

Effect of mosses and lichens on the elemental composition and dynamics of carbon in the water of thermokarst lakes

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The influence of the plant substrate on the formation of the elemental composition of water and the dynamics of carbon (DOC and CO₂) in thermokarst lakes in the discontinuous permafrost zone of Western Siberia was studied. Mesocosm experiments were conducted during 3 weeks on large thermokarst lake waters interacting in 30-L tanks with the dominant ground vegetation (lichen *Cladonia* sp. and moss *Sphagnum* sp.). As a result of mesocosm experiments is that lichen is able to change the chemical composition of melt water more strongly than mosses. An increase in the DOC concentration upon contact with lichen shows a rapid increase in the DOC concentration (2–3 weeks) at a high substrate concentration. The increase in conductivity, DOC and SUVA₂₅₄, and concentrations of CO₂ and CH₄ in lake water in the presence of moss and lichen in the first week of the experiment are within the range of values characteristic of natural thermokarst subsidence and lakes. Thus, the conducted field experiments on setting up mesocosms with the addition of the dominant vegetation of flat-hilly frozen bogs (mosses and lichens) can serve as experimental models of the formation of the elemental composition and the formation of dissolved greenhouse gases in thermokarst subsidence.

Key words: lichen, moss, thermokarst lake water, leaching, mesocosms.

Introduction

The impacts of ongoing climate change on shallow aquatic ecosystems in arctic and sub-arctic regions include, but are not limited to: i) an increase in the number and frequency of land fires and, as a consequence, ash leaching, ii) an increase in precipitation and hence the degree of flooding of land vegetation, such as lichens, and iii) increased thawing of frozen peat, leading to lateral distribution of small thawed water bodies and an increase in the flow of peat residues into surface waters (Schuur et al., 2015; Vonk et al., 2015; Bring et al., 2016). To assess the relative impact of these three main drivers of lake water's chemical evolution, detailed, long-term, seasonal observations of the aquatic environment of permafrost (Laurion et al., 2010; Christensen et al., 2012; Manasyov et al., 2015) or precise paleoreconstructions (e.g. Swindles et al., 2015). This is an expensive and somewhat clumsy measure as it is difficult to distinguish between different sources of dissolved organic carbon (DOC), other solutes, and various control factors based solely on monitoring lake water chemistry and sediment.

An important feature of boreal water bodies is the presence of high concentrations of dissolved organic matter (DOM) of essentially allochthonous nature and, hence, the colloidal state of most trace elements and heavy metals, which form strong organic and organo-mineral associates complexes. The quantity, bioavailability, transformations and transport flows of organic colloids between different reservoirs are the main indicating parameters of the biogeochemical cycle of carbon and associated chemical elements (Pokrovsky et al., 2011, 2016; Shirokova et al., 2013; Manasyov et al., 2015 and others).

Leaching of organic substrates is the main source of dissolved elements in waters of thermokarst lakes. The main sources of dissolved carbon and associated chemical elements are: 1) surrounding peat soil, 2) vegetation, such as lichen, which dominates in the area and 3) ash leaching after burning of lichen, moss and top peat layer (Manasyov et al., 2017). In contrast to extensive studies of surface flows of chemical elements in the boreal zone exposed to forest fires, leaching of peat horizons and plant litter (Drake et al., 2015; Parham et al., 2013), data on the effects of lichens and moss on the formation of the lake water elemental composition are meager. It is known that redistribution and migration of chemical elements in aquatic ecosystems are closely related to the processes occurring in the biota inhabiting these ecosystems.

Unlike monitoring, mesocosm experiments are very effective to identify and quantify the main environmental factors that determine the system behavior under various external effects (Hering et al., 2015; de Rozari et al., 2016; Conroy et al., 2016, etc.).

Materials and methods

When setting up the experiment, we used low-mineralized water from a large thermokarst lake (Trisino) with an electrical conductivity of $9 \mu\text{S cm}^{-1}$ and $\text{pH} = 5.09$, and a DOC content (8.1 ppm). The dominant species of lichen (*Cladonia* sp.) and moss (*Sphagnum* sp.) were used as substrates in three concentrations: 1 g dry weight/L of lake water, 10 $\text{g}_{\text{dw}}/\text{L}$ and 30 $\text{g}_{\text{dw}}/\text{L}$. The substrates for the experiment were the apical (living) parts of lichen and moss, which are widespread in flat-hilly frozen bogs of this territory and make up 70% of the vegetation cover. Mosses and lichens were sampled at the edge of the thermokarst lake, then washed with MilliQ ultrapure deionized water and air dried using Osmofilm® osmotic bags for 5 days. The water used for the experiment was taken from the surface of the lake and pre-filtered through a nylon mesh (pore diameter 100 μm) into PVC tanks with a volume of 30 liters in order to remove zooplankton, insects, and large organic detritus. Duplicate reservoirs with the addition of lichens and moss were tightly closed and placed directly into the lake. Aeration of the incubated water was achieved by periodically opening the reservoir and gently stirring the contents with a pre-cleaned plastic spatula. During the experiment, three different concentrations of substrates were used to reveal the differences in the influence of the vegetation cover on the dynamics of leaching of chemical elements and the formation of dissolved CO_2 and CH_4 .

