**Table 2**). The number of species varies between 0 and 14. Whereas 7 of the lakes seem to have no fish at present, 9 of the lakes have a fish community of 9 species or more.

Table 1. *Geographical and physico-chemical characteristics of the investigated Killarney lakes. * Lakes with palaeo analysis on microcrustaceans . Acidification status; 1: Reference lakes/slightly acidified, 2: Acidified (pH: 5-6) and show a fast chem. recovery, 3: Acidified (pH <5) and show a slow chem. recovery.*

	Acid. status	W-E ZONE 17	N-S ZONE 17	year sampled	elevation m a.s.l.	area km^2	depth max (m)	depth mean (m)	Secchi median	Water colour mid-summer
Acid*	3	465700	5198000	97,98,99	275	0.20	29	10.9	12.7	blue/green
Bell*	2	484500	5108500	97,98,99	221	3.47	27	8.1	5.0	yellow/brown
Burke	2	463000	5197400	97	304	0.08	16		3.8	-
Carlyle	2	478000	5100500	98,99	206	1.57	15	5.7	5.1	yellow/brown
Chain*	3	483700	5009800	98,99	226	0.11	11	2.7	4.7	yellow/brown
Clearsilver*	3	480300	5007200	98,99	227	0.31	14	5.3	9.6	blue/green
David*	2	477000	5009500	98,99	238	4.06	24	7.0	9.1	blue/green
George*	2	469000	5096000	97,98,99	189	1.89	37	16.4	8.8	blue/green
Helen*	1	456500	5006300	97,98,99	187	0.83	41	20.5	6.7	yellow/brown
Ishmael*	1	454000	5006500	97,98,99	185	0.73	20	11.3	6.6	yellow/brown
Johnnie*	2	482000	5003000	97,98,99	206	3.42	34	10.0	6.0	yellow/brown
Kakakise*	2	475500	5001300	98,99	189	1.13	31	13.5	8.8	blue/green
Killarney*	2	471800	5000700	97,98,99	200	3.27	61	10.8	22.1	blue/green
Low*	1	456800	5005500	97,98,99	182	0.34	28	14.4	8.5	yellow/brown
Lumsden	2	466500	5096700	98,99	241	0.24	22	9.0	13.7	blue/green
Nellie*	3	460000	5008800	98,99	267	2.61	55	19.2	28.4	blue/green
Norway*	2	476000	5003600	98,99	205	0.63	34	15.1	14.7	blue/green
OSA*	3	470000	5000500	97,98,99	205	2.79	40	12.0	18.5	blue/green
Partridge*	3	476500	5003400	98,99	206	0.11	17	6.2	7.6	blue/green
Ruth-Roy	2	480800	5004500	97,98,99	214	0.55	18	4.3	13.8	blue/green
Teardrop*	1	468000	5098900	97,98,99	325	0.03	17	9.6	11.9	blue/green
Terry*	2	477800	5001400	98,99	207	0.12	8	3.1	2.7	yellow/brown
Tyson*	2	491007	5107010	98,99	210	11.42	40	11.9	5.1	blue/green

Table 2. *Fish communities of the investigated Killarney lakes: total species richness and species numbers in main feeding habitat (P: pelgaic, L: littoral). Note: some species occurs in several habitats.*

	Fish species richness			Bluegill	Bluntnose minnow	Brook stickleback	Brown bullhead	Central mudminnow	Cisco	Fathead minnow	Golden shiner	Iowa darter	Johnnie darter	Lake trout	Lake whitefish	Largemouth bass	Northern pike	Pumkinseed	Rock bass	Rainbow smelt	Slimy sculpin	Smallmouth bass	White sucker	Yellow perch
	Total	P	L																					
Acid	0	0	0																					
Bell	12	4	7				1		1		1			1	1	1	1	1	1			1	1	1
Burke	-	-	-																					
Carlyle	9	2	6				1		1		1						1	1	1			1	1	1
Chain	0	0	0																					
Clearsilver	0	0	0																					
David	1	1	1																					1
George	11	4	5		1	1	1		1					1	1		1	1	1				1	1
Helen	11	4	9	1	1		1		1			1		1				1	1		1	1		1
Ishmael	10	4	7	1	1				1			1		1			1	1	1			1		1
Johnnie	11	4	6				1		1		1			1	1		1	1	1			1	1	1
Kakakise	12	3	9		1			1	1	1	1	1		1				1	1		1	1		1
Killarney	4	1	2				1	1										1						1
Low	14	5	10	1	1				1			1	1	1		1		1	1	1	1	1	1	1
Lumsden	0	0	0																					
Nellie	0	0	0																					
Norway	2	1	1					1																1
OSA	0	0	0																					
Partridge	1	1	1																					1
Ruth-Roy	0	0	0																					
Teardrop	2	1	1											1							1			
Terry	3	1	2				1											1						1
Tyson	9	3	5						1					1		1	1	1	1			1	1	1

2.1.2 Water chemistry

Lake water has been sampled as surface grabs or composite tube (length: 5 m) samples by the Cooperative Freshwater Ecology Unit in Sudbury (CFEU). All lakes were samples two times in 1998 (July and November) and three times in 1999 (March, July and November). In addition, 18 of the lakes were sampled in January 1996 and nine of the lakes in July 1996 and 1997. Secchi depth was measured in January 1996 and five times in 1998, but for many of the lakes Secchi depth has been measured only once during the period.

Analyses for pH and alkalinity were performed at the CFEU. All other analyses were done at the Ontario Ministry of Environment and Energy (OMOEE) laboratory in Toronto (Snucins & Gunn 1998). Analytical procedures for water chemistry from the Killarney lakes were as outlined by OMOEE (OMOEE 1996). Calculation of Acid Neutralizing Capacity (ANC), using the ion balance method (Reuss & Johnson 1986), was performed by NINA. Median, minimum and maximum for the whole period was calculated based on data from 1996-1999.

Information on fish communities were given by CFEU.

The studied Killarney lakes represent a pronounced acidic gradient, with a between-lake variation in pH (4.6 – 7.6), total aluminium (tot-Al; 6 – 499 $\mu g\ L^{-1}$), ANC (-80 – 424 $\mu eq\ L^{-1}$) and dissolved organic carbon (DOC; 0.1 – 5.5 mg C L^{-1}) (**Table 3**). Aluminium concentrations and ANC showed high within-lake variation for many lakes (**Appendix 1**). During the three years of

this study, measurable water quality improvements occurred in many of the lakes (Snucins et al. 2001, Keller et al. 2003).

Table 3. *Chemical characteristics of the studied Killarney lakes (median values based on monitoring data from 1996-1999).*

	pH	Cond mS m^{-1}	Ca mg L^{-1}	Tot-P µg L^{-1}	DOC mg C L^{-1}	Tot Al µg L^{-1}	LAl µg L^{-1}	ANC µeq L^{-1}
Acid	5,03	2.12	1,10	2	0,9	165	112	-24
Bell	6,05	2.62	2,05	6	4,2	68	14	38
Burke	5,10	2.54	1,40	4	1,8	185	149	-35
Carlyle	6,23	2.60	1,83	5	3,4	28	8	32
Chain	4,73	2.72	1,30	6	4,5	207	72	-21
Clearsilver	4,92	2.25	1,08	3	1,2	170	131	-36
David	5,05	2.10	1,26	2	1,3	83	53	-20
George	6,00	2.53	1,85	2	1,6	46	5	11
Helen	6,82	2.99	2,53	4	3,5	29	2	89
Ishmael	6,75	3.17	2,73	5	3,4	16	1	105
Johnnie	5,73	2.46	1,80	4	3,2	76	22	15
Kakakise	6,61	2.87	2,30	4	2,6	15	4	56
Killarney	5,10	2.63	1,58	4	0,5	173	128	-28
Low	7,57	6.90	8,15	5	2,8	8	3	424
Lumsden	5,21	2.10	1,20	2	0,7	135	75	-21
Nellie	4,63	3.35	1,45	2	0,1	499	447	-80
Norway	5,17	2.46	1,55	2	1,0	147	86	-14
OSA	4,88	3.10	1,98	2	0,4	170	128	-30
Partridge	5,81	2.73	2,00	2	1,6	33	18	1
Ruth-Roy	4,82	2.45	1,05	2	0,6	331	218	-44
Teardrop	6,76	2.55	1,83	4	1,0	6	1	48
Terry	5,68	2.43	1,70	12	5,5	131	27	19
Tyson	6,00	2.79	1,90	8	4,1	48	10	39

Except for Lake Low all studied lakes are characterized as siliceous (low calcium concentrations) and electrolyte poor (low conductivity). Most lakes are also clear water lakes with low humic content. Only the Lakes Bell, Chain, Terry and Tyson with DOC > 4 mg C L^{-1} (estimated TOC > 5 mg C L^{-1}) are considered as humic lakes. Most lakes are also nutrient poor (ultraoligo-/oligotrophic) with total phosphorus (Tot-P) < 7 µg L^{-1}. Lake Low belongs to the calcareous, clear water type (Ca > 4 mg L^{-1}, DOC < 4 mg C L^{-1}) according to the Norwegian lake typology developed for the implementation of the Water Framework Directive (Solheim & Schartau 2004). All other Killarney lakes belong either to the siliceous, clear water type (Ca 1-4 mg L^{-1}, DOC < 4 mg C L^{-1}) or the siliceous, humic water type (Ca 1-4 mg L^{-1}, DOC > 4 mg C L^{-1}). Both water types are very common in Norway, especially in the boreal climate region. However, in the most acidified region of Norway (Southern- and South-Western coast of Norway) many lakes have even lower calcium concentrations than the levels measured in Killarney and the majority of acidified Norwegian lakes have Ca < 1.0 mg L^{-1} (SFT 2006).

Concentrations of copper (Cu) and Nickel (Ni) in the early 1970s were elevated relative to lakes further from industrial sources (Beamish 1976). Analysis of sediment profiles indicate that maximum peak concentrations of metals appear generally in the 1960s and 1970s and are followed by a decrease in recent years (Belzile et al. 2004). Significant declines in Cu and Ni concentrations in the water have been observed and current (1999-2001) average summer concentrations of Cu and Ni in 21 Killarney lakes ranged from <1 to 2 (median for all lakes: <1), and <1 to 15 µg L^{-1} (median: 6.4), respectively (Keller et al. 2003). In 42 reference lakes in Dorset, Ontario, the median concentrations were lower, always <1 µg L^{-1}. The potential of trace

metal toxicity is present, especially since the lakes in Killarney are siliceous (soft-water). However, there is no evidence suggesting that current lake-water levels of Cu and Ni are affecting the biota in Killarney lakes.

Increased post-industrial sedimentary pigment concentrations, which can be linked to temporal shifts in whole-lake algal community structure and increased algal abundance may indicate increased deposition of phosphorus during the acidification period in Killarney lakes (Vinebrooke et al. 2002). However, there may also be other explanations for changes in the algal communities, for instance changes in other regional factors, such as climate, and acidification induced changes in biological interactions.

2.2 Lakes near Sudbury

2.2.1 Geographical position and physical characteristics

Plankton and littoral crustaceans were also sampled in five lakes near Sudbury, Ontario (**Figure 2**), in the years 1997-99. Two of the lakes, Swan and Clearwater, are situated about 13-15 km from the smelters while Hannah, Lohi, and Middle are located less than 5 km away. Surface area varies from 0.06 km^2 (Swan Lake) to 0.76 km^2 (Clearwater Lake) and maximum depth from 8.5 meter (Hannah Lake) to 21.5 meter (Clearwater Lake) (**Table 4**). The lakes cover a comparable gradient with regard to elevation, size (area) and depth as the Killarney lakes, but differ in water chemistry (see **Table 5**).

The area is extensively damaged by SO_2 and metal emissions from Cu and Ni smelters during the 1900s (Keller et al. 1992).

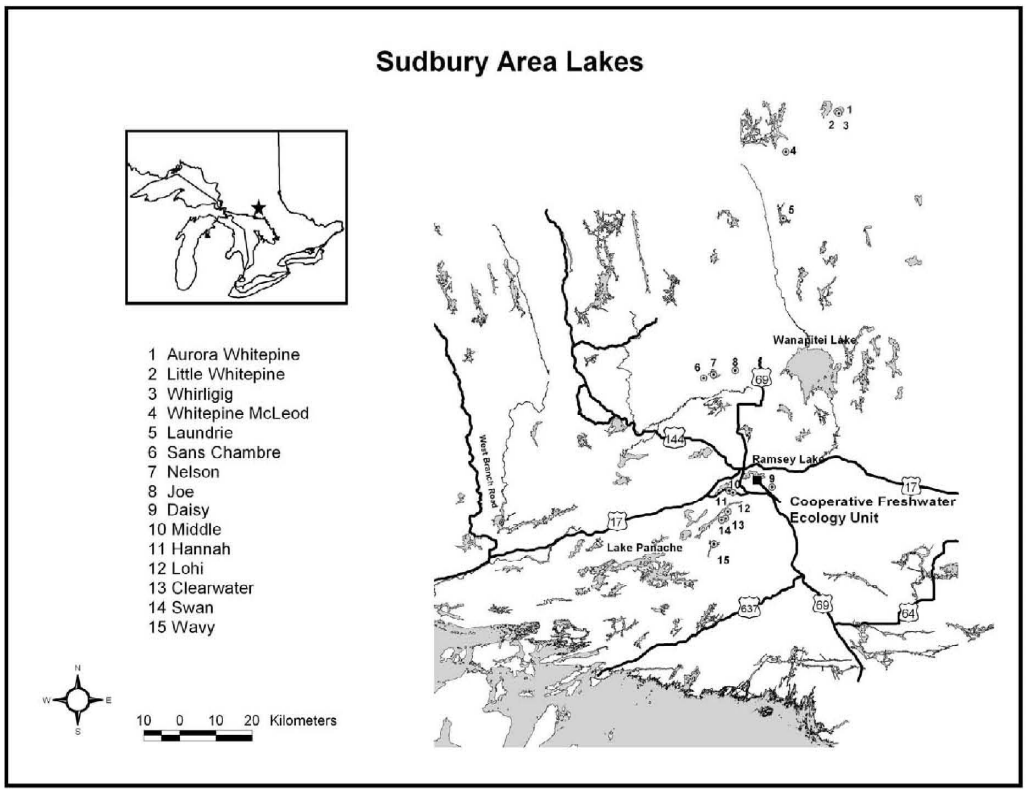

Figure 2. *Lakes in the Sudbury area including studied lakes (Lakes Clearwater, Hannah, Lohi, Middle and Swan), Ontario, Canada.*

Table 4. *Geographical and physico-chemical characteristics of the investigated Sudbury lakes. Information on fish communities are from studies performed after 2002.*

	W-E ZONE 17	N-S ZONE 17	year sampled	elevation m a.s.l.	area km^2	depth max (m)	depth mean (m)	Secchi median (m)	Fish # species
Clearwater	496133	5134972	97,98,99	267	0.76	21.5	8.4	8.2	3
Hannah	497440	5143830	97,98,99	269	0.27	8.5	4.0	6.2	5
Lohi	497437	5136422	97,98,99	265	0.41	19.5	6.2	5.1	3
Middle	497439	5141978	97,98,99	268	0.28	15.0	6.2	6.9	6
Swan	-	-	97,98,99	285	0.06	9.0	7.5	5.6	0

2.2.2 Water chemistry

Except for Lake Swan, there exist no data on water chemistry from the period of our study. Data from 1990 and 2003 (**Table 5**, **Appendix 2**) show that there have been a clear water quality improvement in all lakes during this period. These lakes are located close to the smelters in Sudbury and all lakes have been severely affected by acidification as well as heavy metals (Keller et al. 1992). Due to reduced emissions pH and alkalinity has increased, total aluminium has decreased and also concentrations of copper, nickel and zinc, among other metals, have decreased since the 1970s (Yan 1979).

The chemistry of the lakes Middle, Hanna and Lohi has been manipulated also by liming since 1973-75 (Yan 1979, Yan et al. 1996). pH rose from around 4.5 before to above 6.0 after liming. In Lake Swan the water quality improved until the mid-1980s when a drought driven re-acidification occurred (1986-87). During the drought, lake levels fell and lake surface area shrank by 18%, exposing littoral sediments.

Compared to the Killarney lakes the studied lakes in the Sudbury area have higher concentrations of Ca and other ions. All lakes, except Lake Swan, belong to the calcareous, clear water type (Ca 1-4 mg L^{-1}, DOC < 4 mg C L^{-1}) according to the Norwegian lake typology developed for the implementation of the Water Framework Directive (Solheim & Schartau 2004).

Table 5. *Chemical characteristics of the studied Sudbury lakes. Data from Urban Lakes Survey (1990) and NLRS (1997-98, 2003).*

	Year	pH	Cond mS m^{-1}	Alk µeq L^{-1}	Ca mg L^{-1}	Tot Al µg L^{-1}	Cu µg L^{-1}	Ni µg L^{-1}	Zn µg L^{-1}	Tot-P µg L^{-1}	DOC mg C L^{-1}
Clearwater	1990	4.88	8.05	-17	6.10	130	35	160	23	<=2	0.5
	2003	6.33	6.10	24	4.30	16	10	70	11	5	2.9
Hannah	1990	7.06	35.90	242	13.40	200	64	180	11	21	3.8
	2003	7.25	19.00	339	10.60	13	22	111	3	8	3.6
Lohi	1990	4.92	9.08	-14	6.18	130	50	200	29	<=2	1.1
	2003	6.28	7.16	51	4.34	22	12	59	10	9	3.4
Middle	1990	6.57	25.80	116	10.30	<30	28	230	16	<6	3.3
	2003	6.91	28.60	234	11.00	13	24	114	11	7	3.6
Swan	1990	4.87	6.99	-20	6.10	70				7	1.2
	1997-98	5.45	4.21	0	3.51	18				7	2.4
	2003	5.69	6.00	4	3.44	18				9	2.8

3 Material and methods

3.1 Sampling and processing

3.1.1 Microcrustaceans – pelagic and littoral samples

The lakes were sampled twice a year, in early summer (May-June) and in the autumn (September-October). At each sampling date 3 qualitative zooplankton samples were taken from the deepest part of the lake (45, 90 and 224 µm mesh). From each lake, two qualitative samples were taken from the littoral zone, respectively from stony substrate and in stands of vegetation. The samples were taken by dragging a 30-cm diameter, 90 µm mesh net horizontally and slowly over the substrate.

All samples were preserved in the field in 6% buffered sugar-formalin. In general, entire samples were counted, but when >400 organisms were present, successive 10 ml subsamples were examined until at least 200 organisms were counted. Altogether 288 planktonic and 432 littoral samples were analyzed.

We followed Wilson (1959) to identify the free-living copepods. The basic Cladoceran taxonomy followed Brooks (1959) and Pennak (1978), as modified by De Melo (1994) for bosminids. *Sinobosmina freyi* and *S. liederi* were pooled into *Sinobosmina* spp., as the characters that purportedly distinguish the species, antennule curvature and number of spines on the proximal pectin of the abdominal claw (De Melo 1994), did not uniquely distinguish some populations in our survey. *Chydorus brevilabris* and *C. sphaericus* were pooled into *C. brevilabris/sphaericus.*

According to Hudson et al. (1998) true *Eucyclops speratu*s is not found in North America and the appropriate name for North American species is *E. elegans*. This species was imperfectly described by Herrick in 1884. Later Dussart & Fernando (1990) described a new species, *E. neomaruroides*. Hudson et al. (1998) has examined this new species and concluded that it is indistinguishable from *E. elegans* which is the name used in this report.

Identifying the two *Eucyclops* species *E. serrulatus* (agilis) and *E. prionophorus* has also been difficult. According to Wilson (1959) the antennules in the latter species is much shorter than the cephalothorax. However, according to Hudson et al. (1998) the length of the antennules relative to cephalothorax varies within the different parts of the Great Lakes and it may be almost as long as the cephalothorax. Also the appearance of the furca may vary and makes it therefore difficult to identify these species, which we consequently decided to pool in our dataset.

3.1.2 Microcrustaceans – sediment cores

Most of the species preserved in the sediment are littoral species transported to the deeper part of the lake, even if some of the planktonic species (*Bosmina* spp. and *Daphnia* spp.) may dominate in abundance. One main assumption is that the sediment at the deeper part is representative for the whole lake (Korhola & Rautio 2001), integrating both spatial and temporal variations. This assumption may not always be true as shown by Kattel et al. (2006) in a small mountain loch in Scotland, and the best sampling place should be between the deepest part of the lake and the shallow littoral zone.

