Limnologica 62 (2017) 38–46

Contents lists available at ScienceDirect

Limnologica

journal homepage: www.elsevier.com/locate/limno

Multiple extreme environmental conditions of intermittent soda pans in the Carpathian Basin (Central Europe)

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A R T I C L E I N F O

Article history:
Received 9 February 2016
Received in revised form 19 October 2016
Accepted 24 October 2016
Available online 4 November 2016

Keywords:
Alkaline
Hypertrophic
Intermittent
Polyhumic
Turbid
Water temperature fluctuation

A B S T R A C T

Soda lakes and pans represent saline ecosystems with unique chemical composition, occurring on all continents. The purpose of this study was to identify and characterise the main environmental gradients and trophic state that prevail in the soda pans (n = 84) of the Carpathian Basin in Central Europe. Underwater light conditions, dissolved organic matter, phosphorus and chlorophyll *a* were investigated in 84 pans during 2009–2010. Besides, water temperature was measured hourly with an automatic sensor throughout one year in a selected pan. The pans were very shallow (median depth: 15 cm), and their extremely high turbidity (Secchi depth median: 3 cm, min: 0.5 cm) was caused by high concentrations of inorganic suspended solids (median: 0.4 g L^{-1}, max: 16 g L^{-1}), which was the dominant (>50%) contributing factor to the vertical attenuation coefficient in 67 pans (80%). All pans were polyhumic (median DOC: 47 mg L^{-1}), and total phosphorus concentration was also extremely high (median: 2 mg L^{-1}, max: 32 mg L^{-1}). The daily water temperature maximum (44 °C) and fluctuation maximum (28 °C) were extremely high during summertime. The combination of environmental boundaries: shallowness, daily water temperature fluctuation, intermittent hydroperiod, high turbidity, polyhumic organic carbon concentration, high alkalinity and hypertrophy represent a unique extreme aquatic ecosystem.

1. Introduction

Most inland saline waters are shallow with unique physical and chemical conditions. Soda lakes and pans can be found on all continents, but they are much less frequent than other types of saline waters (Hammer, 1986). Soda lake formation depends on low levels of dissolved calcium and magnesium and the dominance of bicarbonate (HCO_3 » Ca + Mg). They represent the most stabile high-pH environments (pH > 9) on Earth, which clearly distinguishes them from other inland saline waters (Grant, 2004, 2006; Warren, 2006; Brian et al., 1998).

Soda lakes are interesting also for evolutionary biology. Zavarzin (1993) argued that alkaline soda lakes have ancient prokaryotic communities. According to Brian et al. (1998), the "Precambrian explosion" of prokaryote diversity might had taken place in alkaline environments. The Archaean ocean was perhaps dominated by Na-Cl-HCO_3, and did not resemble the Na-Cl ocean of today (Kempe and Degens, 1985; Maisonneuve, 1982). According to this so-called "soda ocean hypothesis", this early Archaean hydrosphere might had a chemistry similar to that found in modern soda lakes (Warren, 2006). This hypothesis however remains controversial.

European soda pans were formed on various geological substrates by specific climatic, geologic and hydrologic conditions in the groundwater discharge areas of the Carpathian Basin at the end of Pleistocene and the beginning of Holocene. These relatively old habitats were strongly influenced by human impacts in the last two centuries, leading to the disappearance of the majority of soda pans (Boros et al., 2013). According to available knowledge, European soda pans are restricted to the Carpathian Basin (in Austria, Hungary and Serbia). Due to their unique conditions and biota, as well as the significant decline in their number and territory, soda pans are listed in the habitat directive (92/43/EC) as "Pannonian steppes and salt marshes" with high protection priority in the Natura 2000 network of the European Union (Boros et al., 2013). In addition, several of these habitats are listed as Ramsar sites or Important Bird Areas, and most soda pans in Austria are part of a UNESCO World Heritage site.

Abbreviations: CHL, chlorophyll *a*; CDOM, chromophoric dissolved organic matter; DOC, dissolved organic carbon; K_d, vertical attenuation coefficient; SRP, soluble reactive phosphorus; TP, total phosphorus; TSS, total suspended solids; TSS-Alg, suspended solids without algae; Z, water depth; Z_{eu}, euphotic depth; Z_{mix} Z_{eu}^{-1}, ratio of mixed and euphotic depth; Z_S, Secchi disc transparency.

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http://dx.doi.org/10.1016/j.limno.2016.10.003
0075-9511/

The most frequent ionic type of soda pans is the basic alkaline type ($Na\text{-}HCO_3$), which represents more than half of the natural soda pans in the Carpathian Basin, being widely distributed on the lowland part of the region. The second most frequent subtype is the chloride subtype (13% of all pans), which is concentrated to the Danube Valley in Central Hungary, while the third is the sulphate subtype (11%), which is rather frequent in Seewinkel (Austria). Magnesium can sometimes be a secondary dominant cation beside sodium. The high number of ionic subtypes reflects the chemical diversity of alkaline soda pans within the relatively small territory of the Carpathian Basin. Salinity varies between sub- and hypersaline ranges, with pH in the alkaline range (Boros et al., 2014).

The intermittent soda pans of the Carpathian Basin are very shallow compared to other saline lakes of the World (Boros et al., 2014), which is a key feature of these pans. Because of their shallowness, water temperature strongly follows air temperature, and notable daily temperature fluctuations can occur. Furthermore, polymixis and high turbidity are also usual conditions in most shallow lakes, and they are also key physical factors in the soda pans (Hammer, 1986).