Measurements of conductivity (TetraCon 325; $\pm 1.5\%$), pH (SenTix 41; ± 0.02 pH) and water temperature (± 0.2 °C) were carried out at a depth of 20 cm using a WTW 3320 multimeter.

DOC and DIC were analyzed using a total carbon analyzer (Shimadzu TOC VSCN) with an uncertainty of less than 3%. To calculate the SUVA_{254} , we measured the ultraviolet absorbance at 254 nm (UV_{254}) using a 10 mm quartz cuvette on a Bruker CARY-50 UV-VIS spectrophotometer.

Dissolved CO_2 and CH_4 concentrations were measured using a Bruker GC-456 gas chromatograph (GC) equipped with a flame ionization detector.

Results and discussion

The temperature in the mesocosms during the experiment gradually decreased from 12 ± 0.3 °C to 5 ± 0.5 °C during the first 5 days of exposure, then, before the end of the experiment, there was a sharp increase to 20 ± 3 °C (Fig. 1). These temperature fluctuations are normal for the spring period (the end of active snow melting and flooding of depressions with rain and melt waters) in this area.

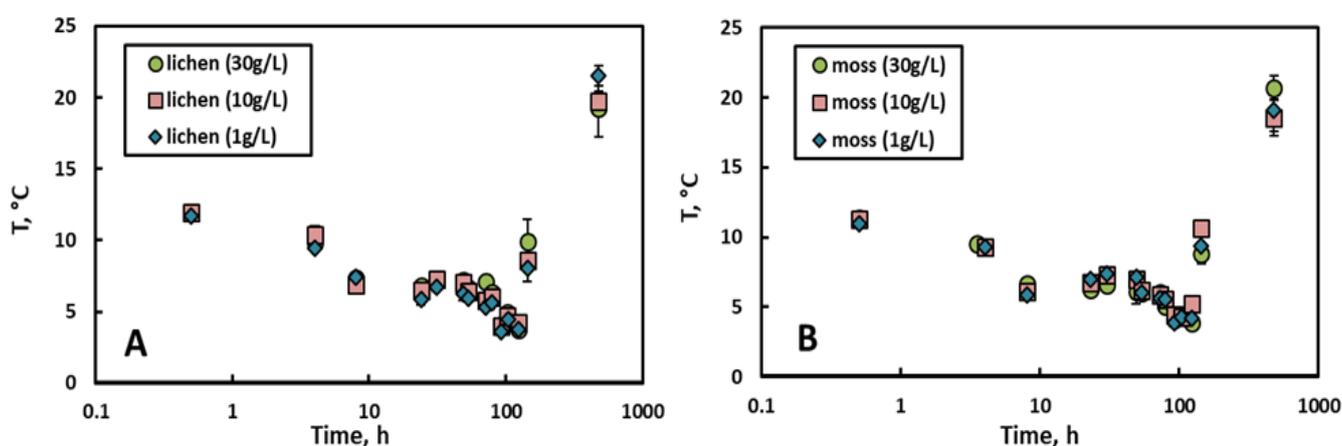


Fig. 1. Temperature values in mesocosms with the addition of lichen (A) and moss (B) as a function of Exposure Time

The addition of both substrates resulted in a rapid acidification of the lake water in the reservoirs. The pH value decreased in 30 minutes by about 1 unit (from 5.09 to 4.2 ± 0.2) for all moss concentrations and remained stable during the experiment, which is confirmed by the absence of a significant correlation between the exposure time and the pH value (Fig. 2a). In the case of the addition of lichen (1 $\text{g}_{\text{dw}}/\text{L}$), a sharp decrease in pH by 0.5 units occurred within 30 minutes, and then a gradual decrease in the course of the experiment to a value of 4.2 ± 0.3 was observed. With the addition of concentrations of 10 and 30 $\text{g}_{\text{dw}}/\text{L}$, there was a sharp decrease by about 1 unit and remained stable during the experiment ($\text{pH} = 4.1 \pm 0.3$). When both substrates were added, the conductivity increased in the order: $1 < 10 < 30 \text{ g}_{\text{dw}}/\text{L}$ (Fig. 2b).

