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20th century acidification and warming as recorded in two alpine lakes in the Tatra Mountains (South Poland, Europe)

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ABSTRACT

Sediment profiles of two alpine lakes located in the Tatra Mountains, the Toporowy Staw Niżni (TSN) and the Zielony Staw Gąsienicowy (ZSG), were studied for their chronology, lithology, diatom and cladoceran remains. The sediment sequences, 50 cm long from TSN and 30 cm long from ZSG, were deposited during the last 1000 and 300 years, respectively. Vertical changes in lithology, diatom and Cladocera allow the reconstruction of three periods in the lakes' evolution: mild climatic conditions during Medieval Warm Period (MWP, only in TSN), severe conditions between the end of 14th and 19th centuries, identified as the Little Ice Age (LIA), and 20th century warming. The LIA was recorded in the sediments of both lakes in the form of intensified erosion and lower lake ecosystem productivity, as indicated by organic matter lower content, changes in diatom species composition, and decline in *Daphnia*.

The 20th century was a time of acidification in both lakes. The scale of acidification was assessed based on the decline in diatom-inferred pH (DI-pH). DI-pH dropped by 1.2 pH units during the last century in TSN and by 0.4 pH unit in ZSG. The decline of DI-pH was noted in both lakes, but its intensity was clearly higher in TSN due to the lower acid neutralisation capacity (ANC) of this lake. The lower pH during the final decades of the 20th century was lethal to some water organisms while attracting others, such as *Daphnia*. The *Daphnia* population increased after the pH drop, probably due to the high food flexibility of this genus. A similar increase was not observed in ZSG, where planktonivorous fishes were introduced in the 1940s, which effectively limited the crustacean plankton density.

1. Introduction

Artificial acidification is not a global-scale process, although it can be observed from many sites at high elevation and high latitude areas, both remote (Curtis et al., 2005) and close to industrial centres (Sienkiewicz et al., 2006). Recovery from acidification has been recorded in many sites over the last two decades (Forsius et al., 2003; Vrba et al., 2003; Lento et al., 2008; Wright, 2008), while the biocenoses in others are still affected by low pH (Ek and Renberg, 2001; Sienkiewicz et al., 2006).

An anomalous climate warming during 20th century is accepted by most scientists, but its causes, scale, and the role of humans as an inducing factor are still controversial issues (Jones and Mann, 2004; Riedwyl et al., 2008; Hoerling et al., 2008; Zorita et al., 2008). Records of climate changes during the last century from high elevation and/or high latitude sites are abundant, but they do not always indicate significant warming (Vincent et al., 2007).

Mountain lake sediments represent a good material for observing environmental changes at the regional and global scale. These lakes are inhabited by specific biocenoses that are usually highly sensitive to climatic and environmental variability. Because mountain lake samples are highly useful for reconstructing past climate and environmental conditions at both the millennial and century scale, they have been studied intensively in the past two decades. Several international projects were being run at that time in Europe that produced significant data, including AL:PE, MOLAR and EMERGE (Mosello et al., 1995; Battarbee et al., 2002). Lakes located in the Tatra Mountains (Poland and Slovakia) were also analysed by numerous scientists due to changes in their biota (e.g., Marciniak, 1986; Kamenik et al., 2005; Štefková, 2006; Dumnicka and Boggero, 2007), sedimentological and geomorphological changes (e.g., Kotarba, 2004, 2006), catchment vegetation changes (e.g., Krupiński, 1983; Obidowicz, 1996; Rybníčková and Rybníček, 2006) and acidification (Kopáček et al., 2002, 2006; Curtis et al., 2002; Kawecka and Galas, 2003; Rzychoń and Worsztynowicz, 2007). However, palaeolimnological papers offering high resolution studies of Tatra lake sediments that have accumulated during the last millennium are still infrequent (Šporka et al., 2002).

The aim of our study was to reconstruct the development of two mountain lakes (the Zielony Staw Gąsienicowy and the Toporowy Staw Niżni lakes) in the Polish Tatra Mountains (West Carpathians) in recent centuries. In spite of different altitude and geological and geomorphologic characteristics of the lakes, we expected to find

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similar responses to 20th century warming and acidification, as these processes act at the regional and global scale. The reconstruction was based on sedimentological and palaeobiological records (diatom and cladoceran remains) identified from the sediments by analysing them with high resolution.

2. Study sites

Both lakes that were analysed are situated in the Polish part of the High Tatra Mountains (Fig. 1); their origin is related to the presence of local mountain glaciers during the last glaciations. In this region, soils contain various forms of podsolic rankers and lithosols. The Toporowy Staw Niżni (TSN) is located on the end moraine in the west part of the Sucha Woda Valley, situated at the lowest altitude of all the lakes in the Polish Tatra Mountains, on the moraine of a Würm age glacier. It is a dystrophic, fishless lake surrounded by coniferous forest and peat bogs; the overgrown banks of the lake are causing its gradual disappearance. The Zielony Staw Gąsienicowy (ZSG) is located in a post-glacial cirque surrounding by dwarf pine, alpine meadows and rock cliffs. This oligotrophic lake is one of the biggest in the Polish part of the Tatra Mountains. The bedrock consists of granite and granodiorite rocks and moraine deposits. The lake was fishless until the beginning of 20th century, when brook charr were introduced. Some morphologic and limnologic data concerning these lakes are given in Table 1.