The sediment samples for paleolimnological analysis have been provided by CFEU (J. Gunn and E. Snucins). The samples were taken near the deepest, central part of the lakes. Altogether 20 lakes in the Killarney Provincial Park were sampled. The depth at the sampling station varied between 7 and 39 m (**Table 1**). Of these 19 have been analysed (samples from Lake Carlyle is missing) with respect to remains of microcrustaceans. In six of the lakes (Lakes

Acid, OSA, Bell, Helen, Teardrop, George) the depth-time profile for the sediment core was analysed using the ^{210}Pb activity, and the age is given in unadjusted ^{210}Pb years. From these six lakes and from Lakes Norway and Nellie five intervals have been analysed. The depth-time curve is missing from Lakes Norway and Nellie, and here we have used the same age curve as in Lake OSA since the length of the sediment core and the depth of the selected segments were similar. Therefore, the age curves for Lakes Norway and Nellie are less accurate than the other age curves. In all the other lakes only two levels were analysed.

The sediment samples were taken in February and March 1999 using a Glew gravity corer (Glew 1989), with a 60 cm long lexan coring tube with inner diameter of 7.5 cm. The cores were sectioned at close intervals using a vertical extrusion device (Glew 1988). The top 5 cm of each core was sectioned into 0.5-cm intervals while the rest of the core was sectioned into 1-cm intervals down to 35 cm depth, or to its maximum depth if it was shorter than 35 cm. The individual samples were stored in twist-tie plastic sample bags in a refrigerator.

The treatment has followed standard procedures (Berglund 1986, Korhola & Rautio 2001). About 2 g of sediment has been treated with warm 10% KOH, filtered through 60 µm mesh size and diluted to 25 ml. One ml (four 0.25 ml sub-samples) has been analyzed, and all identifiable remains of cladocerans have been counted. A list of useful identification keys and papers are given by Korhola & Rautio (2001) and Bredesen et al. (2002).

The number of individuals for each species is given according to Frey (1986) by the most abundant remain, e.g. two carapax halves or one head shield is one individual.

In eight of the lakes five intervals have been analysed, tentatively two intervals from the upper part of the sediment, younger than 1970, and two from the pre-industrial period from 1880 or earlier. The fifths interval was from the period with the most intense acidification (1930-1940). In the remaining lakes only two intervals are analysed, one from a period before 1880 (pre-industrial period) and one from the period after 1970 (post-industrial period). Most of the cores go back to 1700 or even earlier. Because of differences in sedimentation rates and lack of dated cores when segments for analysis were selected, we missed the most acid period in Lake Acid, and also in other lakes the chosen segments were not always optimal. More segments from the most acid period should also have been analysed to get a better material from this period.

The current cladoceran communities are compared with paleolimnological data from the same lakes. Due to problems with species identifications, paleolimnological data give a minimum estimate of acid-sensitive chydorids present prior to acidification.

3.2 Analyses

3.2.1 Acid sensitivity

According to Walseng et al. (2003) good indicators of acidity may be of two types – acid-tolerant species that are rare in non-acidic lakes, or acid-sensitive species that are commonly observed in non-acidic lakes, and have sharp pH thresholds below which they are not observed. The last group is assigned as highly acid-sensitive in this report. Species which are clearly more common in non-acidic lakes than in acidic lakes but does not have sharp pH thresholds are assigned as moderately acid sensitive.

Identification of acid-sensitive species was based on information from several studies within Ontario. Sprules (1975) and Locke et al. (1994) studied crustacean zooplankton from 80 lakes on the Precambrian Shield in north-eastern Ontario from the most acidified period (Sprules 1975). This dataset covers lakes within 165 km of Sudbury, also including lakes in and around Killarney Provincial Park. Information on microcrustaceans (littoral and pelagic samples) from

18 lakes located near Dorset, 300 km to the SE of Killarney Provincial Park (Walseng et al. 2003), and from sediment records of cladocerans from seven Adirondack lakes in New York, USA (Patterson 1994) is also taken into consideration. All lakes were situated within the same zoogeographical region with respect to pelagic and littoral microcrustaceans and were evenly distributed along a pH gradient between 3.8 and 7.2. Identification of acid-sensitive/tolerant species was based on data from altogether 105 lakes.

In Walseng et al. (2003) only one indicator species of the first type (acid-tolerant species that are rare in non-acidic lakes), *Acanthocyclops vernalis,* was found. It was recorded in six lakes with pH less than 6.0. The two cladocerans, *Acantholeberis curvirostris* and *Alona rustica*, are known as indicators of acidic water in Norway. In North America they are also associated with low pH (Hann & Turner 2000). However, whereas they rarely occur in neutral water in Norway they seem to be found all along the pH gradient in North America. *Simocephalus serrulatus, Chydorus piger* and *Disparalona acutifrons* were also more common at low pH in the experimentally acidified lake 302S (Hann & Turner 2000) than what our results from Dorset/Killarney indicate. In Norway, *C. piger* is not found in the most acidified lakes and is characterized as a moderately acid-sensitive species. Based on zooplankton samples from 47 lakes in the La Cloche mountains (pH 3.8-7.0) (Sprules 1975), there were a very few examples of species only associated with the acidic lakes. For instance, *Dapnia pulicharia*, which was not found in our study, was only recorded from four lakes of pH 4.2-4.8.

Based on microcrustacean data from Killarney and Dorset, Walseng et al. (2003) concluded that there were several good acidification indicators of the second type (acid-sensitive species that are commonly observed in non-acidic lakes, and have sharp pH thresholds below which they are not observed). *Sinobosmina* sp. was found in all of the lakes except the five most acidic (pH <4.8). *Tropocyclops extensus* and *Mesocyclops edax* were also very common when pH was above >5.1 and >4.9, respectively, but were not found below these thresholds. *Ceriodaphnia pulchella* was never found at pH<5.4, while it occurred in 13 out 16 lakes above this pH. Of the nine species found in 20-50% of the lakes, several were good indicators of acidity. *Chydorus faviformis* was never found in lakes with pH less than 5.9. *Sida crystallina* and *Scapholeberis kingi* were only found in lakes with pH above 4.9, while the other species in this group appeared when pH was between 5.0 and 6.0. Another 28 species were observed in <20% of the lakes or lake-years, and included several, generally planktonic indicators of acidity (i.e. sensitive to acidification). This group included daphnids (*Daphnia ambigua*, *D. mendotae*, *D. dubia, D. longiremis* and *D. retrocurva*), calanoids *(Leptodiaptomus ashlandi* and *Skiptodiaptomus oregonensis*) and cyclopoid copepods (*Cyclops bicuspidatus thomasi,* and *C. varicans rubellus*).

Among littoral species Walseng et al. (2003) described the following as indicators of non-acidic lakes: *Alona costata, A. circumfimbriata/setosa, Alonella nana, Chydorus bicornutus, Camptocercus rectirostris* and *Kurzia latissima*. Five species within the genus *Pleuroxus* sp. (*P. denticulatus, P. hastatus, P. procurvis, P. striatus* and *P. truncatus*) also belong to the same category and were never found at pH <5.2.

3.2.2 Main gradients in microcrustacean communities

Patterns in the inter-species covariance structure among lakes and lake-years were summarized using Detrended Correspondence Analysis (DCA) (Hill 1979, 1980). The analyses were run using CANOCO version 4.5 with down-weighting of rare species (ter Braak & Smilauer 1998). The aim of the DCA was to arrange objects (e.g. lakes and lake-years) in a low dimensional space such that neighbouring ones have more similar species composition than more distant ones (ter Braak 1998).

Analyses of the current microcrustacean fauna from the Killarney lakes were performed on different subsets of the total dataset (all lake-years or cumulative species lists for each lake), including presence/absence data or dominance classes (see chap. 4.1.1).

Analyses of the current microcrustacena fauna from the Sudbury lakes were performed on a combined dataset including both Killarney lakes and Sudbury lakes (see chap. 4.1.2).

Analysis of the paleodata based on core samples was performed on presence/absence data including all samples (see chap. 4.1.3).

Comparison of the pre-industrial fauna, based on core samples, and the current microcrustacean fauna (see chap. 4.3). Data from the current microcrustacean fauna represented by cumulative species records 1998-99 (22 lakes) were combined with data from core samples (8 lakes). The pre-industrial fauna was represented by cumulative species records from segments representing approximately the years 1750 and 1880. Only species expected to be present in the core samples were included in the analysis.

Comparisons of historical and current microcrustacean zooplankton faunas were performed on a combined data set including all lakes (lake-years) sampled both in 1972-73 (Sprules 1975) and in our study in 1997-99 (19 lakes) (see chap. 4.4). Since Sprules handled Bosmidae as one group, *Bosmina* sp. and *Sinobosmina* sp. were pooled in our dataset from 1997-99.

Correlations with environmental variables and DCA site scores were calculated as Pearson correlation coefficients.

3.2.3 Correlations with environmental variables

We wanted to analyse the relationship between the microcrustacean species richness and composition and environmental variables. Further we wanted to evaluate which of the acidification related variables (pH, Al, ANC) most strongly correlated with the variations in these biological metrics. For these analyses we produced several subsets of the microcrustacean data (**Table 6**). Analyses were performed on the total microcrustacean community as well as for species only recorded in pelagic samples (crustacean zooplankton) with the aim to evaluate the importance of including littoral versus pelagic microcrustaceans in ecological assessment studies.

Table 6. *Data subsets from 23 Killarney lakes, Sudbury, Canada, 1997-99 used in the CCA analyses. The number of active samples (subsets III-IV: lakes x years) are presented in parentheses. Only subsets A-I and A-II were used in the regressions (table from Schartau et al. 2001a).*

Data subset	Crustacean data	Environmental data
A-I	Microcrustaceans, total dataset cumulative records (23)	Median, min and max
A-II	Microcrustaceans, total dataset separate years (57)	Yearly late autumn data
A-III	Microcrustaceans, separate years 1998-99 (22 x 2)	Yearly late autumn data
A-IV	Microcrustaceans, separate years 1997-99 (12 x 3)	Yearly late autumn data
B-III	Pelagic microcrust., separate years 1998-99 (22 x 2)	Yearly late autumn data
B-IV	Pelagic microcrust., separate years 1997-99 (12 x 3)	Yearly late autumn data

Environmental variables included in both the correlations and in multivariate analyses were as follows: pH, ANC, tot-Al, labile aluminium (LAl), DOC, Ca, conductivity (cond), total phosphorus (tot-P), Secchi depth (secchi-d), lake area, average lake depth (depth-a), maximum lake depth

(depth-m), elevation (elev), fish species richness (fish). For chemical variables, we used data obtained from water samples taken during October/ November, after fall turnover in these lakes. In analyses including cumulative species records, median, minimum and maximum values for the period 1996-1999 were used. In analyses including yearly records of microcrustaceans, yearly late autumn values were used.

The analyses of relationships between species richness and composition and environmental variables were performed in 2001, i.e. before the decision to pool records of *Sinobosmina freyi* and *S. liederi* into *Sinobosmina* spp. and *Eucyclops serrulatus* (agilis) and *E. prionophorus* into *E. serrulatus/pronophorus*. However, this has no consequences the main results from the correlation analyses.

Regressions

Simple and multiple regression analyses were used to relate the number of microcrustacean species to environmental variables. In multiple regressions, the predictive power of the model parameters are given by the adjusted coefficient of determination (r^2). The correlations between species richness and environmental data were analysed for two separate subsets including all lakes: the subset A-I representing cumulative species records, and subset A-II representing yearly species records (see **Table 6**). All regression analyses were performed using SPSS.

Ordinations

Direct gradient analyses with forward selections (CCA: Canonical Correspondence Analysis) were used to provide an overview of the relationships between the sample sites, based on records of presence/absence of microcrustacean species, and environmental variables. The analyses were performed using the program CANOCO version 4 (ter Braak and Smilauer 1998). Down-weighting was applied to all species with a frequency below the median frequency (Eilertsen et al. 1990) to reduce the effect of unusual samples on the ordination (ter Braak & Smilauer 1998). All of the environmental data except pH, lake depth and fish species number were transformed (Ln (x+1)) to improve normality. The correlation between the microcrustacean composition and environmental data were evaluated for subsets I, III and IV (**Table 6**). For subsets III and IV our aim was to control for autocorrelation in time and to use the ordination to focus on effects of acidification and other explanatory variables. The effect of time (sampling year) was first tested and then removed by specifying time as a covariable. Each environmental variable was tested by Monte Carlo permutation significance tests with 199 unrestricted permutations (ter Braak & Smilauer 1998) before adding it to the model. Sequential Bonferroni adjustments of the significance level were performed for all multiple tests (Rice 1989).

4 Results

4.1 Current microcrustacean community

4.1.1 Killarney lakes

4.1.1.1 General description

We found 81 microcrustacean species, including 58 cladocerans and 23 copepods (**Appendix 2**). Five of the copepods were calanoids whereas 18 were cyclopoid copepods. Three cladocerans; *Acroperus harpae*, *Chydorus piger* and *Polyhemus pediculus* and the calanoid, *Leptodiaptomus minutus*, were found in all lakes (**Appendix 3**). Among cyclopoid copepods, *Eucyclops serrulatus* occurred most frequently, and was found in 21 lakes. Altogether 25 species were found in more than 50 % of the lakes.

The total species richness among lakes ranged from 13 in the acidic Nellie Lake (11 cladocerans and two copepods) to 51 in the non-acidic Ishmael Lake (34 cladocerans and 17 copepods) (**Figure 3**).

The DCA analysis run on presence/absence data for all years/lakes separated acid from non-acid lakes (**Figure 4**). The lengths of the first two axes were 2.2 and 1.8 SDs, respectively (**Table 7**). The first axis explained 14.8% of the total variance in the presence-absence data. Additionally 6.9% was explained by axis 2. When dominance data were used instead of presence-absence as input for the DCA analyses, only in minor changes were resulted. Teardrop Lake is an outlayer along axis 2 in both analyses. This is mainly caused by some unique species not found in any other lake. The number of *Daphnia* species, is for instance higher in Lake Teardrop compared to other lakes. When this lake was excluded from the analysis, the length of axis 2 decreased to 1.4 SD`s. The correlation between pH and axis 1 was very strong (r^2=0.80, p<0.001) (**Figure 5**).

The cladocerans *Acantholeberis curvirostris*, *Alona intermedia*, *A. rustica*, *Ilyocryptus spinifer* and *Ophryoxus gracilis* are associated with the acidic lakes (**Figure 6**). *A. curvirostris* and *A, rustica* is also the strongest indicators of acidity among cladocerans in Norwegian lakes. *I. spinifer* is not found in Europe but its relative, *Ilyocryptus sordidus* is commonly found in acidic lakes in Norway. However, *A. intermedia* and *O. gracilis* do not occur in the most acidic lakes in Norway and are both categorized as moderately sensitive species. Differences in tolerance towards pH for the same nominal species in the two continents may raise the question whether they are the same species or not. Among copepods *Orthocyclops modestus* was most stronly associated with acidic lakes.

The calanoid *Lepodiaptomus minutus* is dominating in all acidic lakes but since it also dominates in non-acidic lakes it has a central position in **figure 6**. The calanoid *Eudiaptomus gracilis* in Europe also dominates in both acidic and non-acidic lakes. *L. minutus* and *E. gracilis* may therefore ecologically be equivalent species.

The *Dapnia* species, *D. longiremis*, *D. galeata mendotae* and *D. retrocurva* are found in the non-acidic end of the DCA plot (**Figure 6)**. In Norway *Daphnia* species have also been shown to be good indicators of recovery. While all *Daphnia* species are defined as acid-sensitive in Norway, there are one acid-tolerant species, *D. catawba*, in North America. The occurrence of this species has been shown to decline when pH increases (Holt & Yan 2003).

Alona costata, Lathonura rectirostris and *Leptodora kindti* are species known as acid-sensitive in Norway (Walseng 1994, Walseng & Bongard 2001).

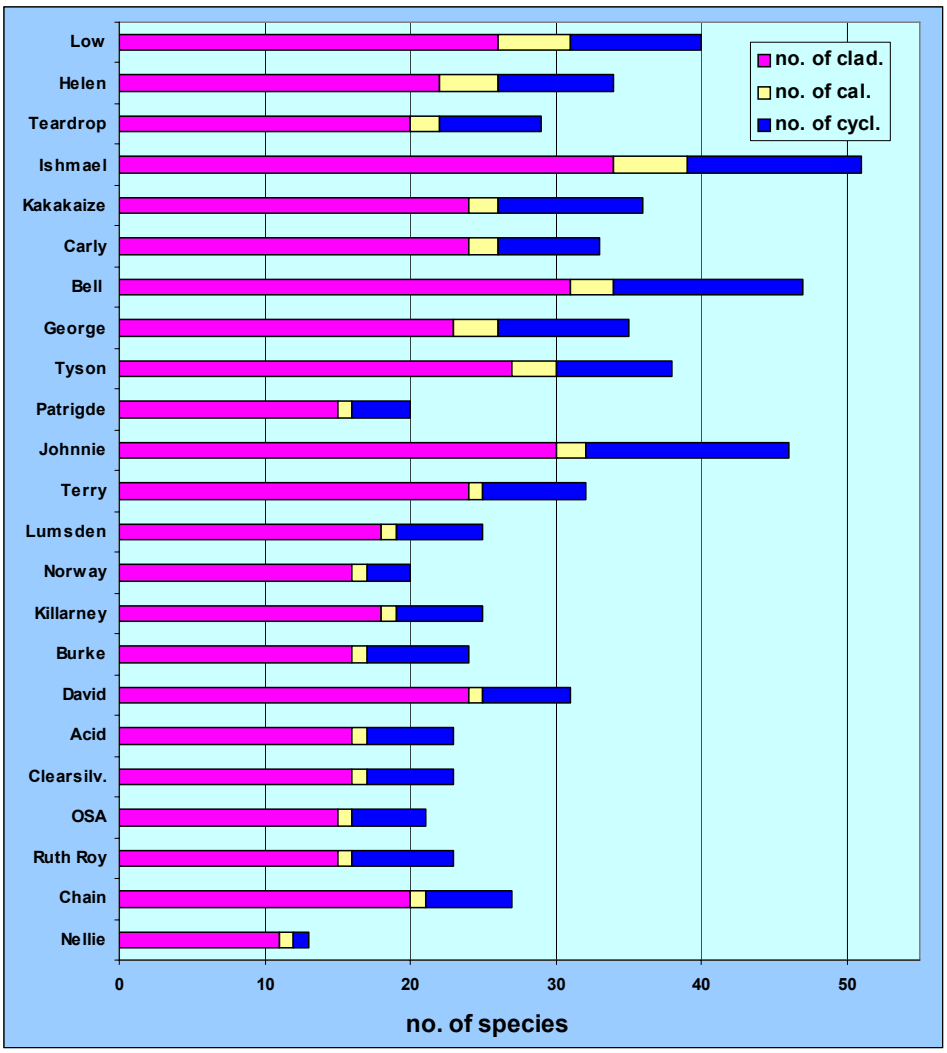

Figure 3. *Species richness of microcrustaceans (Cladocera+Calanoida+ Cyclopoida) in 23 Killarney lakes. Species richness are based on accumulated species records from 1998-1999, except for Burke Lake, which was included in the study for only one year. The lakes are sorted by decreasing pH (median values based on monitoring data from 1995-99) (top-bottom).*

Walseng & Schartau (2001) compared the species composition of planktonic and littoral crustaceans in lakes along a pH gradient in Canada and Norway. Based on two similar studies that had been conducted, one in North America (Killarney, Sudbury, Canada) and one in North Europe (Norway, Østfold county), the paper focused on: (i) do the same species occur in lakes of similar pH in the two countries, (ii) do ecologically equivalent but taxonomically different species occur in lakes with similar pH in the two countries and (iii) do the same species occur at different pH in the two countries. Though the paper mainly had addressed the crustaceans as indicators of ecological recovery of acid-stressed lakes, it also concluded that “Differences in ecological traits between similar species, may also contribute to a better understanding of their taxonomy. In the future, besides more detailed ecological studies, there is a need for genetic and morphological studies to improve our overall knowledge of the freshwater crustaceans in Europe and North America.”.