In contrast with the known prevalence of strong environmental stress gradients due to extreme local conditions (salinity, pH, turbidity, desiccation), there are only a relatively few recent studies that have investigated the effect of this environment on the local biota. According to them, benthic and planktonic communities reflect a strong structuring role of salinity, turbidity and trophic state (e.g. Wolfram et al., 1999; Horváth et al., 2013a, 2014, 2015; Stenger-Kovács et al., 2014, 2016).

Zavarzin (1993) observed that endorheic soda lakes have a closed nutrient cycling, where carbon and nitrogen input is predominantly dominated by CO_2 and N_2 fixation by cyanobacteria. However, others argue that soda lakes are not entirely closed systems, due to large populations of waterbirds (Brian et al., 1998; Sorokin et al., 2014). Apart from the apparent role of local conditions, aquatic communities of soda pans are also strongly linked to waterbirds in two ways: habitats with a high zooplankton biomass attract more planktivorous waterbirds (Boros et al., 2006; Horváth et al., 2013b), while waterbirds (especially large-bodied herbivorous species e.g. geese) provide a high nutrient input, regulating trophic relationships, causing net heterotrophy, and a generally high trophic state (Boros et al., 2008a,b; Vörös et al., 2008).

Although data are available on a selected number of European soda pans and their physical and chemical conditions, a large-scale evaluation of multiple environmental conditions together with the respective trophic state is still missing. It is currently also unknown whether the major ionic composition, which shows some geographical pattern in the region (Boros et al., 2014), has any relationship with other physical and chemical variables.

The purpose of this study was to identify and characterise the main environmental gradients and trophic state that prevail in the natural soda pans of the Carpathian Basin. For this, we used a dataset covering all natural intermittent soda pans (Boros et al., 2013) in the Carpathian Basin (Austria, Hungary, Serbia). Secondly, we also aimed to study the seasonal and daily water temperature fluctuations in a selected typical shallow soda pan, which can pose another type of stress for the biota developing on a daily basis.

2. Methods

2.1. Study sites

The Carpathian Basin is influenced by Continental, Atlantic and Mediterranean climate, with the predominance of Continental climate on the lowland steppe territories where the soda pans are located. Yearly mean air temperature is between +10 and +11 °C and the yearly sum of rainfall is between 500 and 600 mm on the lowlands. Daily air temperature fluctuation is the lowest in December (4–6 °C), and the highest in July (10–11 °C), based on the mean of 30 years (1971–2000), but the occurrence of irregular extremes is significantly increasing during the last decade. The time of sunshine is relatively high (1800–2000 h per year) and the yearly mean of windy days (wind speed > 10 m s^{-1}) is 122 (www.met.hu). All these climatic conditions contribute to the high water level fluctuation and summer drying out of the soda pans.

The biomass of phytobenthos is low in soda pans, because of strong underwater light limitation (Boros et al., 2013), and previous studies have found that picophytoplankton is one of the fundamental contributors to planktonic primary biomass production (Keresztes et al., 2010). Macrophytes are relatively scarce because of the extreme conditions. Marshland (*Bolboschoeno-Phragmitetum*) and wet meadow vegetation (*Lepidio crassifolii – Puccinellietum limosae*) are the most typical around the shoreline, while submerged macrophytes are sparse or absent. More details on the ecology and overall characteristics of soda pans were recently published by Boros et al. (2013).

The study area covers the whole lowland territory of the Carpathian Basin (Pannonian Plain), where the natural intermittent soda pans are located. This involved the survey of the Seewinkel region of Austria, the Great Hungarian Plain of Hungary and the Vojvodina region of Serbia. In this way, we included all the characteristic soda pans of the Pannonian ecoregion (Fig. 1).

2.2. Water sampling and field measurements

The survey of intermittent soda pans took place from March 2009 to August 2010. Each pan (Appendix A) was sampled once during this period. In spite of a single observation per habitat, the large spatial scale with the complete dataset of existing natural (n = 84) soda pans in the region can give a representative overview on environmental conditions and trophic state. The exact position of sampling sites was obtained with a GPS device. Details on measuring the open water area are given in Boros et al. (2014). Water samples were taken from the open water area of the pans taking particular care not to disturb the sediment, by filling plastic containers with water subsequently analysed in the laboratory in triplicates. Water depth (Z) was measured at each sampling location with a centimetre-scale pole.

Underwater light conditions were measured on the field with a Secchi disc (Z_S), except when the lake bottom was visible (n = 14). We used a Secchi disc constructed specifically for these turbid systems: the disc was a round tray (with a rim), with a measuring stick attached to its centre. In most habitats, we used it by immersing into the water, while in the most turbid habitats, we took some water from the surface layer (1–2 cm) and by pouring it on the tray, we could measure transparency with an accuracy of 0.5 cm. Electrical conductivity was measured with a WTW Multiline field instrument with a TetraCon 325, and pH with a SenTix 41 electrode on site. Salinity was calculated from conductivity (with a multiplying factor of 0.8) based on a formerly established experimental relationship (Boros et al., 2014).

2.3. Measurement of TSS, TSS-Alg, CDOM, SRP, TP, CHL

The concentration of total suspended solids (TSS) was measured gravimetrically. Water samples of 100–150 ml were filtered through a previously dried and pre-weighed GF-5 glass fibre filter (nominal pore size = 0.4 μm), then dried for 2 h at 105 °C, then weighted again. The concentration of total suspended material was calculated based on the volume of the filtered sample.

Concentration of the chromophoric dissolved organic matter (CDOM) was measured spectrophotometrically at 440 nm accord-