3. Material and methods

3.1. Coring and chronology

Sediment cores (500 and 300 mm in length from TSN and ZSG, respectively) were collected in April 2003 from the lake centres using a Kajak-type gravity corer. The cores were divided in the field into 1-cm-thick sections and were stored in plastic bags.

The chronology of the sediment cores was based on ^{210}Pb and ^{14}C measurements. For ^{210}Pb analysis, 3 cm^3 samples of homogenised sediment were taken from each level. The fresh sediment samples were weighed, dried, and weighed again to determine bulk density and water content. The ^{210}Pb activity of sediments was indirectly determined by alpha-spectrometry measurements of ^{210}Po ($E_{\alpha} = 5.31$ MeV, $T_{1/2} = 138$ days) activity (Flynn, 1968) in the Laboratory of Quaternary Geochronology in the Institute of Geological Sciences, at the Polish Academy of Sciences in Warsaw. ^{210}Po is generated by the decay of ^{210}Pb, followed by ^{210}Bi, and is assumed to be in equilibrium with its

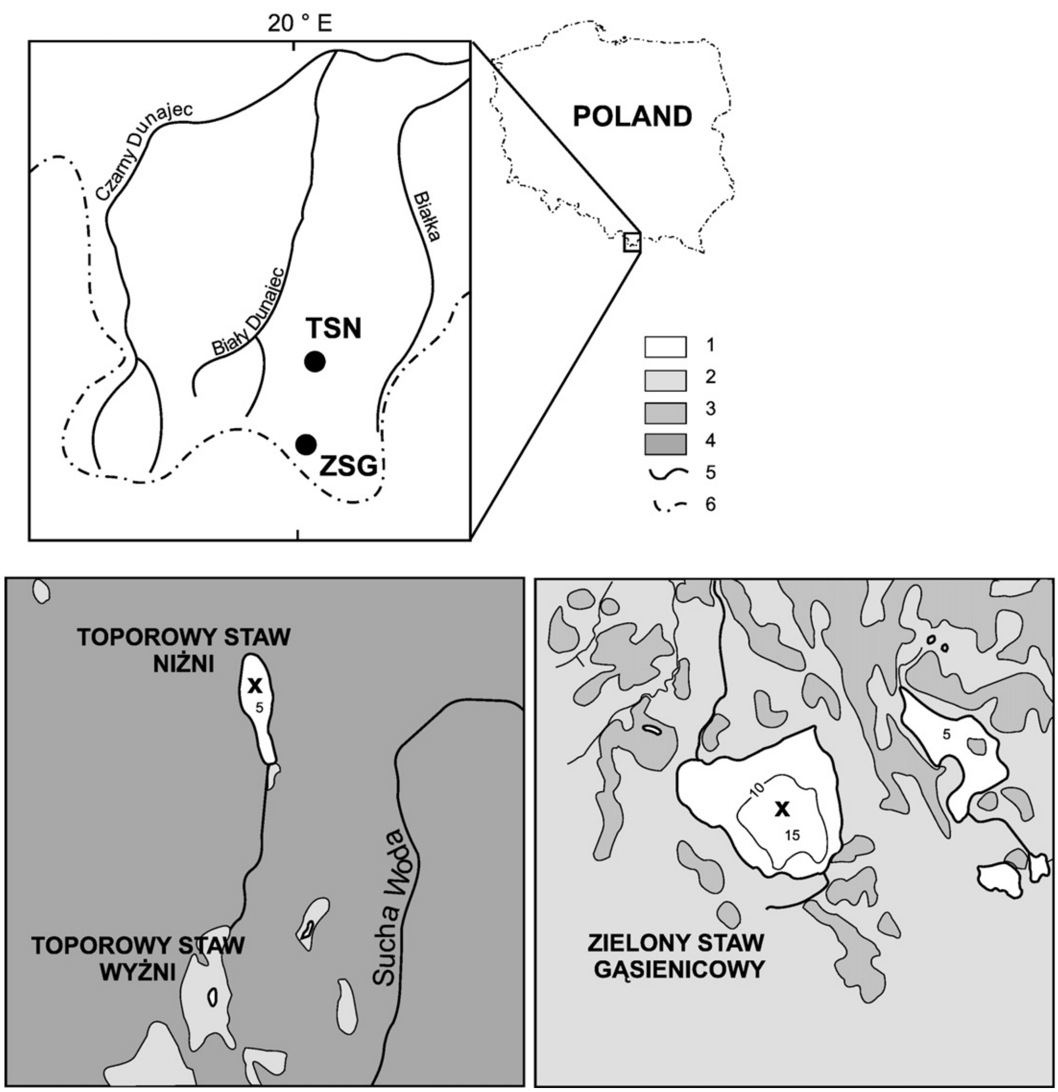

Fig. 1. Location of studied sites. TSN — the Toporowy Staw Niżni lake, ZSG — Zielony Staw Gąsienicowy lake. 1 — lakes, 2 — bogs and meadows, 3 — dwarf pine shrubs, 4 — forests, 5 — streams, 6 — state border. X marks indicate coring sites.