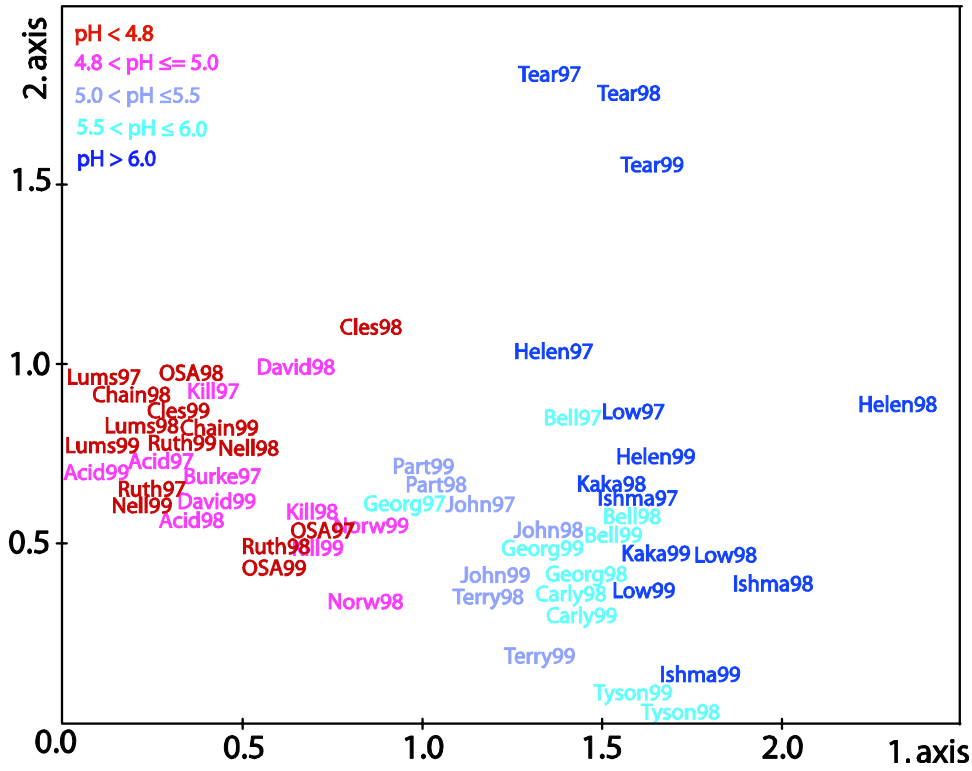

Figure 4. *Site plot (axes 1-2) based on DCA-analysis of absence/presence data from recent microcrustacean fauna in 23 Killarney lakes. The plot is based on analysis of all lake-years (1997-99).*

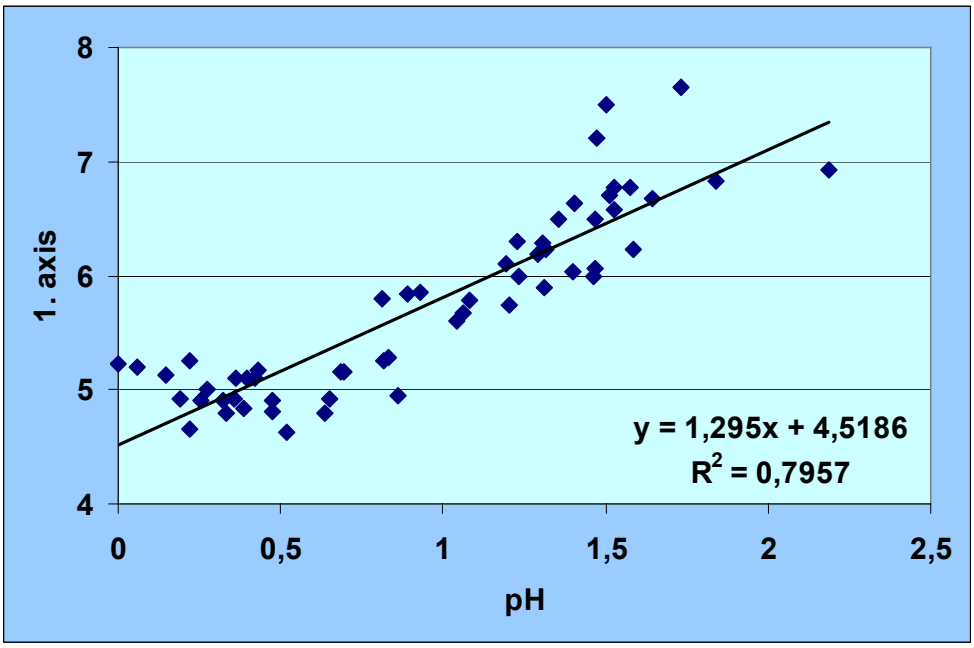

Figure 5. *Correlation between site scores (axis 1; cf.* ***Figure 4****) and pH.*

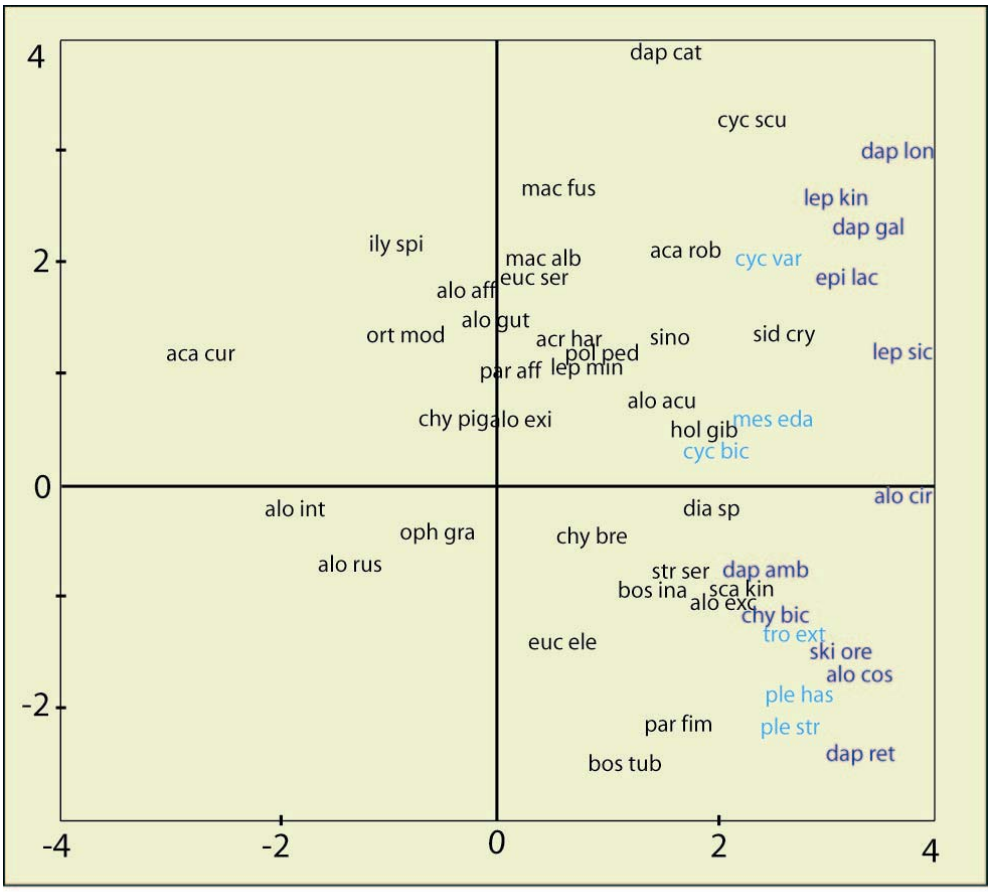

Figure 6. *Species plot (axes 1-2) based on DCA-analysis (cf. **Figure 4**). Only species that were found in more than 10% of the lakes are shown. Species indicated as acid sensitive (**see Appendix 3**) is given in light blue (moderately sensitive) or blue (highly sensitive).*

Analysis of the combined 1998/99 data set (22 lakes, Lake Burke, which was only sampled in 1997, was not included) differed only slightly from the analysis run on the all lake-year data set (1997-99). The length of axis 1 became shorter, 1.65 and 1.80, when respectively absence/presence data and dominance data were used (**Table 7**). Correspondingly, axis 1 explained respectively 17.7% and 20.5% of the variance. Also this dataset exhibited a strong correlation between pH and axis 1 (r^2=0.80, p<0.001).

Walseng et al. (2003) assessed whether two different sampling techniques, quantitative sampling by use of activity traps and qualitative sampling by use of net hauling, would differ in the identification of acid-sensitive taxa and changes in species composition associated with acidity. The DCA analysis discriminated between different sampling techniques as well as different acidification status of the lakes. However, whereas the fauna of the non-acidic lakes differed between surveys using different sampling techniques, similar faunas were identified in the acidified lakes in both surveys. The sampling bias may have disappeared for the acidified lakes with their greatly simplified communities.

Table 7. *Length of gradients, cumulative % variance of species data and total intertia from analysis run on absence/presence and dominance data from each year (1997-1999) and accumulated over years (1998-99).*

Dataset	Axis	Lengths of gradient 1	2	3	4	Cum. % var. of species data 1	2	3	4	Total inertia
I Absence/precence all years		2.19	1.75	1.23	1.28	14.8	21.7	26.0	29.5	1.504
II Dominance all years		2.06	1.82	1.05	1.13	16.6	24.8	29.4	32.9	1.353
III Absence/precence all years accumulated		1.65	1.35	1.42	1.20	17.7	24.6	30.0	33.1	1.223
IV Dominance all years accumulated		1.80	1.67	1.05	1.06	20.5	29.0	34.1	37.1	1.092

4.1.1.2 Acid-sensitive species

In total 10 microcrustacean species found in the Killarney lakes were assigned as moderately acid-sensitive and 18 species as highly acid-sensitive (see **Appendix 3**). Some of the species mentioned as acid sensitive in the literature from North America (see chap. 3.2.1) are not found in Killarney.

The relative occurrence of acid-sensitive species (moderately + highly sensitive) varied between 0 and 50 % of all microcrustacean species recorded in 1998 and 1999 (accumulated species lists). Only Lake Nellie had no acid-sensitive species. The fraction of highly acid-sensitive microcrustaceans varied between 0 and 32 %. Except for the lakes Clearsilver, OSA and David no highly acid sensitive species were found in any lake with median pH <5.5. In these three lakes, the highly sensitive species *Daphnia ambigua* or *D. galeata mendotae* were found in small numbers, and only in one of the years during the monitoring period 1997-99. It is also necessary to note that the sensitivity of the species found in our study is based on information from a small number of lakes (approximately 100 lakes). Therefore, the indication of acid-sensitivity is associated with relatively high uncertainty. In comparison the acid-sensitivity for Norwegian species is based on information from approximately 2800 lakes (B. Walseng pers.com.).

Correlation between relative presence of sensitive species and pH is shown in **Figure 7**. In non-acidified clear water lakes (pH>6.0) a minimum of 30 % of total species richness should be covered by species assigned to be moderately or highly sensitive, according to **Appendix 3**. In Norway this fraction varies between 20 and 40 %; the lowest values are found for electrolyte and nutrient-poor lakes (Schartau et al. 2001b, Schartau et al. 2006).

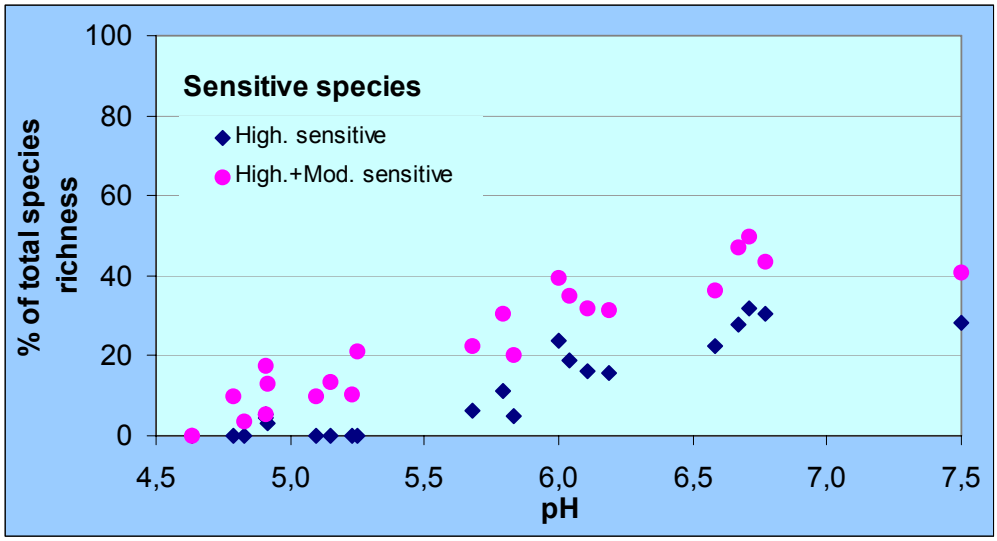

Figure 7. *Acid sensitive microcrustaceans (pelagic and littoral, see **Appendix 3**) versus pH (median values based on monitoring data from 1996-99). Sensitive species are given as % of total species richness based on accumulated species records from 1998-99. Regression between number of highly sensitive species and pH: y = -0.647 + 0.133 x, R^2 = 0.837.*

4.1.1.3 Microcrustacean communities versus environmental variables

Of the total number of 81 crustacean species recorded 34 crustaceans were defined as pelagic species.

Microcrustacean species richness (range 13-53 species/lake) was positively correlated with fish species richness, dissolved organic carbon (DOC), pH, Acid Neutralizing Capacity (ANC), total phosphorus (tot-P) and lake area and negatively correlated with aluminium, secchi disk readings and elevation (Schartau & Walseng, unpublished). Fish species richness and mean depth explained 79 % of the variance in dataset A-I whereas DOC, fish species richness and mean depth together accounted for 67 % of the variance in the dataset A-II (**Table 8**). The microcrustacean species richness was correlated with acidification-related variables (ANC, pH, aluminium), as indicated by significant linear regressions (Schartau & Walseng, unpublished). For the subset A-I the explanatory value, given by r^2, was highest for labile aluminium (LAl; r^2=0.54) followed by pH (0.49), ANC (0.44) and total aluminium (tot-Al; 0.37), For the subset A-II, ANC (0.30) was followed by pH (0.28), LAl (0.24) and tot-Al (0.13). The contributions made by LAl, fish species richness and mean depth (subset A-I) and ANC, DOC and lake area (subset A-II) yielded r^2 of 0.79 and 0.63, respectively. The results demonstrate that it is difficult to evaluate the direct and indirect effects of acidification on microcrustacean diversity.

The main gradient in the crustacean composition (CCA) was most strongly correlated with pH, which explained 13-16% of the variance in the species data (**Table 9**). The other acidification-related variables, ANC, LAl and tot-Al, explained 9-15 %, 10-16 %, and 12-14 %, respectively. Fish species richness, conductivity and DOC were positively correlated with pH but, for three of the subsets, still significant after controlling for the effect of pH. Relative to analyses based on the total species records (subset I), stronger correlations were obtained when between-year differences (subset III and IV) were taken into account. Furthermore, analyses of pelagic microcrustaceans gave stronger correlations between species composition and environmental data than analyses of total microcrustaceans. In total, the significant variables explained 30-40% and 40-54% of the total variance based on subset A and B, respectively (**Table 9**). Higher inter-sample variance for the littoral microcrustaceans relative to the pelagic microcrustaceans is expected due to the higher habitat heterogeneity in the littoral zone. We might have been

able to explain more of the variance in the total microcrustacean composition had data been available for some of the environmental variables that are thought to be of high ecological importance to littoral species, e.g. biomass and diversity of macrophytes (Duigan & Kovach 1994). Walseng (2002) has shown that by including both pelagic and littoral microcrustaceans in the analysis a better correlation between species composition and acidification is obtained compared to correlation with littoral or pelagic communities separately. The littoral species are probably especially important as indicators of lake recovery in Norway because the numbers of pelagic species in Norwegian lakes are so low. However, also for Canadian lakes littoral microcrustaceans are shown to be good indicators of acidification and biological recovery (Walseng 2002, Walseng et al. 2003).

Table 8. *Relationship between microcrustacean species richness and environmental variables identified by stepwise linear regression analyses. The analyses are based on data from 23 Killarney lakes, Sudbury, Canada. Only significant regressions (p<0.05) are listed (table from Schartau et al. 2001a).*

Subset A-I		Subset A-II	
Variables	r^2	Variables	r^2
fish species richness	0.70	DOC	0.58
+ mean depth	0.79	+ fish species richness	0.63
		+ mean depth	0.67

The influence of time was small (0.5-4.4%) and a significant correlation (p<0.05) between variation in species composition and time was found for subset A-IV only (**Figure 8**). Changes in microcrustacean species composition during the three years of study may be an indication of recovery, but may also be due to year-to-year variations in other environmental variables, e.g. the climate. Evidence of recovery over a longer period of time by pelagic crustaceans in Killarney lakes is presented by Locke et al. (1994) and also presented in chap. 4.4.

Table 9. *Relationship (extra fit/total inertia in %) between microcrustacean composition and environmental variables identified by CCA with forward selection. Time (sampling year) is included as covariable in analyses of subset III and IV. The analyses are based on data from 23 Killarney lakes, Sudbury, Canada. Only significant variables (p<0.05) are listed (table from Schartau et al. 2001a). Explanations to variable abbreviations: fish: fish species richness, cond: conductivity, elev: Elevation, area: lake area, DOC: dissolved organic carbon, depth-a: mean depth, ANC: Acid Neutralizing Capacity*.

Subset A-I		Subset A-III		Subset A-IV		Subset B-III		Subset B-IV	
pH	16	pH	13	pH	15	pH	14	pH	16
+ fish	24	+ elev	18	+ elev	22	+ elev	22	+ elev	28
+ cond	30	+ cond	23	+ area	29	+ DOC	28	+ DOC	34
		+ area	27	+ cond	33	+ cond	34	+ area	40
		+ DOC	31	+ fish	37	+ fish	37	+ ANC	45
		+ fish	34	+ depth-a	40	+ area	40	+ cond	51
		+ tot-Al	36					+ fish	54

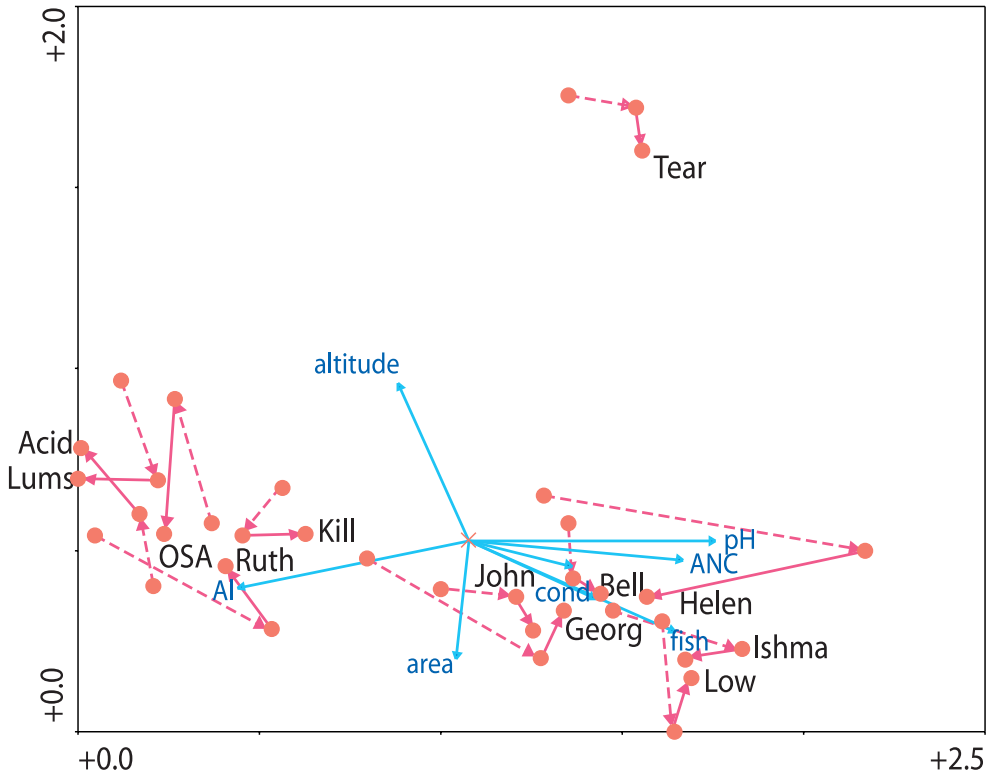

Figure 8. *Site plot (axes 1-2) based on DCA analysis of absence/presence data from recent microcrustacean fauna in 12 Killarney lakes (subset A-IV, see **Table 6** and **9**) showing the sample scores from three subsequent years, 1997-99 (dots), and the environmental variables-of-interests (arrows). Samples from the same lake are linked by arrows (1997-1998: dotted lines, 1998-99: solid lines) to indicate the year-to-year variation.*

4.1.2 Sudbury lakes

We found 41 microcrustacean species, including 25 cladocerans and 16 copepods, in the five lakes near Sudbury (**Appendix 4**). Twice as many species, it means 81, were found in 23 Killarney lakes during the same period. Four cladocerans, *Diaphanosoma brachyurum, Sinobosmina* sp., *Chydorus brevilabris/sphaericus* and *Polyhemus pediculus*, one calanoid, *Leptodiaptomus minutes,* and the cyclopoid copepods *Eucyclops serrulatus* and *Cyclops bicuspidatus thomasi* were found in all lakes. The acid-tolerant cladoceran, *Acantholeberis curvirostris* was found in the lakes Clearwater and Swan, while *Alona rustica*, also an acid-tolerant species, was found in Lake Lohi.