The DOC concentration increased during the experiment with lichen upon the addition of high substrate concentrations (3 times at 10 $\text{g}_{\text{dw}}/\text{L}$ and 7 times at 30 $\text{g}_{\text{dw}}/\text{L}$, from 12 mg/L to 27 mg/L and from 14 mg/L to 67 mg/L, respectively) and practically did not increase at a concentration of 1 $\text{g}_{\text{dw}}/\text{L}$ (Fig. 3a). A decrease in the SUVA_{254} index during the experiment with lichen may indicate leaching of an optically inactive non-chromophoric OM, such as carboxylic acids (Fig. 3b), it correlates significant with DOC concentrations.

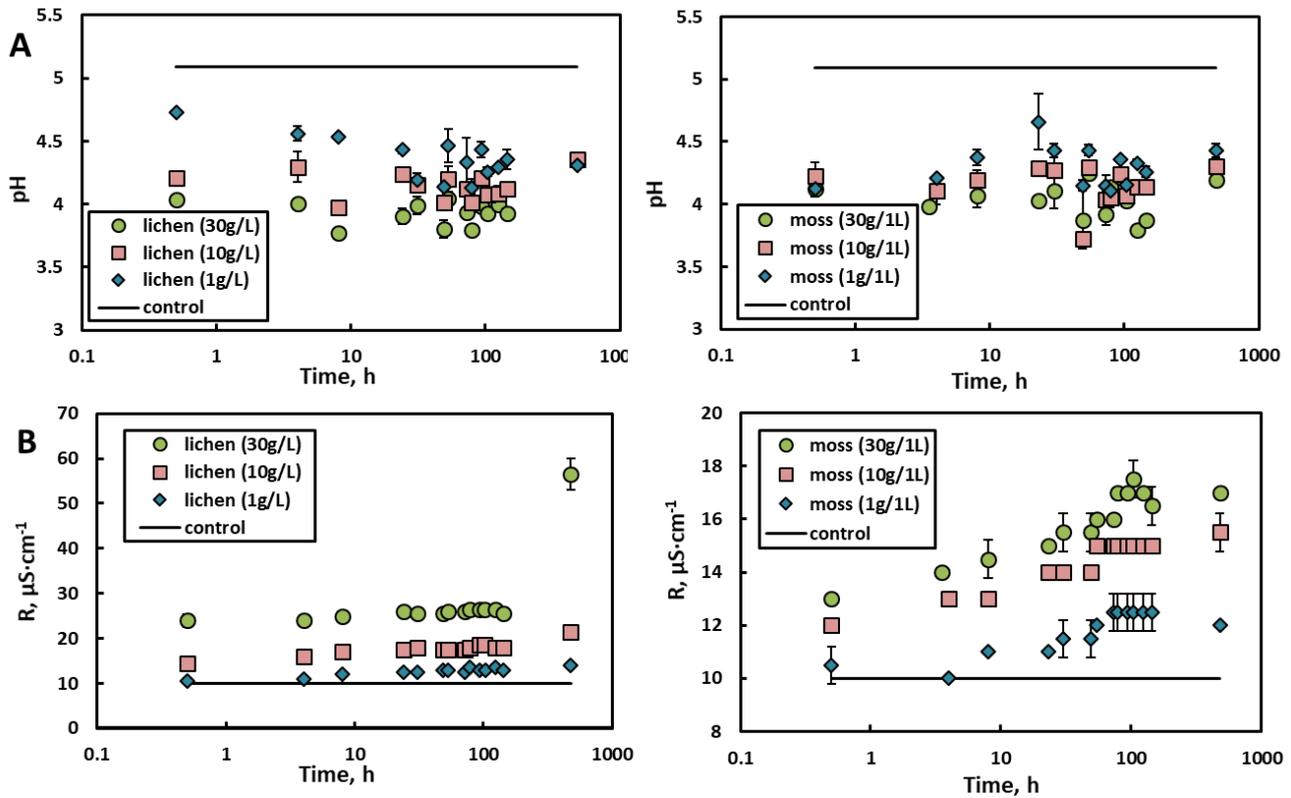


Fig. 2. pH (A) and conductivity (R , $\mu\text{S}/\text{cm}$) (B) in mesocosms with the addition of lichen (A) and moss (B) as a function of Exposure Time

