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Recent changes in chironomid communities and hypolimnetic oxygen conditions relate to organic carbon in subarctic ecotonal lakes

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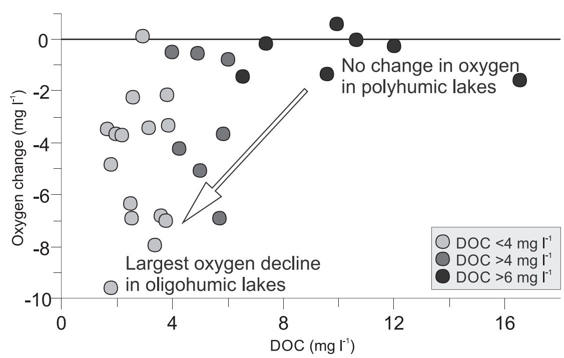
HIGHLIGHTS

- A key question in elemental cycling is the oxygen influence on carbon release.
- Top-bottom paleolimnological approach was used in 30 subarctic lakes.
- Hypolimnetic oxygen was reconstructed using a fossil chironomid-based model.
- Oxygen has declined in oligo-mesohumic lakes compared to the Pre-Industrial Age.
- Polyhumic lakes are more resilient toward climate-induced reductions in oxygen.

GRAPHICAL ABSTRACT



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ABSTRACT

A key question in aquatic elemental cycling is related to the influence of bottom water oxygen conditions in regulating the burial and release of carbon under climate warming. In this study, we used head capsules of Chironomidae larvae to assess community and diversity change between the past (estimated as Pre-Industrial Period) and present and to reconstruct changes in hypolimnetic oxygen conditions from 30 subarctic ecotonal lakes (northeastern Lapland) using the top-bottom paleolimnological approach applying surface sediment (topmost 0–2 cm) and reference (4–5 cm) samples. Subsequently, we tested the findings against dissolved organic carbon (DOC) concentration of the sites. We found that the benthic communities were statistically dissimilar between the past and the present with largest changes occurring in the more transparent oligo-mesohumic lakes. However, murky polyhumic lakes displayed uniformly a decrease in diversity. The chironomid-inferred oxygen values showed a general decrease toward the present with largest shifts in low-DOC lakes, whereas no significant changes were found in the hypolimnetic oxygen conditions of high-DOC lakes, which were often located in wetland areas. These finding suggest that lakes associated with constant organic carbon inputs are more resilient toward climate-induced reductions in hypolimnetic oxygen.

1. Introduction

Carbon storage in high-latitude peatlands represents a major share of the global soil carbon pool (Tranvik et al., 2009; Schuur et al., 2015). With permafrost thawing and subsequent formation of thaw

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lakes, larger emissions of carbon dioxide (CO_2) and methane (CH_4) are expected (Walter et al., 2006; Wauthy et al., 2018). Since lakes are important sources of greenhouse gases (Aben et al., 2017), in the context of climate change, it is essential to understand how carbon release is regulated by different levels of oxygen availability at the surface-sediment interface of lakes (Liikanen et al., 2002). Although there is CH_4 formation also in oxic water layers (Tang et al., 2016), CH_4 is mostly produced by anoxic decomposition of organic carbon and, importantly for the ongoing climate change, it has a multifold atmospheric warming potential compared to CO_2 (Deemer et al., 2016).

While in lakes with well oxygenated bottom waters a significant part of the produced CH_4 is oxidized into CO_2 and not emitted to the atmosphere, a contrasting situation occurs in oxygen depleted lakes. In addition to hypolimnetic oxygen, there appears to be a consistent temperature dependency of CH_4 fluxes across microbial to ecosystem scales (Yvon-Durocher et al., 2014) that well-represents the cascading climate change impacts and feedback systems. In particular, methanogenesis, carried out by strictly anaerobic Archaea, is the terminal step in the remineralization of organic matter and, like most other forms of metabolism, methanogenesis is temperature-dependent (Yvon-Durocher et al., 2014). Therefore, since climate warming is emphasized in subarctic and arctic regions (Linderholm et al., 2018), northern lakes play a significant role in the ongoing climate change through their functions in carbon release and sequestration.

Chironomid (Insecta: Diptera: Chironomidae) larvae take part in benthic processes that are essential for lake ecosystem functions (Benke and Huryn, 2010; Hölker et al., 2015). Most importantly, chironomids living in the water-sediment interface have a major role in the biogeochemical cycling of carbon, nitrogen and phosphorus (Nogaro et al., 2008; Belle et al., 2017). The functional roles of chironomids are mostly reflected by their feeding preferences (Heino, 2008; Luoto and Nevalainen, 2015), but their taxonomical compositions typically respond to climate conditions at the regional scale (Brooks, 2006) and hypolimnetic oxygen and nutrient conditions at the local/site-specific scale (Brodersen and Quinlan, 2006). In Finnish Lapland, the most important environmental factors controlling chironomid distribution and abundance are temperature, organic content of the sediment, nutrients/oxygen and water depth (Olander et al., 1997; Nyman et al., 2005; Luoto et al., 2016). Hence, chironomids contribute as sensitive indicators of climate changes, limnology and elemental cycling. The influence of temperature on chironomids can be direct (metabolism) or indirect (e.g. habitat) and mediated through air (flying adults) or water (aquatic larval stage) temperature (Eggermont and Heiri, 2012), whereas the influence of hypolimnetic oxygen is related to the species-specific respiration rates and oxygen demands (Brodersen et al., 2008). Using the transfer function approach (calibration-in-space), it is possible to provide long-term quantitative reconstructions of these variables (Quinlan and Smol, 2002; Luoto et al., 2017a, 2017b; Wohlfarth et al., 2018).