The highest number of species was found in Swan (29) whereas the species numbers varied between 17 and 22 for the other lakes. Except for Lake Swan these figures must be characterized as low compared with the diversity found in the Killarney lakes.

Daphnia galeata mendotae was regularly found in the lakes Middle and Hannah. Before liming in respectively 1973 (Middle Lake) and in 1975 (Hanna Lake), both lakes were dominated by *Bosmina longispina* while *D. galeata mendotae* was not found.

To get information about the recovery status of the lakes near Sudbury, they were threated passively (they do not affect the analysis) in the DCA ordination run on the Killarney lakes; cf. **Figure 4**). The analysis was run on presence/absence data for all years/lakes and the derived DCA plot divided the lakes in two groups (**Figure 9**). Lake Clearwater was associated with the acidic lakes while the lakes Hannah and Middle had more in common with the non-acidic lakes.

The crustacean fauna in the lakes Swan and Lohi was dominated by acid-tolerant species in 1997 and 1998, while a change in species composition resulted in a more “acid-sensitive” fauna in 1999. This change was mainly explained by acid-tolerant species (*Latona setifera, Alona rustica* and *Acanthocyclops vernalis*) that were not found in 1999 and to a lesser extent by the occurrence of acid-sensitive species. The lengths of the first two axes were 1.7 and 1.3 SDs, respectively. Axis 1 explained 26 % of the variance in the presence-absence data, while another 11 % was explained by axis 2.

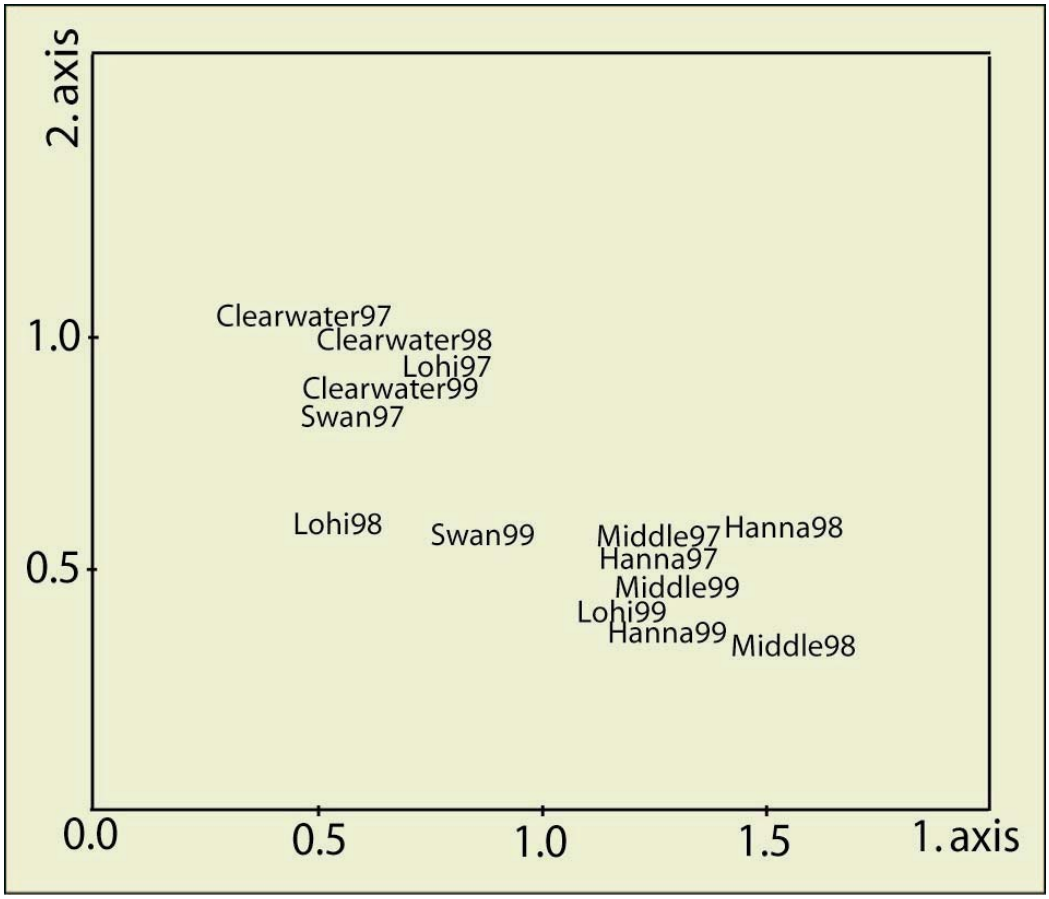

Figure 9. *Site plot (axes 1-2) based on a DCA analysis of absence/presence data from the current microcrustacean fauna in 23 Killarney lakes and 5 Sudbury lakes. The plot is based on analysis of all lake-years (1997-99) where the Sudbury lakes are treated passively. Only the Sudbury lakes are shown.*

Studies of recovery have shown that when DCA analysis is run on data sets including both acidified (<5) and near neutral lakes (about pH 7), the first axis is not only correlated with pH but also other parameters, both chemical and biological, that covary with pH. Diversity is one of these parameters (Hesthagen et al. 2007). Species number may be twice as high in acidic lakes compared with neutral lakes. A correlation between species numbers and pH shows that the species richness is as expected for Lake Swan, taken its acidification status into consideration (**Figure 10**). The remaining lakes in Sudbury (Lakes Clearwater, Hannah, Middle and Lohi) have less species than expected compared to lakes in Killarney with similar pH (indicated by the distance between the position of the lake-of-interest and the regression line, **Figure 10**). The Sudbury lakes have higher concentrations of Ca compared to most Killarney lakes. Species richness is generally positively correlated with levels of Ca (Schartau et al. 2001b, 2006), and therefore, we should expect that the species numbers in the Sudbury lakes when fully recovered from both acidification and heavy metal contamination, to be higher than for the non-acidified Killarney lakes. Compared with non-acidified lakes in Killarney at least 15-20 species

are missing from these Sudbury lakes (indicated by the distance between the position of the lake-of-interest and the maximum species numbers, **Figure 10**). Many years with heavy metal contamination in combination with acidification may directly or indirectly have caused this reduction in diversity.

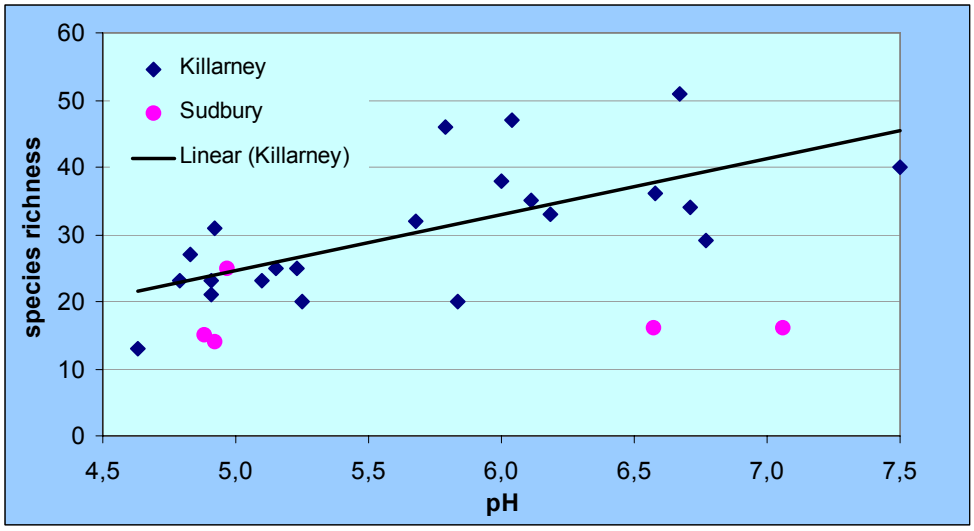

Figure 10. *Number of microcrustacean species versus pH for Killarney and Sudbury lakes. Species richness is based on accumulated species records for the period 1997-99. pH is given as respectively median values based on monitoring data from 1996-99 (Killarney) and data from 1990 (Sudbury). Regression between number of species and pH, Killarney lakes: y = 8.272 x - 16.672, R^2 = 0.457.*

4.2 Paleolimnological data on microcrustaceans

The sedimentation rates calculated from the depth profile combined with ^{210}Pb age in six lakes vary from about 0.8 mm year^{-1} in Lake Helen to 1.7 mm year^{-1} in Lakes OSA and George (S. Dixit, Queen's University, unpublished data). The sedimentation rate is usually much higher in the upper 5 cm of the sediments due to a less consolidated sediment. This was not true in Lakes OSA and George where the sedimentation rate increased with the depth. We have no explanation for this. Because of differences in sedimentation rates and lack of dated cores, the chosen segments were not always optimal for our purpose.

Altogether 33 species were found in the paleolimnological samples (**Appendix 5**). Copepods and many of the cladoceran species are not preserved in the sediment and the number of species is thus quite high compared with 58 cladoceran species found in recent samples (**Appendix 3**). We also have to take into account the fact that *Daphnia, Bosmina, Alona, Alonella, Sphaericus* and *Pleuroxus* were not fully identified to species level. Two species, *Leydigia acanthocercoides* and *Pleuroxus aduncus*, were only found in core samples. Missing records of *L. acanthocercoides* in samples from the current fauna is probably related to the ecology of this species, which inhabits the sediment surface. Missing records of *P. aduncus* in the current fauna may be due to acidification. In core samples there are no records of this species after 1970, except for Lake Clearsilver.

The number of species varied, from seven in Lake Johnnie to 25 in Lakes Acid and Tyson and 28 in Terry Lake. The number of species is generally higher in lakes where the analysis is based on five segments.

Species such as *Alona costata*, *Alona circumfimriata, Alonella nana, Chydorus bicornutus, Chydorus faviformis*, *Eurycercus* sp*., Kurtzia latissima* and *Pleuroxus hastatus* may be characterised as acid-sensitive (Patterson 1994, Walseng et al. 2003). Except for *D. catawba* which is tolerant and may occur even in the most acid lakes, *Daphnia* species are acid-sensitive, While *Daphnia* species are found in the paleolimnological samples from all lakes (**Appendix 5**), the genus was not represented in the current fauna from four of the most acidic lakes (Lakes Norway, Nellie, Chain and Killarney) (**Appendix 3**). Only a few fragments were found in Lakes OSA, Clearsilver, Killarney, Johnnie and Kakakise while Lake Terry was especially rich in fragments. In Lake Chain *Daphnia* spp. were only found in the pre-industrial period, and in Lake Nellie no remains were found in the uppermost segment.

Remains of *Bosmina* spp. were totally dominant in all but one lake and in all segments. Usually more than 60 % of all individuals were from these species (**Figure 11**). In Lake Teardrop *Bosmina* spp. were missing in the deepest stratum and occurred in very low numbers in the upper strata. In the present fauna four species of *Bosmina/Sinobosmina* occur, two species of the *Bosmina* group and the two *Sinobosmina*-species, *S. freyi* and *S. liederi*. The dominant species in the sediment in all lakes seems to be *B. longispina*. In 14 out of 19 lakes the frequencies of *Bosmina* spp. were highest in the deeper segments. In the Lakes Bell, Helen, Nellie, and George there was a tendency to a reduced dominance in the most recent, uppermost sediment layers. It is also observed a reduction in Lakes OSA, Chain and Terry during the last 50 years.

Other common species were *Acroperus harpae* and *Alona affinis*, only missing in one lake, and *Sida crystallina, Chydorus bicornutus* and *Eurycercus sp.,* only missing in two lakes. *Latona setifera* and *Alona guttata* were also common. Except for *C. bicornutus* and *Eurycercus* sp. the other species are not acid-sensitive.

Daphnia spp. were found in all the lakes in the pre-industrial period (before 1880), as well as in the most acid period between 1880 and 1970 (only eight lakes studied), though often in very low numbers (**Appendix 6**). In the post-industrial period (1970 and later) *Daphnia* spp. were found in all except for Lakes Clearsilver and Nellie and. In Lakes Chain, Killarney and OSA they occurred in low numbers (**Appendix 6, Figure 12**). All these are naturally acid or were strongly acidified during the industrial period with slow recovery.

Daphnia remains are usually not identified to species but some belong to the *longispina* group, with *D. galeata mendotae* and *D. longiremis* as probably the most common species according to the current fauna. *D. galeata mendotae* occurs in 80 % of the lakes in the Sudbury area (Pollard 2000), compared to ca 40% in our lakes (**Appendix 3**). Species in the *Daphnia pulex* group, occurred in the lakes David, Chain, Kakakise, Killarney, and Tyson. The acid-tolerant *D. catawba* was observed with certainty only in Lake OSA.

The occurrences of *Daphnia* spp. from the pre-industrial period until the present time, vary between lakes (**Figure 12**). In Lakes George and Helen the abundance of *Daphnia* spp. increased or was very high during the most acid period and then decreased up to the present. In Lake Nellie *Daphnia* spp. were not found in the uppermost layer. This corresponds to a lack of daphnids also in the current fauna. In Lakes Norway and Bell, however, the abundance decreased during the most acid period and increased afterwards. These two lakes have experienced fast chemical recovery. This may also be the situation in Lake Acid although there are no data from the most acid period. These different responses to acidification can have different explanations. Some fish species can be even more sensitive to acidification than many of the crustacean species. Therefore, the increase in *Daphnia* spp. during the most acid period may be due to reduced predation caused by extinction of plaktivorous fish. The reduced occurrence of fish will also enhance the invertebrate predation. A parallel increase in invertebrate predation will, however, not directly affect the *Daphnia* population. Following the chemical recovery from 1970 and onwards, the predation pressure on daphnids and other large zooplankton has probably increased by the introduction and reestablishment of fish.

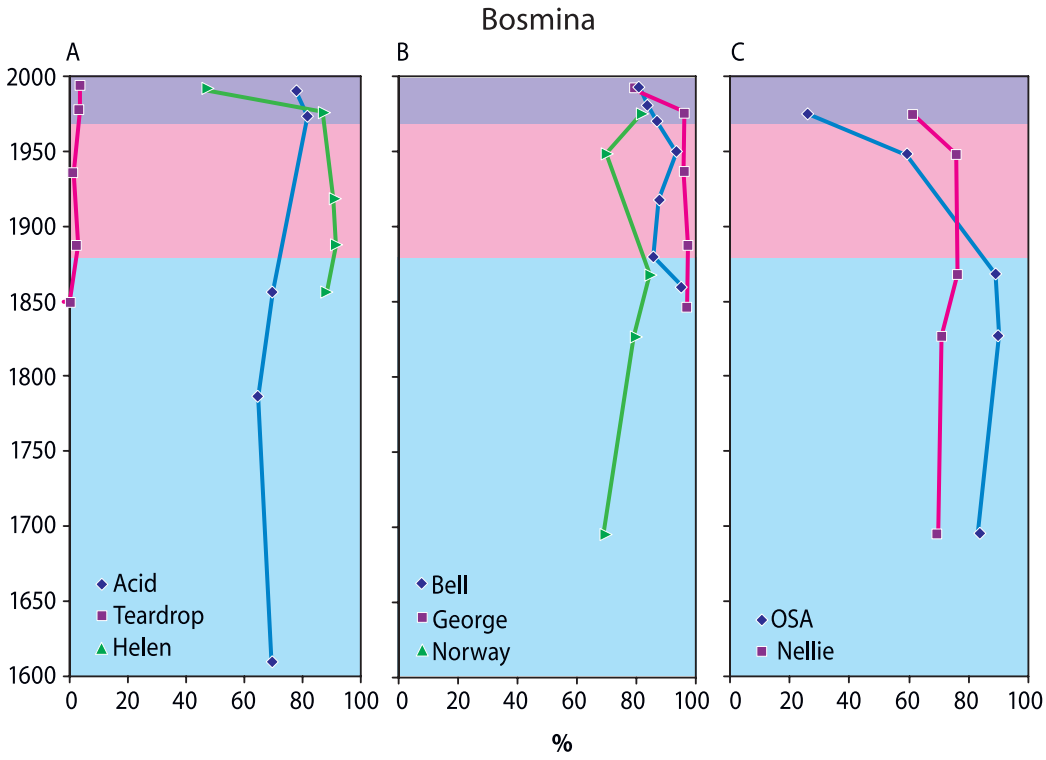

Figure 11. *Relative abundance (% of all Cladocera remains) of* Bosmina *spp. in sediment cores from 8 Killarney lakes. Depth-time profile for the sediment cores were estimated as described in the main text. The main three periods with regard to acidification are indicated with different colours; light blue: pre-acidification period, pink: acidification period, blue: period with chemical recovery A: Lakes which have never been severely acidified, B: Lakes which have been acidified but have shown a clear chemical recovery, C: Lakes which have been severely acidified and only show a slow chemical recovery.*

Pollard (2000) studied the accumulation of *Daphnia*-ephippia in sediment layers in 12 Sudbury lakes. The accumulation rate varied greatly between the lakes but statistical comparisons with lake morphology, water chemistry (including acidification), and trophic status could not explain these variations in deposition rates. In some of the lakes *Daphnia* spp. disappeared totally during the most acid period while in others they withstood the acidification. Similar results are found in our lakes. Other studies also show confusing results concerning the effects of acidification and recovery (Hann & Turner 2000).

Pollard et al. (2003) also analyzed the occurrence of *Daphnia* species back to 1400 in one lake (Hannah Lake), a lake suffering both from acidification and metal pollution. The dominating species in the whole period was *D. pulicaria*, a member of the *pulex group,* while at least three other species alternated at different depth intervals. This may also be the situation in our lakes.

Diversity calculated as the Shannon diversity index, 'H, varied somewhat with depth (age) (**Figure 13**). *Bosmina* spp. is not included in the calculation of the diversity index as they normally are totally dominating. There were no clear patterns in the species diversity over time. In Lakes Acid, Norway, George and Helen the diversity was at it lowest in the period 1940-1960 with some increase in the later years. In Lakes OSA, Nellie and Bell the diversity also decreased during this period, but here the decrease continued after 1970. In Teardrop no changes were observed.

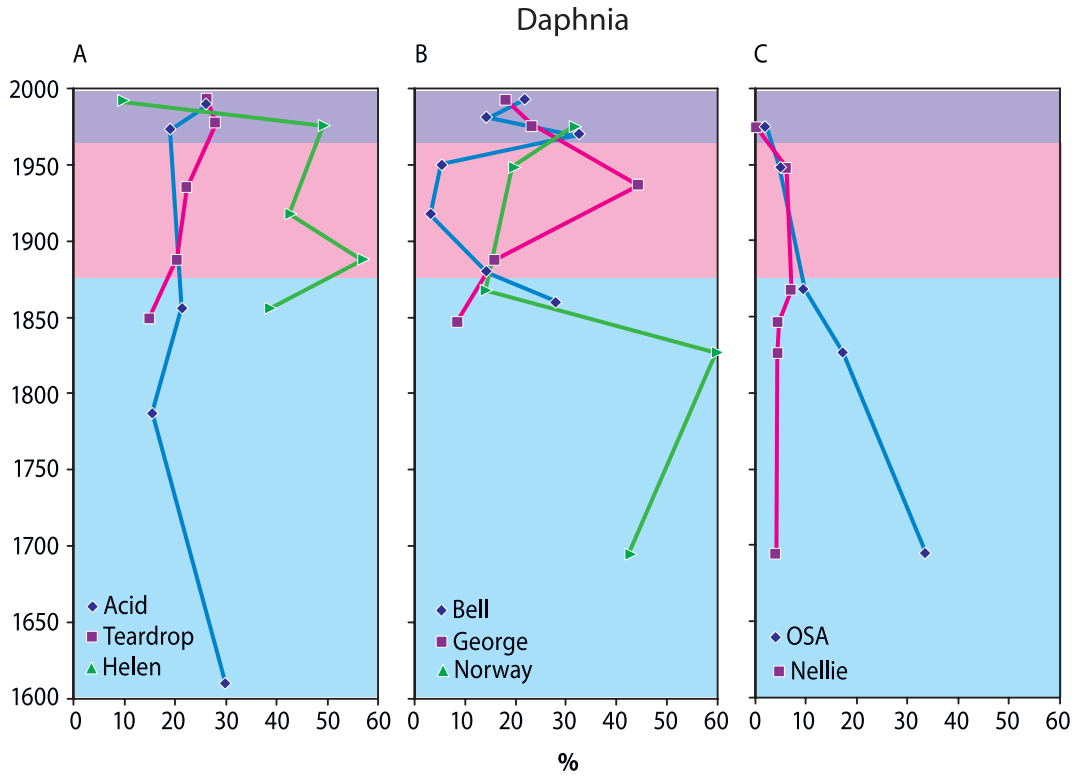

Figure 12. *Relative abundance (% of all Cladocera remains) of Daphnia spp. in sediment cores from 8 Killarney lakes. See **figure 11** for further description.*

Neither the comparison of the total microcrustacean communities (DCA) did indicate any clear patterns with regard to spatial or temporal variation (figure not shown). One reason for this may be that most of the species are quite tolerant against acidification. Some of the lakes are naturally acid and, probably, the most sensitive species were not occurring even in the pre-industrial period. Sensitive species may also occasionally be found in very low numbers even during the most acid period as they may occur in small subpopulations in the littoral zone, more or less unaffected by the acidification, or they may be transported into the lake by the inflow (Pollard et al. 2003). Since our DCA analysis is based on presence/absence of species a few observations of a species may be assigned too high importance in the assessment.