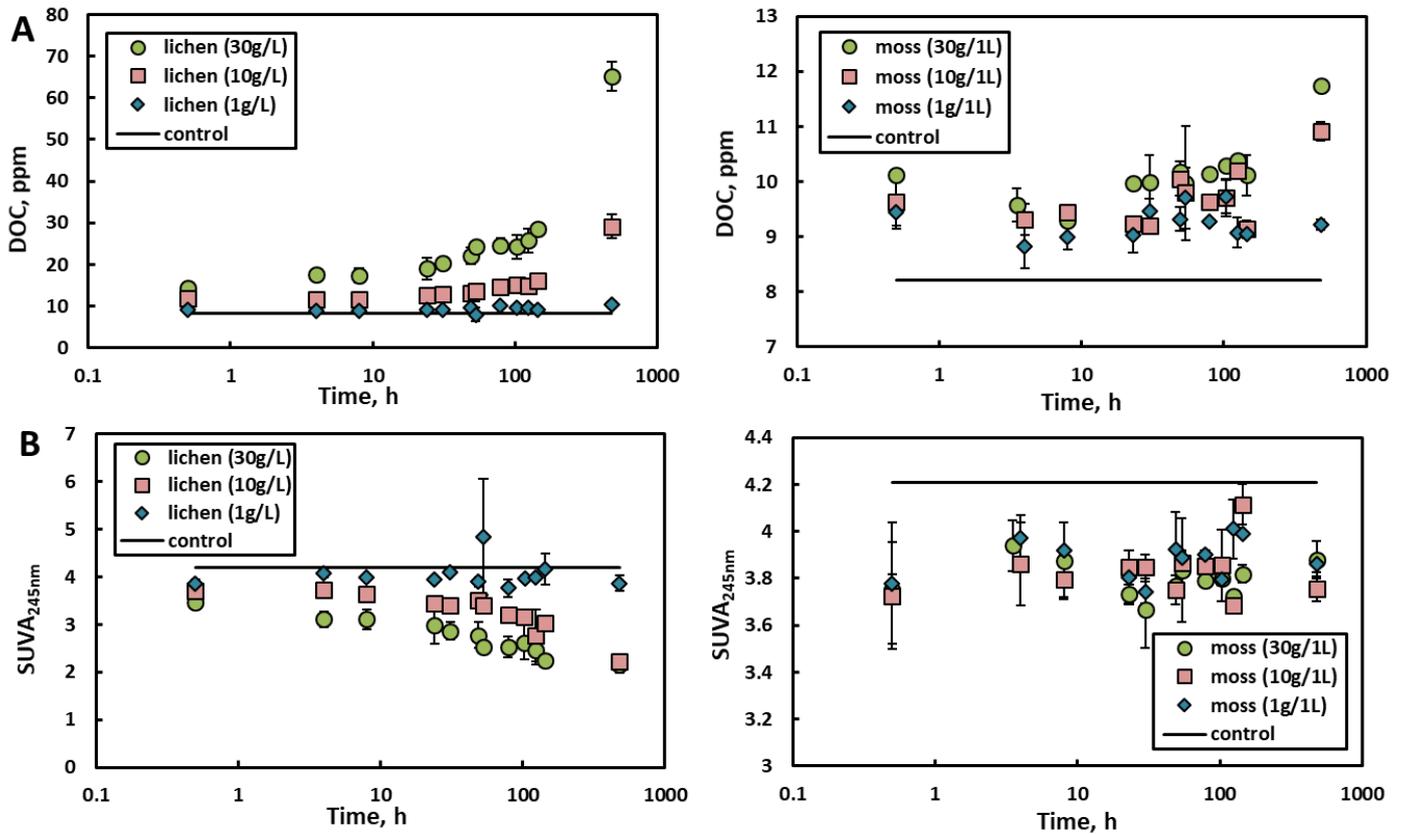


Fig. 3. DOC (A) и SUVA₂₅₄ (B) in mesocosms with the addition of lichen and moss as a function of Exposure Time

The feature of the organic substrates used in this study is the high specific surface area (SSA). Although there are no data on the specific surface area for lichen, by analogy with mosses, it can be assumed that it is also quite high (10–20 m^2/g for Sphagnum, Gonzalez et al., 2016). These values are much higher than the typical SSA of mineral substrates (0.1–1 m^2/g for sand

and silt) that underlie the peat deposit of the study area. Consequently, after the addition of solid substrates with a high SSA, some dissolved elements contained in lake water can be adsorbed on the surface of moss and lichen.