In this study, we investigate chironomid assemblages and changes in chironomid-inferred hypolimnetic oxygen conditions in 30 subarctic lakes in northern Finnish Lapland using the top-bottom (or before-after) paleolimnological approach (Quinlan and Smol, 2002), where the surface sediment samples (top) represent the present and the reference samples (bottom) the past. We examine the findings against the modern dissolved organic carbon (DOC) gradient of the lakes to find out potential differences caused by catchment characteristics, with special interest on the influence of peatlands.

2. Material and methods

2.1. Study sites and sampling strategy

The study sites include 30 lakes from northeastern Finnish Lapland (68°47′–69°55′N) with a catchment gradient from mixed pine and birch forest to mountain birch woodland and barren tundra (Fig. 1). The study area is located in a sporadic permafrost region. All the lakes are small and shallow (<7.5 m) and distributed along a truncated mean July air temperature transect from 12.3 to 13.3 °C. While minimizing the temperature gradient, the lakes were sampled to characterize different catchment types from forest and bog environments to tundra vegetation to encompass a broad dissolved organic carbon (DOC) gradient from 1.7 to 16.6 mg l^{-1}. The sampling strategy was originally designed to study spatio-temporal zooplankton responses to UV radiation (the DOC screening effect) (Nevalainen et al., 2018) and to investigate the sources and controls of organic carbon in these lakes (Rantala et al., 2016a). The dataset consists of 15 oligohumic (DOC <4 mg l^{-1}), 10 mesohumic (DOC = 4–6 mg l^{-1}) and 5 polyhumic (DOC >6 mg l^{-1}) lakes. Total phosphorus in the lakes varies from 5 to 24 μg l^{-1}, total nitrogen from 138 to 806 μg l^{-1} and pH from 5.1 to 8.4. Environmental characteristics and limnology of the study sites are described in detail in Rantala et al. (2016a). The lakes and their codes (numbers) are the same as in Rantala et al. (2016a), with the exception that one tundra site (#34) was removed from this study due to low number of chironomid head capsules.

Surface (top, 0–2 cm in core depth) and reference (bottom, 4–5 cm) sediment samples were collected from the centres of the lakes using a Limnos gravity corer (Kansanen et al., 1991) in July 2014. According to several sediment cores dated from the study area (Luoto and Sarmaja-Korjonen, 2011; Luoto et al., 2017b; Rantala et al., 2016b), the average sediment accumulation in the lakes refer to past 20 years in the "top" surface sediment samples and to 150 years in the "bottom" reference samples. The top and bottom samples are discussed herein as modern and Pre-Industrial age samples, respectively, but since the samples were not independently dated, we emphasize that these general timeframes are only tentative and the bottom sample may not always represent Pre-Industrial times. Although the widely employed top-bottom (or before-and-after) approach allows for efficient spatio-temporal regional assessment of environmental change, the disadvantage of this approach is that there are no continuous data on the timing or rate of changes occurring between the two points in time represented by those samples (Smol, 2017). In addition, it cannot be assumed that there is only one Pre-Industrial/reference environmental state from which lakes have deviated (Perren et al., 2009). These limitations of the applied approach should be kept in mind when interpreting the data.

2.2. Chironomid analysis

Standard methods were applied in fossil chironomid analysis (Brooks et al., 2007). The wet sediment was sieved through a mesh (100-μm) and the residue was examined under a stereomicroscope. Larval head capsules were extracted and mounted permanently with Euparal on microscope slides. Taxonomic identification following Brooks et al. (2007) was performed under a light microscope. The minimum chironomid head capsule number per sample was set to 50 (Heiri and Lotter, 2001; Larocque, 2001; Quinlan and Smol, 2001). Two split head capsules were considered as one individual. The surface sediment chironomid assemblages have been previously published in Luoto et al. (2016), whereas the reference samples were analyzed in this study by the same chironomid analyst using identical methodology and taxonomy.

2.3. Numerical methods

Bray-Curtis similarity was used as a measure to assess the difference between present and past chironomid communities. In this measure, 0 refers to a completely different community and 1 to an analogous community. N2 (Hill, 1973) was used as a diversity measure, corresponding to effective number of occurrences, i.e. the effective diversity of a sample's community.