Generally, the number of cladoceran species decrease during acidification, and also the abundance and dominance are changing (cf. Patterson 1994). Our results show, however, that there is no simple correlation between individual species occurrence and acidity. In recent material from the same lakes Schartau et al. (2001a) found that species richness was positively correlated with acidification related variables like pH and ANC, although the variation in species richness was best explained by a combination of DOC, fish and lake size (see **Table 8**). Results from other areas indicate some unexplained changes in the sediment records also in non-acidified lakes (Patterson 1994).

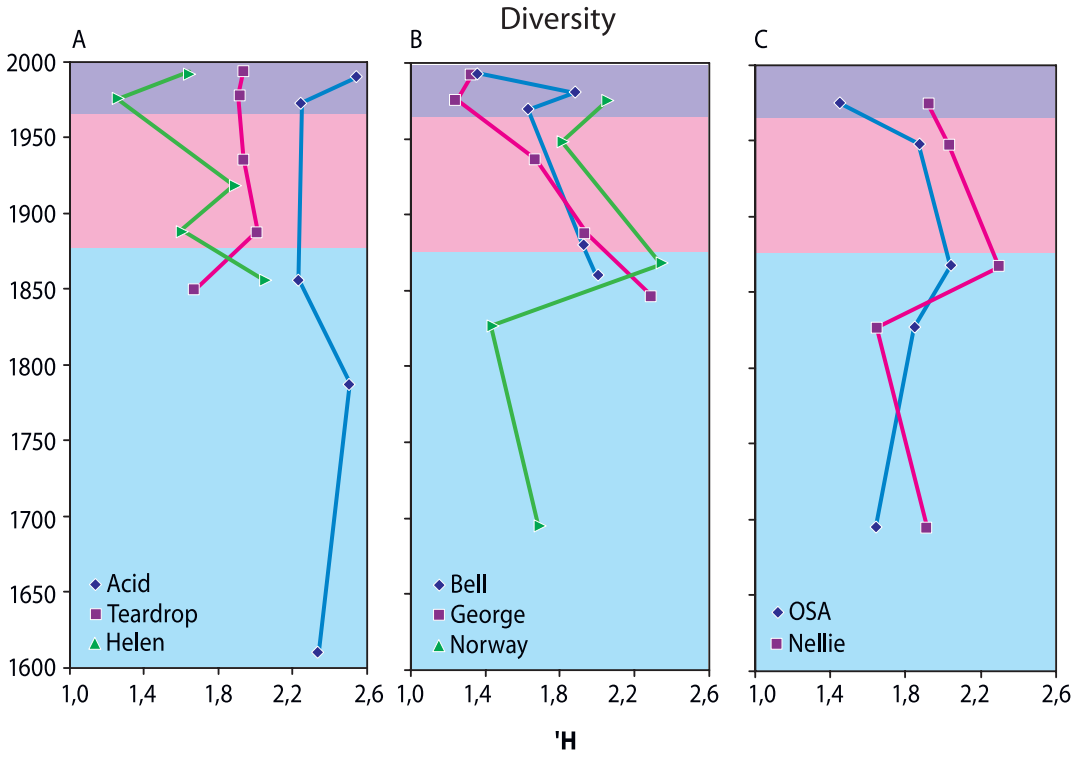

Figure 13. *Shannon diversity index, 'H, calculated on basis of sediment records on cladocerans (*Bosmina *spp. is not included, see main text) from 8 Killarney lakes. See* ***figure 11*** *for further description.*

To summarize, we have not observed any significant changes in the cladoceran fauna from the pre-industrial (before 1880) period until the present, and no significant differences between the fauna from the strongest acidified period before 1970 and the pre-industrial period based on sediment records. There are several reasons for this:

i) the number of segments analysed is too small, especially from the most acid period,
ii) possible problems due to variation in preservation rates of different species,
iii) some of the lakes are naturally acid, and have been acid also long before the industrial period, and therefore the most acid-sensitive species have never been present,
iv) we have no information about the fish population in the pre-industrial period, and in later years natural recovery and restocking of the fish fauna has occurred, influencing the pelagic and littoral fauna,
v) there is no information about invertebrate predation,
vi) long-term changes in metal (Belzile et al. 2004) deposition and algal composition (Vinebrooke et al. 2002) in the Killarney area with unknown effects

4.3 Comparison of current and pre-industrial faunas

Comparison of acid-sensitive microcrustaceans in the pre-industrial fauna and in the current microcrustacean fauna illustrates how far the lakes are from full recovery (**Figure 14**). Although the community of a fully recovered lake is not expected to be identical to the pre-industrial community, the species richness and fraction of acid-sensitive species should not be far from what is indicated by the pre-industrial community. In this comparison we have taken into account that only some species are well conserved in sediment samples and are possible to identify to species level (see chap. 4.2). Therefore only 9 of 27 sensitive species presented in **Appendix 3** are included in this analysis, varying around 40 % for single lakes. Generally there is a decreasing difference between the pre-industrial and current faunas with decreasing difference in acidification status. The core samples indicate that some lakes, like OSA, Partridge and George, probably always have had a low fraction of acid sensitive species, although we have no information that could confirm or explain this situation. The pre-industrial fauna is based only on one or two samples. Due to high heterogeneity in the sediments and pronounced variation between samples, the number of samples is probably too low to give a good estimate of the reference conditions. Difficulties with species identification may also underestimate the total number of species as well as the number of sensitive species Therefore, the estimated difference between pre-industrial and current species richness may be underestimated, meaning that for some lakes the pre-industrial species richness should be higher than the actual number recorded. On the other hand, the paleo records of cladocerans confirm that lakes which today are assigned as severely acidified (e.g. Lakes Nellie, Norway, Acid), in pre-industrial time had a fauna with several acid-sensitive species.

Lake Chain shows the greatest difference between the pre-industrial and current faunas (6 acid-sensitive species missing). Taken into account that probably not more than 40 % of sensitive species in the pre-industrial fauna is included in our core samples, approximately 15 acid-sensitive species should be expected when this lake is fully recovered. Except for Lakes Terry and Helen, lakes which are expected to have recovered chemically (difference between pre-industrial and current pH is less than 0.2 units) show relatively small differences between pre-industrial and current numbers of acid-sensitive species. Samples from 1997 (not included in the analysis) indicate that the current number of sensitive species in Lake Helen probably is underestimated. Analyses of species composition (see **figure 15**), comparison of the current fauna in Lake Helen with data from other lakes in the region and comparison of the current fauna with historical data from the most acidified period (see chap. 5.2), also confirm the reference status of this lake.

Despite the differences with species identification, results from Killarney are in accordance with our results from Norwegian lakes, showing that differences between the pre-industrial and current microcrustacean faunas reflect the acidification status of the lakes (Schartau & Halvorsen 2003).

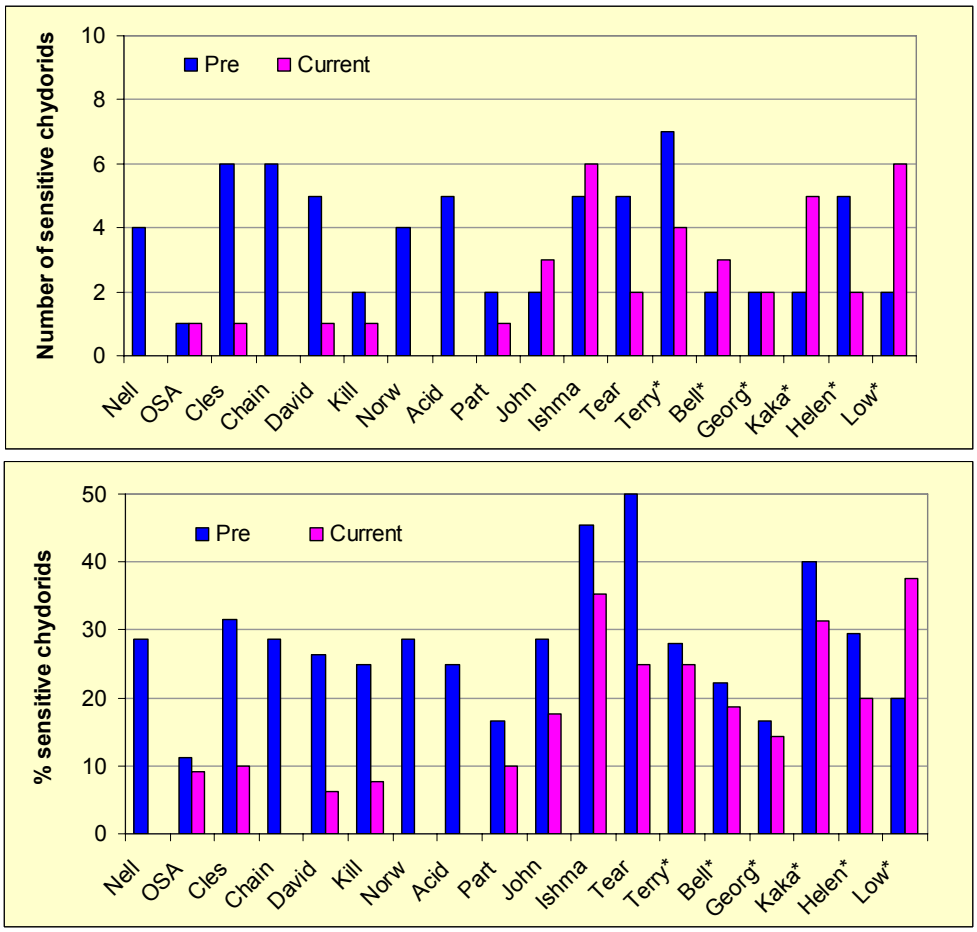

Figure 14. *Acid-sensitive cladocerans (mainly chydorids) in the current (see **Appendix 3)** and pre-industrial faunas (see **Appendix 7**) based on accumulated species records from respectively 1998-99 (current fauna) and core samples representing the pre-industrial fauna. Only taxa that are preserved in core samples and possible to identify to species or genus are included. A. Number of species, B: Sensitive species given as % of total species richness. Lakes are sorted by decreasing difference in acidity (calculated from pre-industrial vs. current H^+), except for lakes with pH difference of less than 0.2 units (*) which are sorted according to increasing pH (left to right).*

A comparison of the species composition (DCA analysis) based on respectively the current fauna and the pre-industrial fauna is shown in **Figure 15**. The analysis was run on accumulated species records for respectively the pre-industrial fauna (two sediment segments per lake) and the current fauna (1998-99).

We had to take into account that there are great differences in how the cladoceran species are preserved in the sediment when we compared the recent fauna with the pre-industrial fauna. *Daphnia* and *Bosmina* species were therefore treated at genus level because species were difficult to identify. In addition to these two genera, non-chydorids were represented by *Lathonura setosa*, *Sida crystallina* and *Ophryoxus gracilis*. Chydorids are generally much better preserved in the sediments than other cladocerans.

The first axis explained 22.7 % of the total variance in the presence-absence data, while 8.3 % was explained by axis 2. Though two third of the species were excluded from the analysis there was still a strong correlation between pH and axis 1 (r^2=0.78, p<0.001). This is also reflected in the site plot (**Figure 15**) showing the acidic lakes and non-acidic lakes at different

ends of axis 1. Except for the Lakes Helen and Teardrop, the differences between the pre-industrial and the current microcrustacean communities (chydorids) are associated with changes in acidity (i.e. shifts in species composition correspond with the changes in water chemistry, both regarding the distance and the direction). When we define the pre-acidification situation as a goal for the lakes, there is still a way to go before the recovery is completed. According to **Figure 15** Lake Acid has the most acidic fauna compared to what is supposed to be the non-acidified reference conditions. This lake does not have *Daphnia* sp. and other sensitive species today, while *Daphnia* sp. (not the acid-tolerant species *D. catawba*), and the acid-sensitive littoral species, *Alona costata* and *Chydorus faviformis*, were found in segments representing the pre-acidification period. These species are found in the neutral end of the species plot (i.e. to the right in **Figure 16**).

The lakes Helen and Teardrop have not been severely affected by acidification and it is therefore not surprising that the recent fauna in both these lakes corresponds well to the fauna found prior to acidification.

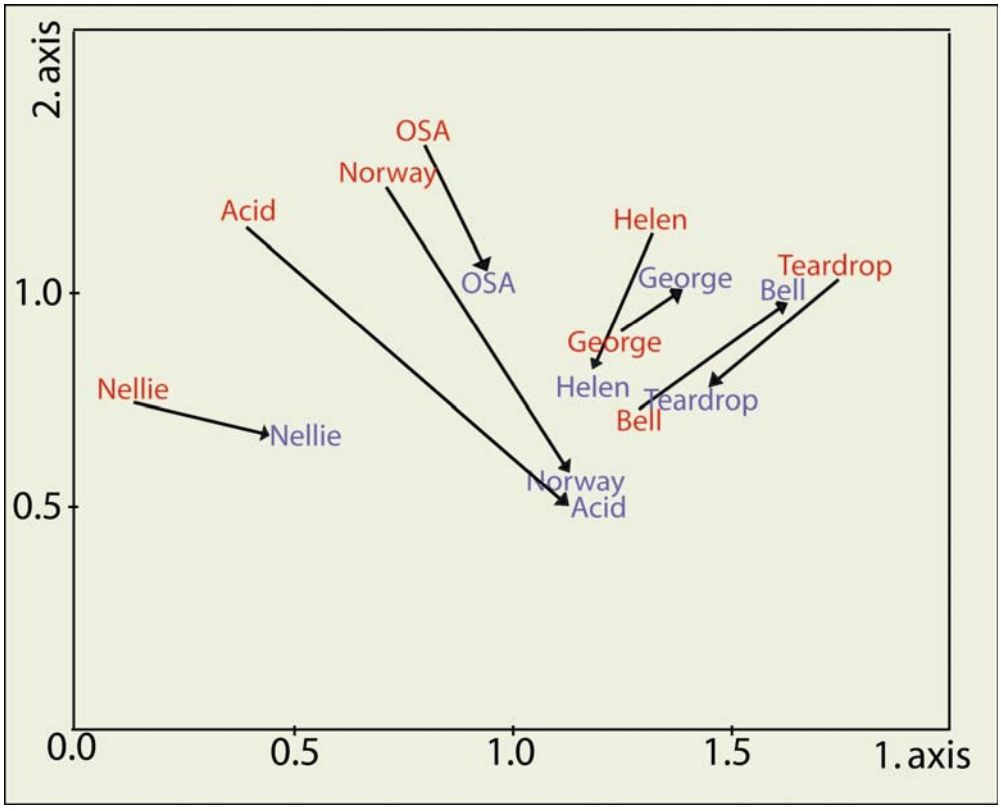

Figure 15. *Comparison of pre-industrial (blue) and current (red) microcrustacean faunas based on DCA analysis of absence/presence data. The plot is based on analysis of 22 lakes with data on the current fauna but only lakes with data on both the current and pre-industrial faunas are shown. Data from the latter group (paleo data) is treated passively in the DCA analysis; it means that these data did not influence the main gradients. The length of the first two axes was 1.7 and 1.4 SDs, respectively.*

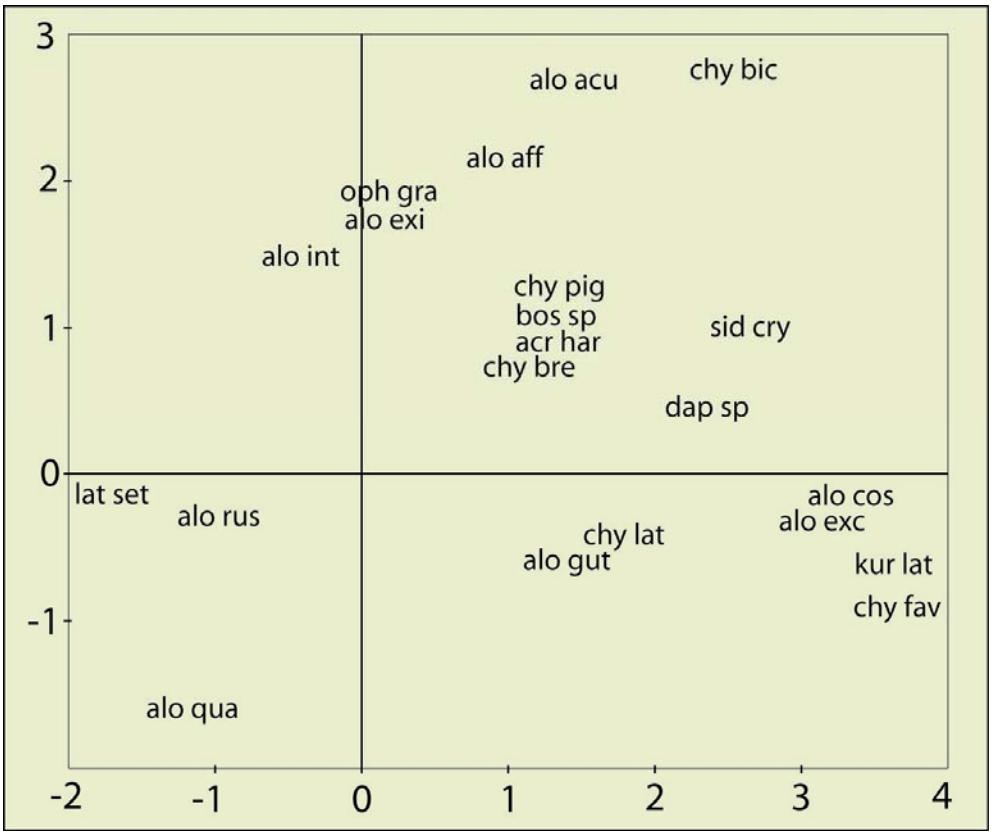

Figure 16. *Species plot (axes 1-2) based on DCA analysis (cf.* ***Figure 15****). Only species that were found in more than 10% of the lakes are shown.*

4.4 Comparison of current and historical faunas

Historical (Sprules 1975) and current microcrustacean zooplankton faunas (this study, including only pelagic samples) have been compared by the help of DCA analysis. In all 27 zooplankton species (16 cladocerans and 11 copepods) were included in this dataset. In the following presentation we have focused on biological responses for respectively 1) lakes that never have been severely acidified (pH always >6.0), 2) lakes that have been acidified and now have a pH >5, 3) lakes that have been acidified and still have a pH ≤5.0, presenting one example lake for each of these acidification categories.

Lakes that never have been severely acidified

The Lakes Helen, Low and Ishmael are all situated in the western part of the Killarney Provincial Park. In this area the bedrock is rich in calcium and these lakes have therefore to a lesser extent suffered from acidification. According to Sprules (1975) pH was 7.0 in Lakes Helen and Low while pH was 6.4 in Lake Ishmael in 1972-73. There have been no or only small changes in the species composition during the last 30 years, here illustrated by Lake Helen (**Figure 17**). The cladocerans are dominated by *Bosmina* sp. and *Daphnia galeata mendota*. *D. dubia* was a new species to the lake in 1997. *Cyclops bicuspidatus thomasi* is the dominant copepod in both periods, but also the cyclopoids *Tropocyclops pratensis mexicanus* and *Mesocyclops edax* are found both in 1972-73 and in 1997-99. Calanoids make up a smaller proportion than cyclopoids and includes three species; *Leptodiaptomus minutus* and *Epischura lacuctris* that were found in both periods while *Leptodiaptomus sicilis* in our study has replaced *Skistodiaptomus oregonensis* which was found in 1972-73.

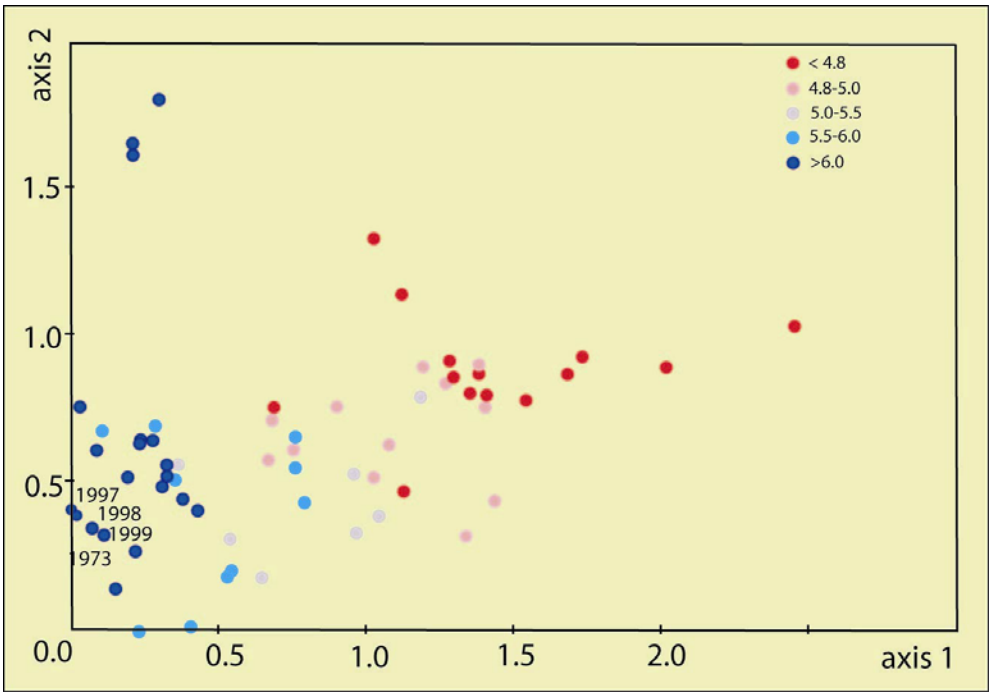

Figure 17. *Biological recovery in Lake Helen (a non- or slightly acidified lake) indicated by comparison of historical (from the most acidic period) and current microcrustacean zooplankton faunas. Sample scores representing Lake Helen is indicated by years. The DCA analysis is based on absence/presence data (only pelagic samples) from 19 lakes with data from respectively 1972-73 (Sprules 1975) and 1997-99 (this study). Data from 1972-73 are treated passively.*

Lakes that have been acidified and now have a pH >5

The weakly acidic Lake George has changed position along axis 1 in the DCA plot (**Figure 18**). In 1972-73 the lake was found in the acidic end of axis 1. Based on zooplankton samples 25 yr later it has moved towards the neutral end of axis 1. Lake George was characterized by an "acid-tolerant" composition of zooplankton species in 1972-73; *Leptodiatomus minutus* (60 %), *Holopedium gibberum* (26 %) and *Bosminidae* (14 %). In addition to these species, the cladoceran *Polyphemus pediculus* was recorded. New species in our study compared to Sprules (1975) was *Diaphanosoma* sp, *Skistodiaptomus oregonensis*, *Cyclops bicuspidatus thomasi* and *Mesocyclops edax*. All these new species indicate that the water quality has been improving since the 1972-73 survey. The Lakes Carlyle, Johnnie and Kakakise have changed their position along axis 1 in the same direction as Lake George, although the biological recovery is less pronounced. Lake Lumsden, on the contrary, has changed position along axis 1 in the opposite direction, indicating that this lake might be more acidic today than 25 years ago. The shift is explained by *Holopedium gibberum* and *Daphnia catabwa* which were found in 1973 and not in 1997-99. However, these two species are not considered to be especially sensitive to acidification. Lake Terry has not changed position along axis 1.

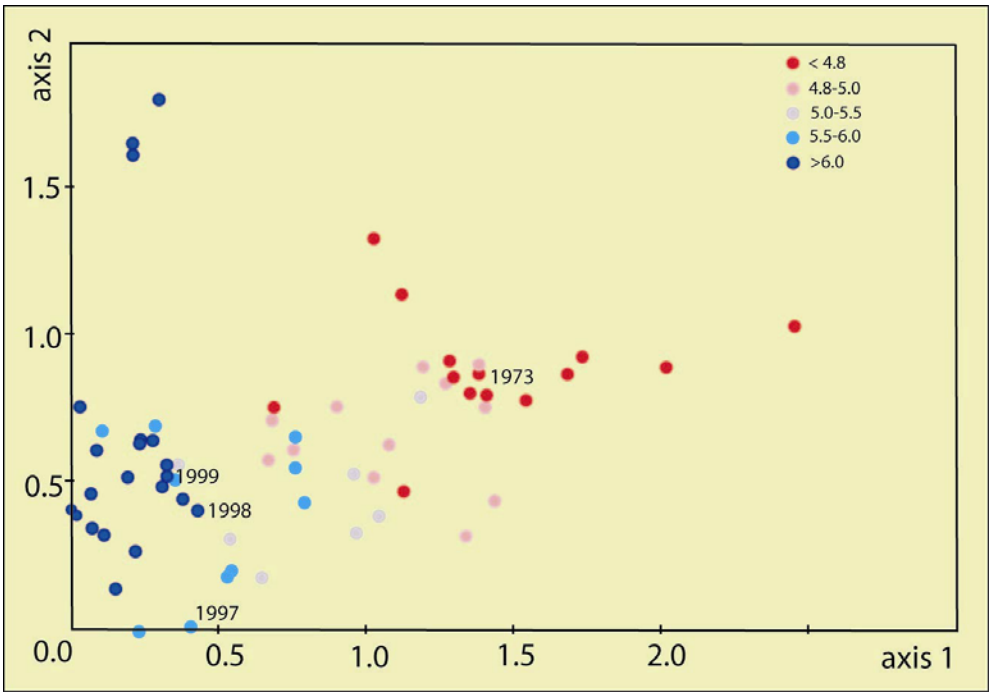

Figure 18. *Biological recovery in Lake George (an acidified lake with relatively fast chemical recovery) indicated by comparison of historical (from the most acidic period) and current microcrustacean zooplankton faunas. See* ***Figure 17*** *for further information.*

Lakes that have been acidified and still have a pH ≤5.0

Lake OSA is still found in the acidic end of axis 1 in the DCA ordination (**Figure 19**). Today's composition of the zooplankton is quite similar to that in 1972-73 with a dominance of *Leptodiatomus minutus* and with smaller fractions of *Holopedium gibberum* and *Bosminidae*. Except for the calanoid *L. minutus*, the zooplankton is poor in copepods and even *Cyclops bicuspidatus thomasi* which is one of the most tolerant, is not found. *Daphnia ambigua* was recorded in 1999 and may be a first sign of recovery. The Lakes Clearsilver, David, Killarney, Nellie, Norway and Partridge show signs of recovery visualized by a change in their position along axis 1 from the acidic towards the neutral end. In contrast, Lake Acid has become more "acidic". The situation in the latter lake is comparable to Lake Lumsden, meaning that the less sensitive cladocerans *Holopedium gibberum* and *Daphnia catabwa,* which were found in 1972-73, were no found during our survey.

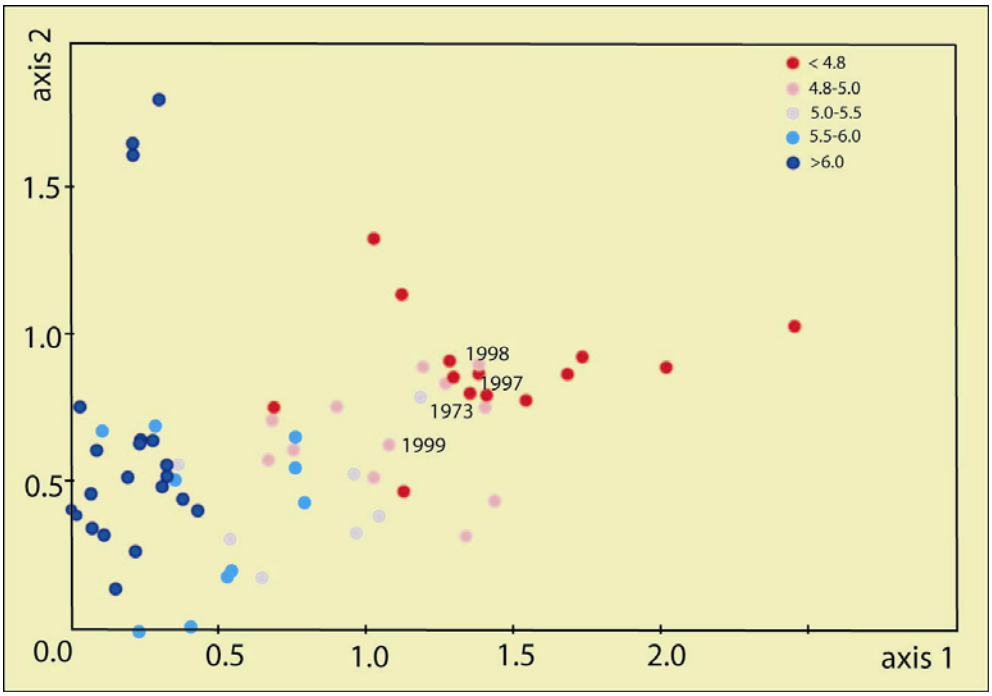

Figure 19. *Biological recovery in Lake OSA (an acidified lake with slow chemical recovery) indicated by comparison of historical (from the most acidic period) and current microcrustacean zooplankton faunas. See* ***Figure 17*** *for further information.*

Relating chemical and biological recovery

Differences in site scores for DCA axis 1 based on historical and recent microcrustacean zooplankton faunas (cf. **Figure 17-19**) have been related to changes in acidity (H^+) during the same period (**Figure 20**). There is a tendency, although not significant, that biological recovery increases with increasing chemical recovery. Lakes that always have had a pH >6 show no biological changes (the differences in DCA score vary around 0). Also two of the lakes with current pH ≤5.0, and with no or only minor chemical recovery (Lakes Acid and OSA), show no significant recovery of the zooplankton during this period. It is more unexpected that two of the lakes that have a relatively fast chemical recovery with current pH >5.0 (Lakes Lumsden and Terry), show no biological recovery, or even an impoverishment of the zooplankton. The concentrations of labile aluminium are quite high in Lake Lumsden and, therefore, the water might still be too toxic for re-establishment of sensitive species. All other lakes are in the process of biological recovery. However, since DCA axis 1 is correlated with the species richness, changes in DCA scores reflect the biological recovery on a relative scale. This means that the appearance of one new species has a greater effect (i.e. the DCA difference will be greater) for species-poor systems than for species-rich systems.

Based on zooplankton data, it is not possible to estimate the rate of biological recovery for Killarney lakes with high precision, neither from historical pH values, current pH values, nor from pH changes. Higher precision of the estimates using the total microcrustacean communities, including the littoral species, should be expected. However, except for paleo-records there are no historical data on littoral microcrustaceans from these lakes.

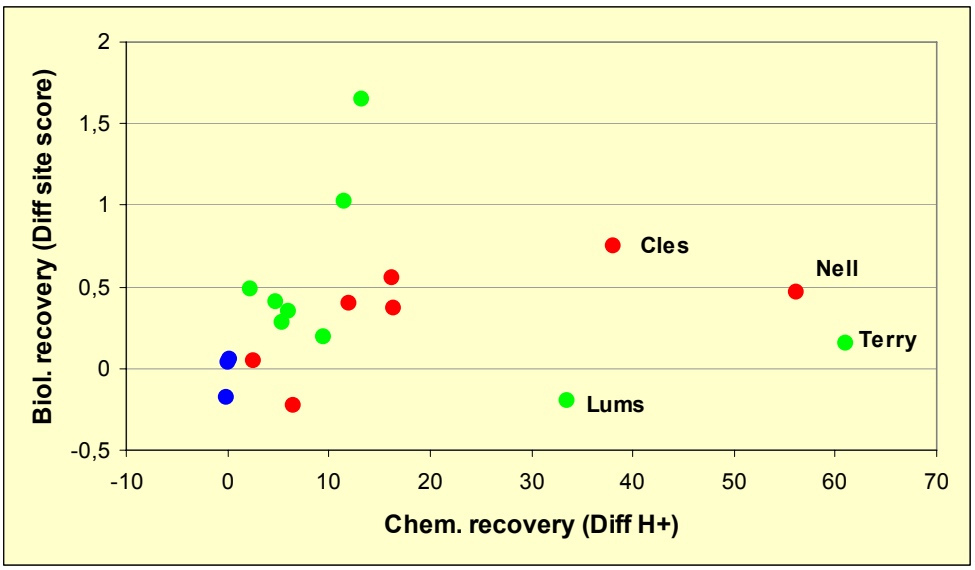

Figure 20. *Differences in site scores for DCA axis 1 from 1972-73 to 1997-99 related to change in acidity (H^+) during the same period. Site scores are based on the DCA analysis presented in* ***figures 17-19****. Red dots: lakes that have been acidified and still have a pH ≤5.0, green dots: lakes that have been acidified and now have a pH >5.0, blue dots: lakes that never have been severely acidified (pH always >6.0).*

5 Final discussion and conclusions

Studies from Canada and Norway have shown that pelagic and littoral crustaceans can be used as indicators of recovery from acidification (this study, Walseng & Schartau 2001, Walseng et al. 2003). Our study demonstrates that metrics such as species richness, occurrence of indicator species as well as species composition can be used linking pelagic and littoral microcrustaceans to acidity. Species richness has the best documented relationship to pH and alkalinity. Reduced numbers of crustacean zooplankton species have been recorded in acidic lakes in Southern Norway (Hobæk & Raddum 1980, Walseng et al. 1995), in Ontario, Canada (Carter 1971, Locke et al. 1994), and several other parts of the northern Hemisphere. Positive relationships between species richness and pH also have been recorded for the littoral crustaceans (Roff & Kwiatkowski 1977, Walseng et al. 1995). However, species richness of microcrustaceans is influenced by several factors, like ecoregion, climate, lake size and biological interactions. In our study of Killarney lakes we found species richness to be highly correlated with acidification-related variables like pH, ANC and aluminium. Fish species richness, which was positively correlated with pH, together with average depth, which was positively correlated with lake area, gave the best explanation for the variation in species richness. The results demonstrate that it is difficult to separate between direct and indirect effects of acidification on microcrustacean diversity. Multivariate metrics of zooplankton community (e.g. ordination scores) have been found to show similar patterns as species richness (Siegfried et al. 1984, Yan et al. 1996). In addition these multivariate metrics are more sensitive to community level changes because they incorporate co-variations between species.

To be able to distinguish between damaged and intact ecosystems, and assess the ecological status of water bodies subjected to acidification and other environmental pressures, knowledge of chemical and biological reference conditions is necessary. Such knowledge is also needed to set chemical and biological end-points for recovery. Biological reference conditions could be established by the following methods:

1. Historical data, i.e. data from the damaged lakes prior to acidification. From the Killarney lakes, as well as for most Norwegian lakes, we have no direct evidence of the microcrustacean fauna from the pre-industrial period.
2. Regional reference lakes representative for the water types affected by acidification. Both the Norwegian and the Canadian monitoring programmes on acidification and recovery include regional reference lakes, or lakes only insignificantly affected by acidification.
3. Paleolimnological reconstructions may provide a powerful chronology of within-lake changes. However, not all species are preserved in the sediments, or they are poorly preserved. Therefore, paleolimnological studies give information on the pre-acidification condition only for parts of the community.

The European Union's Water Framework Directive (WFD) states that different water types differ with regard to their chemical and biological features and thus type-specific reference conditions have to be established. In humic lakes natural acidity may interfere with anthropogenic acidification: natural pH for low alkalinity, humic waters can be 4.5 – 7.0. Therefore, ANC is usually included as a potential predictive variable in models that evaluate biological effects of anthropogenic acidification (Driscoll et al. 1991, Lydersen et al. 2004, Montieth et al. 2005). Most lakes in Killarney have relatively low levels of DOC (i.e. humus compounds), but there might be some lakes, e.g. Lakes Bell, Chain, Terry and Tyson[1], that have been naturally acidic in pre-industrial period. However, in the NLRS study all reference lakes belong to clear water types.

[1] *Pre-industrial pH estimated from paleolimnological studies (diatom inferred pH) indicate that Lakes Ruth-Roy, Chain, Acid, Lumsden and Terry are naturally acidic (pH<6.0). Except for Lakes Chain and Terry, these lakes have very low concentrations of DOC and therefore their natural acidity is unexpected.*

The lake recovery process has two main elements – improvements in habitat quality and biological response. The potential of biological recovery, given the restoration of habitat quality, depends on many factors. Both physical and biological factors, including degree of isolation of the water body, degree and duration of damage, characteristics of the species involved and existing biological communities are shown to influence the recovery process.

With regard to the microcrustacean communities in the Killarney lakes, there exists no historical data from pre-industrial time, nor any time-series data following the acidification and recovery process. Therefore, in the assessment of biological recovery we combined information from different approaches: comparison of the current microcrustacean faunas from acidified lakes and regional reference lakes, comparison of the current microcrustacean fauna with the paleaolimnological reconstruction of pre-industrial fauna (mainly littoral communities) and comparison of current fauna with historical data from the most acidified period (only pelagic communities). Different approaches resulted in somewhat different conclusions (**Table 10**). There are several reasons for this: We have not taken any type-specific differences in reference conditions into account (se above). There are also uncertainties related to the reconstructions of reference conditions based on paleolimnology (see chap. 5.1). Except for some of the most acidified lakes with no or very slow chemical recovery, our results indicate that all previously acidified lakes show some degree of biological recovery. However, the overall biotic response to chemical recovery remains modest and a number of hypotheses could account for this:

1. The chemical recovery is not yet sufficient to allow further biotic recovery.
2. There are time-lags in a response caused by various limitations to the dispersal of acid-sensitive species into chemically recovered sites.
3. Hysteresis in recovery caused by a variety of feasible ecological interactions that effectively close the communities of acidified systems to acid-sensitive colonists.
4. Confounding factors represented by other environmental stressors that may have significant effects on recovery from acidification.

The processes underlying these hypotheses could themselves interact, potentially leading to complex behaviour.

A rise in ANC or pH per se is not necessarily synonymous with a reduction in toxicity. The effects of acidification on aquatic organisms can be influenced by a number of different chemical variables including calcium (Ca), aluminium (Al) and humic content. Knowledge on critical values of labile aluminium and other toxic compounds with regard to microcrustaceans are generally missing. In an overview given by Muniz & Aagaard (1990) 100 µg L^{-1} of labile aluminium at pH 5.0-8.5 is indicated as critical limit for sensitive microcrustaceans. This means that during the course of our study, the water quality of some lakes (Acid, Burke, Clearsilver, Killarney, Nellie, OSA, Ruth-Roy, and probably also Chain, Lumsden, and Norway) are not supporting the re-establishment of acid sensitive organisms (**Table 10**). Holt & Yan (2003) argue that the most acid sensitive species of daphnids have a pH limit of 6.0. This means that only Lakes Bell, Carlyle, George, Helen, Ishmael, Low, Teardrop, and Tyson now have a water chemistry that may support a full biological recovery. Some of the Killarney lakes probably are fully recovered chemically (Keller et al. 2003) and, in fact, our results indicate that the microcrustacean fauna of most of these lakes may be very close to its biological end-points for recovery. These lakes probably have never been severely acidified.

Our results indicate that lakes are recovering differently, some fast while others need more time (**Table 10**). A short acidification period is expected to give a short recovery period while a long-lasting acidification period may give a long recovery period. Many lakes in this area have been severely acidified for a long period, and the recovery by internal recruitment from viable resting eggs in the sediment is probably not possible or strongly reduced (Pollard 2000). The natural recovery is therefore mainly dependent on external dispersion. In order for biological recovery to occur after any disturbance, refuge communities must exist within range (Milner 1994). Thus, Snucins (2003) found that specific benthic macroinvertebrates returned to two acidified lakes within 4-8 years after their estimated pH thresholds being reached. Here, potential refuges for these species occurred within 1-4 km of the recovering sites, thus favouring

rapid recolonisation. Crustaceans are slower colonisers than insects, and therefore, time-lags for recovery of microcrustaceans communities are expected to be significantly longer, especially for the geographically most isolated lakes. The year to year variation in species richness and occurrence may also be great during the recovery even if the species richness is gradually increasing (Keller et al. 2002).

Species interactions may prevent or delay biological recovery (see Lundberg et al. 2000). For example, acid sensitive grazers may be excluded from their former niche by acid-tolerant generalists that have since occupied this role. Holt & Yan (2003) argued that the apparent failure of herbivorous zooplankton to respond to the improved chemistry of the more acidified Killarney lakes was because invertebrate predators suppressed them in these fishless lakes. In other lakes, predation by fish may be of significance to biological recovery.

To limit confounding factors such as eutrophication, shoreline development and other land use changes that may influence recovery from acidification, the wilderness site at Killarney Provincial Park was selected for NLRS. However, even in this rather pristine area, a number of environmental stressors may have significant effects on biological recovery. Gunn et al. (2000) suggest a strong climate effect resulting in increased water clarity (i.e. increased Secchi depth) in some of the lakes (see also Gunn & Sandøy 2003). The increased clarity is caused by declines in DOC from catchments during droughts or by photobleaching of DOC by ultraviolet light. Changes in clarity may have significant effects on the habitat suitability for recovering biota, through changes in thermal structure, or by increased exposure to damaging UV radiation. Other confounding factors are the declining level of base cations that might affect certain crustacean zooplankton species (Alstad et al. 1999, Hessen & Rukke 2000), or the recent arrival of exotic species such as the predatory cladoceran *Bythotrephes cederstroemi*, which was found in three Killarney lakes in 1999. This species has been shown to have a huge negative effect on resident zooplankton communities (Yan & Pawson 1997, Yan et al. 2001)

It is clear that the biological recovery process is complex, involving a multitude of physical, chemical and biotic interactions. This results in immediate, lagged and threshold responses to changing chemistry which are extremely difficult to model. For estimating the time-delay of the biological recovery on a quantitative scale, the communities have to be followed for several years. It is now 10 years since the NLRS was established, and the lakes included in our study show continuous chemical improvements (Keller et al. 2003). Biological re-sampling of the lakes should therefore be considered. Together with paleolimnological analyses of more core samples the basis for estimating degree of recovery and time delays in recovery are expected to be highly improved.

Overall, while paleoecological and spatial surveys demonstrate strong influences of acidity on the microcrustacean composition, it does not necessarily follow that chemical recovery will lead to the precise re-establishment of the pre-acidification biological structure, nor should this be seen as an essential goal of restoration. Even remote aquatic systems, free from anthropogenic influence, change through time and are subject to climatic forcing on various time-scales. However, establishment of expected communities sharing normal functions within the ecosystem appears to be a reasonable recovery target.

Table 10. *Chemical and biological recovery in Killarney lakes indicated by data from NLRS. Chemical recovery indicated by differences in pH (pre-industrial vs 1972-73 vs 1997-99). Biological recovery indicated by differences in crustacean zooplankton (1972-73 vs 1997-99). Deviation from reference conditions (N: no, S: small, M: moderate, L: large) is indicated by: 1) comparing current microcrustacean faunas (acidified lakes versus reference lakes), 2) comparing current and paleolimnological reconstructed pre-industrial cladoceran faunas. Lakes in bold: considered as non-acidified reference site or biological recovered. ? max values of labile aluminium (LAl) > 100 µg/L.*

	Chemical recovery	Improvements in water qual. supporting biol. recovery		Biological recovery	Dev. from ref.cond indicated by	
	Diff pH	Current pH >5.0	Current LAl <100 µg/L	Diff zoopl	1	2
Acid	Slow	No	No	No	L	L
Bell	Fast	Yes	Yes	Yes	S	S
Burke	Fast	Yes	No	-	L	-
Carlyle	Fast	Yes	Yes	Yes	S	-
Chain	Slow	No	?	-	L	L
Clearsilver	Slow	No	No	Yes	L	L
David	Fast	No	Yes	Yes	L	L
George	Fast	Yes	Yes	Yes	S	S
Helen	Ref	Yes	Yes	Ref	N	M
Ishmael	Ref	Yes	Yes	Ref	N	S
Johnnie	Fast	Yes	Yes	Yes	S	S
Kakakise	Slow	Yes	Yes	Yes	S	-
Killarney	Fast	Yes	No	Yes	M	L
Low	Ref	Yes	Yes	Ref	N	N
Lumsden	Fast	Yes	?	No	L	S
Nellie	Slow	No	No	Yes	L	L
Norway	Fast	Yes	?	Yes	M	L
OSA	Slow	No	No	No	L	S
Partridge	Slow	Yes	Yes	Yes	M	M
Ruth-Roy	Fast	No	No	Yes	L	-
Teardrop	Ref	Yes	Yes	-	N	M
Terry	Fast	Yes	Yes	No	S	M
Tyson	Fast	Yes	Yes	-	S	-

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Appendices

Appendix 1. *Water chemistry (median, minimum and maximum values) for studied Killarney lakes based on monitoring data from 1996 - 1999. Note. For parameters that have been measured once, only median value is given.*

	Secchi depth (m)			Colour (TCU)			pH			Cond (mS m^{-1})			Ca (mg L^{-1})		
Lake	Median	Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max
Acid	12,7	11,2	15,3	7,0			5,03	4,93	5,13	2,12	2,00	2,37	1,10	0,95	1,25
Bell	5,0	4,2	6,8	15,2	13,8	21,0	6,05	5,82	6,44	2,62	2,46	2,94	2,05	1,80	2,25
Burke	3,8			9,4			5,10			2,54	0,00	0,00	1,40		
Carlyle	5,1	3,2	5,6	14,6			6,23	5,90	6,46	2,60	2,39	2,84	1,83	1,60	2,00
Chain	4,7	3,1	5,7				4,73	4,65	4,92	2,72	2,47	3,20	1,30	1,25	1,55
Clearsilver	9,6	6,8	11,7	4,4			4,92	4,87	5,01	2,25	2,20	2,43	1,08	1,05	1,20
David	9,1	7,1	11,8	2,6	2,6	2,6	5,05	4,87	5,17	2,10	2,04	2,31	1,26	1,10	1,30
George	8,8	7,8	9,2	3,6	2,8	6,2	6,00	5,76	6,41	2,53	2,06	2,87	1,85	1,70	2,05
Helen	6,7	6,2	8,5	15,0			6,82	6,30	7,11	2,99	2,92	3,25	2,53	2,35	2,70
Ishmael	6,6	6,1	7,2	10,4			6,75	6,50	7,08	3,17	3,02	3,37	2,73	2,35	2,80
Johnnie	6,0	4,7	7,3	9,6	7,8	11,0	5,73	5,59	6,01	2,46	2,33	2,72	1,80	1,65	1,90
Kakakise	6,8	5,4	8,6	8,0	8,0	8,0	6,61	6,30	6,85	2,87	2,76	3,10	2,30	2,10	2,45
Killarney	22,1	14,6	23,0	1,2	0,4	4,0	5,10	4,93	5,16	2,63	2,53	2,92	1,58	1,45	1,65
Low	8,5	7,1	9,0	7,4			7,57	7,20	7,82	6,90	6,72	7,39	8,15	7,45	8,45
Lumsden	13,7	10,5	14,3	6,4			5,21	5,07	5,26	2,10	1,91	2,32	1,20	1,05	1,40
Nellie	28,4	27,4	30,9	1,0	1,0	1,0	4,63	4,49	4,65	3,35	3,20	3,59	1,45	1,35	1,55
Norway	14,7	9,6	15,5	3,8			5,17	5,10	5,28	2,46	2,43	2,92	1,55	1,45	1,75
OSA	18,5	6,8	20,5	1,2	0,6	3,0	4,88	4,71	4,92	3,10	3,00	3,53	1,98	1,85	2,15
Partridge	7,6	5,3	10,5				5,81	5,55	5,85	2,73	2,67	2,98	2,00	1,90	2,30
Ruth-Roy	13,8	13,2	18,0	2,8	2,4	3,0	4,82	4,67	4,92	2,45	2,30	2,83	1,05	1,00	1,20
Teardrop	11,9	11,6	12,1	4,6			6,76	6,50	6,85	2,55	2,44	2,69	1,83	1,65	1,95
Terry	2,7	2,1	3,3				5,68	5,27	5,78	2,43	2,17	3,05	1,70	1,40	2,20
Tyson	5,1	3,0	7,3	19,6	16,0	19,6	6,00	5,60	6,33	2,79	2,70	2,98	1,90	1,75	2,25

Appendix 1. *Continues.*

	Tot-P (µg L^{-1})			DOC (mg C L^{-1})			Tot Al (µg L^{-1})			LAl (µg L^{-1})			ANC (µeq L^{-1})		
Lake	Median	Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max
Acid	2	2	14	0,9	0,4	1,6	165	121	215	112	111	169	-24	-30	4
Bell	6	6	8	4,2	3,9	4,9	68	24	110	14	0	33	38	1	50
Burke	4	2	4	1,8			185			149			-35		
Carlyle	5	2	8	3,4	3,0	3,8	28	21	74	8	6	32	32	26	66
Chain	6	2	10	4,5	3,4	5,3	207	174	283	72	0	144	-21	-31	10
Clearsilver	3	2	4	1,2	0,4	1,8	170	126	230	131	115	136	-36	-46	3
David	2	2	4	1,3	1,0	1,5	83	57	110	53	50	57	-20	-52	13
George	2	2	4	1,6	1,3	1,9	46	11	176	5	3	50	11	2	40
Helen	4	2	6	3,5	3,1	3,7	29	8	64	2	0	27	89	60	98
Ishmael	5	4	6	3,4	3,2	3,5	16	5	18	1	0	9	105	75	128
Johnnie	4	2	9	3,2	2,8	3,5	76	32	120	22	9	61	15	7	40
Kakakise	4	2	4	2,6	2,5	2,8	15	10	53	4	4	4	56	20	60
Killarney	4	2	8	0,5	0,1	1,0	173	131	238	128	125	172	-28	-46	8
Low	5	2	10	2,8	2,7	3,0	8	6	15	3	1	5	424	400	454
Lumsden	2	2	8	0,7	0,2	1,5	135	76	176	75	68	103	-21	-60	-10
Nellie	2	0	10	0,1	0,1	0,2	499	438	540	447	434	459	-80	-86	-56
Norway	2	2	4	1,0	0,3	1,7	147	99	260	86	82	156	-14	-24	18
OSA	2	1	2	0,4	0,1	0,4	170	133	206	128	128	194	-30	-48	4
Partridge	2	2	4	1,6	1,5	1,7	33	26	75	18	16	19	1	-57	7
Ruth-Roy	2	2	8	0,6	0,2	1,5	331	221	385	218	217	240	-44	-98	-14
Teardrop	4	2	6	1,0	0,8	1,1	6	3	12	1	0	2	48	1	65
Terry	12	4	12	5,5	4,6	6,1	131	122	240	27	26	29	19	-23	43
Tyson	8	4	12	4,1	3,8	4,6	48	22	90	10	8	40	39	21	66

Appendix 2. *Water chemistry for studied Sudbury lakes based on Urban Lakes Survey (1990) and Northern Lakes Recovery Study (1997-98, 2003).*

	Clearwater		Hannah		Lohi		Middle		Swan		
Year	1990	2003	1990	2003	1990	2003	1990	2003	1990	1997-98	2003
pH	4,88	6,33	7,06	7,25	4,92	6,28	6,57	6,91	4,87	5,45	5,69
Conductivity (mS/m)	8,05	6,10	35,90	19,00	9,08	7,16	25,80	28,60	6,99	4,21	6,00
Alkalinity (µeq/L)	-17	24	242	339	-14	51	116	234	-20	0	4
Ca (mg/L)	6,10	4,30	13,40	10,60	6,18	4,34	10,30	11,00			
Mg (mg/L)	1,36	1,09	4,56	3,57	1,75	1,31	3,53	3,21	6,10	3,51	3,44
Na (mg/L)	3,14	4,00	44,60	62,80	3,89	5,71	29,70	40,30			
K (mg/L)	0,640	0,575	1,980	1,660	0,850	0,720	1,510	0,730			
Cl (mg/L)	9,10	8,00	76,30	91,90	10,30	10,78	50,30	66,29			
SO_4 (mg/L)	16,74	10,70	28,98	16,60	19,57	10,39	25,37	17,53			
SiO_3 (mg/L)	0,76	1,10	0,38	0,26	0,56	1,12	1,20	0,80			
Al (µg/L)	130	16	200	13	130	22	<30	13	70	18	18
As (µg/L)		<=0.5		<1.0		<=0.5		<=0.5			
Ba (µg/L)		17,6		21,9		14,5		22,6			
Be (µg/L)		<=0.03		<=0.03		<=0.03		<=0.03			
Cd (µg/L)		<=0.6		<=0.6		<=0.6		<=0.6			
Cr (µg/L)		<=1.0		<=1.0		<=1.0		<=1.0			
Co (µg/L)		<=1.5		<=1.5		<=1.5		<=1.5			
Cu (µg/L)	35	10	64	22	50	12	28	24			
Fe (µg/L)	<60	15	290	114	130	106	<80	26			
Mn (µg/L)	250	26	38	70	230	41	110	20			
Mo (µg/L)		<=0.8		<=1.2		<=0.8		<=0.8			
Ni (µg/L)	160	70	180	111	200	59	230	114			
Pb (µg/L)	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11			
Se (µg/L)		<=0.5		<=0.5		<=0.5		<=0.5			
Sr (µg/L)		21,7		57,3		21,4		50,4			
Ti (µg/L)		<=0.30		<=0.30		<=0.30		<=0.30			
V (µg/L)		<=0.9		<=1.5		<=0.9		<=0.9			
Zn (µg/L)	23	11	11	3	29	10	16	11			
P (µg/L)	<=2	5	21	8	<=2	9	<6	7	7	7	9
NH_3+NH_4 (µg/L)	26		20	66	44		20				
NO_2 (µg/L)	<3		6		<1		<1				
NO_3+NO_2 (µg/L)	<5		<=5	<6	45		<20				
TKN (µg/L)	140	233	430	418	<=170	300	270	312			
DOC (mg/L)	0,5	2,9	3,8	3,6	1,1	3,4	3,3	3,6	1,2	2,4	2,8

Appendix 3. *Cladocerans and copepods found in 23 lakes in Killarney (1997-99).Species codes as used in succeeding appendices and DCA plots. Sensitivity to acidification is indicated by HS (highly sensitive) or S (moderately sensitive).*

Cladocera			Chydorus faviformis Birge	chy fav	HS
Diaphanosoma sp	dia sp		Chydorus gibbus Lilljeborg	chy gib	
Latona setifera (O.F.M.)	lat set		Chydorus latus (Sars)	chy lat	
Sida crystallina (O.F.M.)	sid cry		Chydorus piger (Sars)	chy pig	
Holopedium gibberum Zaddach	hol gib		Eurycercus (Bullatifrons) sp.	eur bul	HS
Ceriodaphnia quadrangula (O.F.M.)	cer qua		Graptoleberis testudinaria (Fischer)	gra tes	
Daphnia ambigua Scourfield	dap amb	HS	Kurzia latissima (Kurz)	kur lat	HS
Daphnia catabwa	dap cat		Monospilus dispar	mon dis	
Daphnia dubia	dap dub	HS	Oxyurella tenuicaudis (Sars)	oxy ten	
Daphnia galeata mendotae Birge	dap gal	HS	Pleuroxus hastatus	ple has	S
Daphnia longiremis (Sars)	dap lon	HS	Pleuroxus procurvis	ple pro	HS
Daphnia parvula	dap par	HS	Pleuroxus striatus Schødler	ple str	S
Daphnia pulex Leydig	dap pul	S	Pleuroxus truncatus (O.F.M.)	ple tru	S
Daphnia retrocurva	dap ret	HS	Rhynchotalona falcata Sars	rhy fal	
Scapholeberis kingi (Sars)	sca kin		Polyphemus pediculus (Leuck.)	pol ped	
Simocephalus serrulatus (Koch)	sim ser		Bythotrephes longimanus Leydig	byt lon	
Simocephalus vetulus Schödler	sim vet		Leptodora kindti (Focke)	lep kin	HS
Sinobosmina sp	sin sp	S	**Copepoda**		
Bosmina longispina Leydig	bos ina		Epischura lacustris S.A. Forbes	epi lac	HS
Bosmina tubifen	bos tub		Leptodiaptomus ashlandi Marsh	lep ash	HS
Acantholeberis curvirostris (O.F.M.)	aca cur		Leptodiaptomus minutus Lillj.	lep min	
Ilyocryptus sordidus	ily sor		Leptodiaptomus sicilis S.A. Forbes	lep sic	HS
Ilyocryptus spinifer Herrick	ily spi		Skistodiaptomus oregonensis Lillj.	ski ore	HS
Lathonura rectirostris (O.F.M.)	lat rec		Orthocyclops modestus Herrick	ort mod	
Ophryoxus gracilis Sars	oph gra		Macrocyclops albidus (Jur.)	mac alb	
Streblocerus serricaudatus (Fisch.)	str ser		Macrocyclops fuscus (Jur.)	mac fus	
Acroperus harpae (Baird)	acr har		Eucyclops macrurus	euc mac	
Alona affinis (Leydig)	alo aff		Eucyclops elegans Herrick 1884	euc neo	
Alona bicolor Frey	alo bic		Eucyclops serrulatus (Fisch.)/E.prionophorus Kiefer	euc ser	
Alona circumfibriata/setosa	alo cir	HS	Paracyclops affinis Sars	par aff	
Alona costata Sars	alo cos	HS	Paracyclops fimbriatus poppei Rehberg	par fim	
Alona guttata Sars	alo gut		Tropocyclops extensus Kiefer	tro ext	S
Alona intermedia	alo int		Ectocyclops phaleratus (Koch)	ect pha	
Alona quadrangularis (O.F.M.)	alo qua		Cyclops bicuspidatus thomasi S.A. Forbes	cyc bic	S
Alona rustica Scott	alo rus		Cyclops scutifer Sars	cyc scu	
Alonella acutirostris Birge	alo acu		Cyclops varicans rubellus Lillj.	cyc var	S
Alonella excisa (Fischer)	alo exc		Acanthocyclops capillatus Sars	aca cap	
Alonella exigua (Fischer)	alo exi		Acanthocyclops robustus Sars	aca rob	
Alonella nana	alo nan	S	Acanthocyclops vernalis Fischer	aca ver	
Chydorus bicornutus Doolittle	chy bic	HS	Mesocyclops edax S.A. Forbes	mes eda	S
Chydorus brevilabris/sphaericus	chy bre		Mesocyclops lauckarti Claus	mes leu	

Appendix 4. *Cladocerans and copepods found in 23 Killarney lakes.*

	Acid	Bell	Burke	Carly	Chain	Clearsilv.	David	George	Helen	Ishmael	Johnnie
Cladocera											
dia sp		x	x	x	x	x	x	x	x	x	x
lat set	x	x		x	x	x	x	x	x	x	x
sid cry		x		x				x	x	x	x
hol gib		x	x	x	x		x	x	x	x	x
cer qua										x	
dap amb		x		x			x	x		x	x
dap cat				x			x				
dap dub		x							x		
dap gal		x				x			x	x	
dap lon		x							x	x	
dap par											
dap pul		x					x				x
dap ret		x		x						x	
sca kin		x		x		x		x	x	x	x
sim ser	x		x								
sim vet						x					
sin sp	x	x	x	x	x	x	x	x	x	x	x
bos ina	x	x	x	x		x	x	x		x	x
bos tub			x	x			x				x
aca cur	x		x		x		x	x			x
ily sor											x
ily spi		x			x	x	x	x			
lat rec											
oph gra	x	x	x	x	x		x	x	x	x	x
str ser					x					x	
acr har	x	x	x	x	x	x	x	x	x	x	x
alo aff	x	x	x		x	x	x	x	x	x	x
alo bic		x		x	x			x	x		x
alo cir									x	x	
alo cos		x						x		x	x
alo gut	x	x	x	x	x	x	x	x	x	x	x
alo int					x		x			x	
alo qua					x	x					
alo rus											
alo set	x	x					x	x			x
alo acu	x	x		x	x		x	x	x	x	x
alo exi	x	x	x	x	x	x	x	x	x	x	x
alo exc	x	x	x		x						x
alo nan										x	
chy bic		x		x						x	x
chy bre	x	x	x	x	x	x	x	x	x	x	x

Appendix 4. *Continues.*

	Acid	Bell	Burke	Carly	Chain	Clearsilv.	David	George	Helen	Ishmael	Johnnie
Cladocera cont.											
chy fav										x	
chy gib											
chy lat				x			x				
chy pig	x	x	x	x	x	x	x	x	x	x	x
eur bul									x		
gra tes							x			x	
kur lat										x	
mon dis		x									x
oxy ten										x	
ple has		x		x						x	x
ple pro											
ple str		x								x	x
ple tru											
rhy fal											
pol ped	x	x	x	x	x	x	x	x	x	x	x
byt lon											
lep kin				x				x	x	x	x
Copepoda											
epi lac		x		x				x	x	x	x
lep ash										x	
lep min	x	x	x	x	x	x	x	x	x	x	x
lep sic									x	x	
ski ore		x						x	x	x	
ort mod		x	x		x	x		x		x	x
mac alb	x	x	x		x	x	x	x	x	x	x
mac fus		x	x		x						
euc mac											x
euc neo	x	x	x	x			x	x		x	x
euc ser	x	x	x	x	x	x	x	x	x	x	x
par aff		x	x		x		x			x	x
par fim	x			x				x			x
tro ext		x		x				x	x	x	x
ect pha										x	
cyc bic	x	x	x	x		x		x	x	x	x
cyc scu		x									x
cyc var		x						x	x	x	x
aca cap									x	x	
aca rob		x		x		x	x		x	x	x
aca ver	x	x									x
mes eda		x		x		x	x	x	x	x	x
mes leu					x						
no. of clad.	16	31	16	24	20	16	24	23	22	34	30
no. of cop.	7	16	8	9	7	7	7	12	12	17	16
tot.	23	47	24	33	27	23	31	35	34	51	46

Appendix 4. *Continues.*

	Kakakaize	Killarney	Low	Lumsden	Nellie	Norway	OSA	Patrigde	Ruth Roy	Teardrop	Terry	Tyson
Cladocera												
dia sp	x		x			x		x	x		x	x
lat set		x		x	x				x	x		
sid cry	x	x	x					x		x	x	x
hol gib	x	x	x		x		x	x	x	x	x	x
cer qua											x	
dap amb	x						x	x		x	x	x
dap cat								x		x		
dap dub										x		
dap gal	x		x							x		x
dap lon										x		
dap par										x		
dap pul												
dap ret												x
sca kin	x	x	x			x		x			x	x
sim ser				x								
sim vet	x	x										x
sin sp	x	x	x	x		x		x	x	x	x	x
bos ina	x	x	x		x	x	x			x	x	x
bos tub							x				x	x
aca cur			x	x			x	x	x			
ily sor				x								
ily spi							x					
lat rec			x									
oph gra	x	x	x	x	x	x	x	x	x			x
str ser	x			x		x					x	
acr har	x	x	x	x	x	x	x	x	x	x	x	x
alo aff	x	x		x		x	x	x	x	x	x	x
alo bic						x					x	
alo cir	x		x									
alo cos	x		x									x
alo gut		x	x	x		x				x	x	
alo int		x		x		x	x		x		x	
alo qua			x		x				x			
alo rus			x									
alo set					x				x			
alo acu	x			x		x	x			x	x	x
alo exi	x	x		x	x	x	x	x	x	x		x
alo exc	x		x								x	x
alo nan												
chy bic	x										x	x
chy bre	x	x	x	x	x	x	x	x	x		x	x

Appendix 4. *Continues.*

	Kakakaize	Killarney	Low	Lumsden	Nellie	Norway	OSA	Patrigde	Ruth Roy	Teardrop	Terry	Tyson
Cladocera cont.												
chy fav	x		x							x		
chy gib				x								
chy lat											x	
chy pig	x	x	x	x	x	x	x	x	x	x	x	x
eur bul												x
gra tes			x									
kur lat			x								x	x
mon dis												
oxy ten												
ple has											x	x
ple pro			x									
ple str		x										x
ple tru			x									
rhy fal		x		x								
pol ped	x	x	x	x	x	x	x	x	x	x	x	x
byt lon												x
lep kin	x		x							x		
Copepoda												
epi lac	x		x							x		x
lep ash			x									
lep min	x	x	x	x	x	x	x	x	x	x	x	x
lep sic			x									
ski ore			x									x
ort mod		x		x								
mac alb	x	x	x	x			x	x	x	x	x	x
mac fus	x			x					x	x	x	
euc mac	x											
euc neo	x	x		x			x		x		x	x
euc ser	x	x	x	x	x		x	x	x	x	x	
par aff		x	x						x			
par fim			x									x
tro ext	x	x	x			x					x	x
ect pha			x									x
cyc bic	x		x	x		x		x	x	x	x	x
cyc scu										x		
cyc var	x		x									
aca cap							x					
aca rob	x						x		x	x		x
aca ver												
mes eda	x		x			x		x		x	x	x
mes leu												
no. of clad.	24	18	26	18	11	16	15	15	15	20	24	27
no. of cop.	12	7	14	7	2	4	6	5	8	9	8	11
tot.	36	25	40	25	13	20	21	20	23	29	32	38

Appendix 5. *Cladoceran and copepod species found in five near Sudbury lakes in the period 1997-99.*

	Clearwater			Hannah			Lohi			Middle			Swan		
	97	98	99	97	98	99	97	98	99	97	98	99	97	98	99
Cladocera															
Diaphanosoma sp	x	x	x	x	x	x	x	x	x		x	x	x	x	x
Latona setifera (O.F.M.)	x	x	x				x						x	x	
Sida crystallina (O.F.M.)				x	x	x					x	x	x	x	
Holopedium gibberum Zaddach		x	x	x			x	x	x						
Ceriodaphnia quadrangula (O.F.M.)						x									
Ceriodaphnia reticulata						x									
Daphnia ambigua Scourfield					x										
Daphnia galeata mendotae Birge				x	x	x				x	x	x			
Scapholeberis kingi (Sars)													x		x
Simocephalus serrulatus (Koch)	x														
Simocephalus vetulus Schödler													x	x	
Sinobosmina sp	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Bosmina longispina Leydig				x					x			x			x
Acantholeberis curvirostris (O.F.M.)	x													x	
Ilyocryptus spinifer Herrick														x	
Acroperus harpae (Baird)	x	x	x				x						x	x	x
Alona affinis (Leydig)													x		
Alona guttata Sars			x	x		x				x		x	x		x
Alona rustica Scott								x							
Chydorus brevilabris/sphaericus	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Chydorus gibbus Lilljeborg					x										
Chydorus latus (Sars)													x		
Chydorus piger (Sars)													x	x	x
Chydorus sphaericus (O.F.M.)	x												x	x	
Polyphemus pediculus (Leuck.)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Copepoda															
Leptodiaptomus minutus Lillj.	x	x	x	x	x	x	x	x	x	x		x	x	x	x
Skistodiaptomus oregonensis Lillj.										x	x	x			
Orthocyclops modestus Herrick	x	x	x					x	x				x	x	x
Macrocyclops albidus (Jur.)	x	x	x				x	x		x	x	x	x	x	x
Macrocyclops fuscus (Jur.)	x												x	x	
Eucyclops elegans						x		x						x	x
Eucyclops serrulatus (Fisch.)	x		x	x	x	x	x	x		x	x	x	x	x	x
Tropocyclops extensus Kiefer				x	x	x			x	x	x	x		x	
Paracyclops affinis Sars				x		x	x			x		x	x		x
Paracyclops fimbr. poppei Rehberg			x								x		x		x
Paracyclops fimbriatus						x									
Cyclops bicusp. thomasi S.A. Forbes	x			x	x	x	x			x	x	x			x
Acanthocyclops robustus Sars	x	x	x		x		x		x					x	x
Acanthocyclops vernalis Fischer	x	x											x		
Mesocyclops edax S.A. Forbes	x				x	x				x					
Mesocyclops lauckarti Claus															
cladoceran species	9	7	8	9	8	9	7	6	6	5	6	8	14	12	9
copepode species	9	5	6	5	6	8	6	5	4	8	6	7	8	8	9
total number of crustaceans	18	12	14	14	14	17	13	11	10	13	12	15	22	20	18

Appendix 6. *Cladocerans and copepods found in core (sediment) samples from 19 Killarney lakes. Lakes in bold: 5 segments analysed. For all other lakes: 2 segments analysed.*

Taxa	**Acid**	**Bell**	Chain	Clearsilver	David	**George**	**Helen**	Ishmael	Johnnie	Kakakise	Killarney	Lowe	**Nellie**	**Norway**	**OSA**	Patridge	**Teardrop**	Terry	Tyson	# Localities
Diaphanosoma sp.					1			1										1	1	4
Latona setifera (O.F.M.)	**1**	**1**	1	1	1	**1**	**1**					1	**1**	**1**	1	1		1	1	14
Sida crystallina (O.F.M.)	**1**	**1**	1	1	1	**1**	**1**	1	1	1			**1**	**1**	1	1	**1**	1	1	17
Holopedium gibberum Zaddach			1		1						1							1	1	5
Daphnia spp.	**1**	**1**	1	1	1	**1**	**1**	1	1	1	1	1	**1**	**1**	1	1	**1**	1	1	19
Daphnia catawba Coker	**1**																			1
Daphnia pulex/pulicaria			1		1					1	1								1	5
Bosmina/Eubosmina spp.	**1**	**1**	1	1	1	**1**	**1**	1	1	1	1	1	**1**	**1**	1	1	**1**	1	1	19
Ophryoxus gracilis Sars			1	1	1	**1**	**1**				1	1			1	1		1	1	11
Acroperus harpae (Baird)	**1**	**1**	1	1	1	**1**	**1**		1	1	1	1	**1**	**1**	1	1	**1**	1	1	18
Alona affinis (Leydig)	**1**	**1**	1	1	1	**1**	**1**	1		1	1	1	**1**	**1**	1	1	**1**	1	1	18
Alona circumfimbriata Megard			1	1	1			1			1							1	1	7
Alona costata Sars																			1	1
Alona bicolor Frey	**1**												**1**	**1**						3
Alona guttata Sars	**1**				1	**1**	**1**	1		1	1	1	**1**	**1**		1	**1**	1	1	14
Alona intermedia Sars	**1**		1	1	1		**1**					1	**1**				**1**	1		9
Alona quadrangularis (O.F.M.)	**1**	**1**		1	1						1		**1**	**1**	1	1	**1**	1	1	12
Alona rustica Scott	**1**		1	1	1	**1**	**1**					1	**1**	**1**	1	1		1	1	13
Alonella acutirostris (Birge)	**1**														1					2
Alonella excisa (Fischer)	**1**	**1**	1		1	**1**							**1**	**1**		1	**1**	1		10
Alonella exigua (Fischer)														**1**				1	1	3
Alonella nana (Baird)	**1**	**1**	1	1	1		**1**						**1**	**1**	1		**1**	1	1	12
Chydorus bicornutus Doolittle	**1**	**1**	1	1	1	**1**	**1**	1		1	1	1	**1**	**1**		1	**1**	1	1	17
Chydorus faviformis Birge	**1**			1									**1**							3
Chydorus latus Sars		**1**	1		1		**1**											1		5
Chydorus piger Sars			1		1								**1**					1	1	5
Eurycercus (Bullatifrons) sp.	**1**	**1**	1	1		**1**	**1**	1	1		1	1	**1**	**1**	1	1	**1**	1	1	17
Graptoleberis testudinaria (Fischer)	**1**		1				**1**						**1**	**1**			**1**	1		7
Kurzia latissima (Kurz)	**1**	**1**	1	1	1		**1**	1						**1**				1	1	10
Leydigia acanthocercoides (Fischer)	**1**		1			**1**												1		4
Monospilus dispar Sars	**1**			1			**1**	1	1										1	6
Oxyurella tenuicaudis (Sars)			1					1					**1**				**1**	1		5
Pleuroxus spp.	**1**			1			**1**			1						1		1	1	7
Pleuroxus hastatus Sars																		1		1
Pleuroxus aduncus (Jurine)	**1**			1		**1**	**1**							**1**			**1**		1	7
Rhynchotalona falcata (Sars)	**1**		1	1	1	**1**			1		1			**1**				1	1	10
Number of taxa	**25**	**13**	23	20	22	**15**	**19**	12	7	9	13	11	**19**	**19**	12	14	**15**	28	25	

Appendix 7. *Cladocerans and copepods found in core (sediment) samples, representing pre-industrial (<1880) and post-industrial (>1970) period, from 19 Killarney lakes. Lakes in bold: 2 segments from respectively pre- and post-industrial period are analysed. For all other lakes: 1 segment from each period is analysed.*

Taxa (before 1880)	**Acid**	**Bell**	Chain	Clearsilver	David	**George**	**Helen**	Ishmael	Johnnie	Kakakise	Killarny	Lowe	**Nellie**	**Norway**	**OSA**	Patridge	**Teardrop**	Terry	Tyson	# Localities
Diaphanosoma sp.			1																1	1
Latona setifera (O.F.M.)	**1**		1		1		**1**					1	**1**			1				7
Sida crystallina (O.F.M.)	**1**	**1**	1	1	1	**1**	**1**	1	1	1				**1**	**1**	1	**1**	1	1	16
Holopedium gibberum Zaddach			1															1	1	3
Daphnia spp.	**1**	**1**	1	1	1	**1**	**1**	1	1	1	1	1	**1**	**1**	**1**	1	**1**	1	1	19
Daphnia catawba Coker																				0
Daphnia pulex Leydig			1								1									2
Bosmina/Eubosmina spp.	**1**	**1**	1	1	1	**1**	**1**	1	1	1	1	1	**1**	**1**	**1**	1		1	1	18
Ophryoxus gracilis Sars			1	1	1						1							1		5
Acroperus harpae (Baird)	**1**	**1**	1	1	1	**1**	**1**				1	1	**1**	**1**	**1**	1	**1**	1	1	16
Alona spp.	**1**	**1**	1	1	1	**1**	**1**		1		1	1	**1**	**1**	**1**	1	**1**	1	1	17
Alona affinis (Leydig)	**1**	**1**	1	1	1	**1**	**1**	1			1	1	**1**	**1**	**1**	1		1	1	16
Alona costata Sars	**1**													**1**					1	3
Alona bicolor Frey	**1**												**1**	**1**						3
Alona guttata Sars	**1**				1	**1**	**1**	1		1								1	1	8
Alona intermedia Sars			1	1			**1**					1						1		5
Alona quadrangularis (O.F.M.)	**1**			1	1								**1**		**1**	1		1	1	8
Alona circumfimbriata Sars			1	1	1			1										1	1	6
Alona rustica Scott	**1**		1	1	1	**1**						1	**1**	**1**		1		1		10
Alonella sp.				1																1
Alonella acutirostris (Birge)	**1**														**1**					2
Alonella excisa (Fischer)		**1**	1		1	**1**										1		1		6
Alonella exigua (Fischer)																		1	1	2
Alonella nana (Baird)	**1**		1	1	1		**1**						**1**	**1**			**1**	1	1	10
Chydorus spp.	**1**	**1**	1	1	1	**1**	**1**	1			1	1	**1**	**1**	**1**	1	**1**	1		16
Chydorus bicornutus Doolittle		**1**	1	1	1	**1**	**1**	1		1		1				1	**1**	1	1	13
Chydorus faviformis Birge	**1**			1																2
Chydorus latus Sars			1				**1**											1		3
Chydorus piger Sars			1		1								**1**					1	1	5
Eurycercus sp.	**1**		1				**1**	1	1		1		**1**				**1**	1	1	10
Graptoleberis testudinaria (Fischer)	**1**		1				**1**							**1**			**1**	1		6
Kurzia latissima (Kurz)			1	1	1		**1**	1					**1**					1		7
Leydigia acanthocercoides (Fischer)			1			**1**														2
Monospilus dispar Sars	**1**			1			**1**		1										1	5
Oxyurella tenuicaudis (Sars)								1												1
Pleuroxus spp.	**1**													**1**			**1**	1	1	5
Pleuroxus hastatus Sars																				0
Pleuroxus aduncus (Jurine)																			1	1
Rhynchotalona falcata (Sars)				1	1	**1**			1					**1**				1	1	7
Leptodora kindti (Focke)							**1**													1
Unknown chydorids	**1**	**1**	1	1	1		**1**	1	1	1		1	**1**	**1**	**1**	1		1	1	16
Number of remains	**1953**	**772**	890	3988	3527	**3961**	**3893**	1064	480	741	459	1815	**808**	**887**	**537**	566	**97**	1535	2145	30118
Number of remains except *Bosmina*	**196**	**24**	433	171	88	**36**	**121**	15	12	9	11	111	**68**	**42**	**21**	93	**97**	688	97	2333

Appendix 7. *Continues.*

Taxa (after 1970)	**Acid**	**Bell**	Chain	Clearsilver	David	**George**	**Helen**	Ishmael	Johnnie	Kakakise	Killarny	Lowe	**Nellie**	**Norway**	**OSA**	Patridge	**Teardrop**	Terry	Tyson	# Localities
Diaphanosoma sp.					1			1										1	1	4
Latona setifera (O.F.M.)	**1**		1	1	1								**1**	**1**	**1**	1		1	1	10
Sida crystallina (O.F.M.)	**1**	**1**	1	1	1		**1**		1	1			**1**	**1**	**1**		**1**	1		13
Holopedium gibberum Zaddach			1		1						1							1	1	5
Daphnia spp.	**1**	**1**	1		1	**1**	**1**	1	1	1	1	1		**1**	**1**	1	**1**	1	1	17
Daphnia catawba Coker	**1**																			1
Daphnia pulex Leydig					1					1									1	3
Bosmina/Eubosmina spp.	**1**	**1**	1	1	1	**1**	**1**	1	1	1	1	1	**1**	**1**	**1**	1	**1**	1	1	19
Ophryoxus gracilis Sars			1	1	1	**1**					1	1				1		1	1	9
Acroperus harpae (Baird)	**1**		1	1	1	**1**	**1**		1	1	1		**1**	**1**	**1**	1	**1**	1	1	16
Alona spp.	**1**	**1**	1	1	1	**1**	**1**	1			1		**1**	**1**	**1**	1	**1**	1	1	16
Alona affinis (Leydig)	**1**		1		1	**1**	**1**			1			**1**	**1**	**1**	1	**1**		1	12
Alona costata Sars																				0
Alona bicolor Frey																				
Alona guttata Sars	**1**									1	1	1				1		1		6
Alona intermedia Sars	**1**		1	1	1													1		5
Alona quadrangularis (O.F.M.)	**1**	**1**									1			**1**	**1**	1	**1**			7
Alona circumfimbriata Sars			1					1			1							1		4
Alona rustica Scott	**1**		1	1	1	**1**						1	**1**						1	8
Alonella sp.	**1**			1																2
Alonella acutirostris (Birge)																				0
Alonella excisa (Fischer)	**1**		1		1								**1**							4
Alonella exigua (Fischer)														**1**						1
Alonella nana (Baird)	**1**		1		1								**1**	**1**	**1**					6
Chydorus spp.	**1**	**1**	1	1	1	**1**	**1**	1			1	1	**1**	**1**	**1**	1	**1**	1		16
Chydorus bicornutus Doolittle	**1**				1		**1**			1	1					1		1		7
Chydorus faviformis Birge													**1**							1
Chydorus latus Sars			1															1		2
Chydorus piger Sars			1		1													1		3
Eurycercus sp.	**1**		1	1			**1**	1				1	**1**	**1**		1		1	1	11
Graptoleberis testudinaria (Fischer)													**1**					1		2
Kurzia latissima (Kurz)							**1**							**1**					1	3
Leydigia acanthocercoides (Fischer)	**1**																	1		2
Monospilus dispar Sars							**1**	1												2
Oxyurella tenuicaudis (Sars)			1																	1
Pleuroxus spp.			1							1								1		3
Pleuroxus hastatus Sars																				0
Pleuroxus aduncus (Jurine)				1																1
Rhynchotalona falcata (Sars)	**1**			1							1									3
Leptodora kindti																				0
Unknown chydorids	**1**	**1**	1	1	1		**1**	1	1	1	1	1		**1**	**1**	1	**1**	1	1	17
Number of remains	**1853**	**984**	1205	1139	3184	**1563**	**676**	1604	558	1062	418	1023	**664**	**1229**	**245**	706	**99**	1723	1658	21593
Number of remains except *Bosmina*	**129**	**59**	411	205	220	**112**	**161**	57	27	58	48	39	**99**	**72**	**111**	147	**61**	183	96	2295

Naturens Tålegrenser - Oversikt over utgitte rapporter

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