In this case, the rapid release of divalent metals from organic substrates is presumably associated with the desorption of metals from the surface of the added substrates. pH is considered as the main factor controlling the phenomena of adsorption / desorption of metals on the moss surface (Gonzalez and Pokrovsky, 2014). However, the difference in pH values in both mesocosms was insignificant ($p < 0.05$). Thus, it can be assumed that the release of surface-adsorbed metals (for example, Pb, Ni, Cu and Mn) during the first 10 hours of the interaction of water with the biomass of lichen and, in part, moss, can be explained as a rapid release of soluble salts, probably falling out in the form of atmospheric aerosols and accumulating on the surface of lichens. In contrast to this observation, the decrease in the Mn concentration in the mesocosms with the addition of moss may reflect biological or physicochemical removal in the form of individual hydroxides.

An key result of experiments on setting up mesocosms is that lichen is able to change the chemical composition of melt water more strongly than mosses. An increase in the DOC concentration in the lake water upon contact with submerged lichen shows a rapid increase in the DOC concentration (2–3 weeks) at a high substrate concentration. However, this time is shorter than the typical residence time of water in small thermokarst depressions. Such small reservoirs are mainly preserved during the spring flood, 1–1.5 months after the snow melts (Manasypov et al., 2015). This observation proves the influence of the lichen cover on the formation of the elemental composition of water in thermokarst lakes and subsidence of this territory.

The increase in conductivity, DOC and SUVA₂₅₄, and concentrations of CO₂ and CH₄ in lake water in the presence of moss and lichen in the first week of the experiment are within the range of values characteristic of natural thermokarst subsidence and lakes (Shirokova et al., 2013; Manasypov et al., 2015). Later, in the course of the experiment, quite extreme values of these indicators are observed. Unlike mesocosms with low moss additions, the increase in CO₂ content in lichen mesocosms was very rapid, within 1–2 days of interaction (Figure 4a, b). This is consistent with the increased CO₂ level measured during subsidence of permafrost with submerged lichens, which is especially noticeable in spring (Manasypov et al., 2015). Thus, it can be assumed that submerged lichen is capable of producing a net flow of CO₂ into the atmosphere.

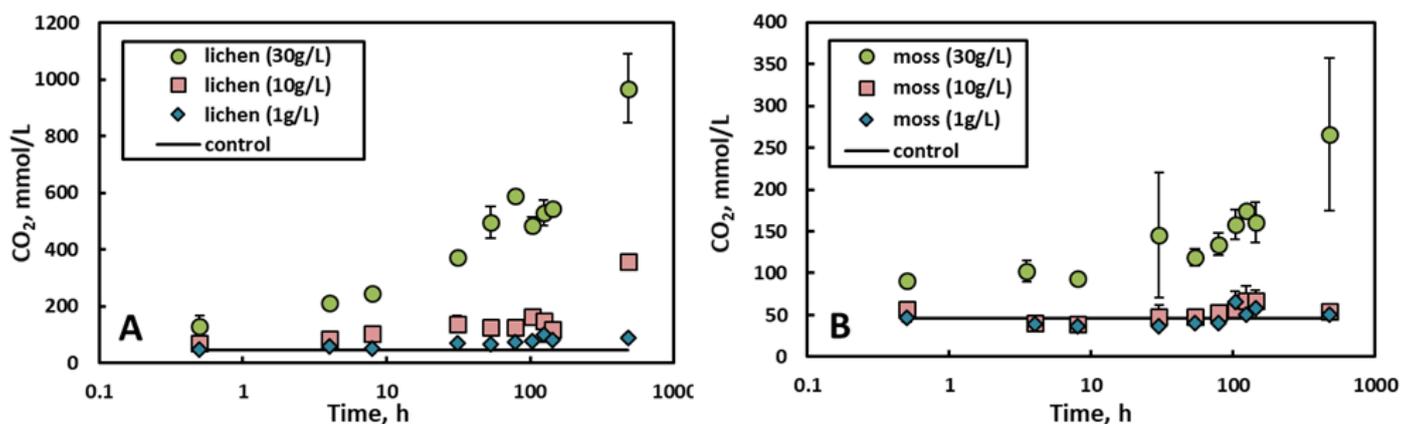


Fig. 4. Dissolved CO₂ concentration in mesocosms with the addition of lichen (A) and moss (B), as a function of Exposure Time

Two processes may be responsible for the observed increase in CO₂ content: 1) respiration of living fungi or algae in lichen and 2) heterotrophic degradation of lichen biomass. Considering the rather rapid response of the increase in CO₂ to the addition of lichens (1–2 days) compared to a more “conservative” increase in DOC (≥ 5 days), we can suggest a subordinate role of leaching and degradation of lichen biomass compared to photosynthesis of lichens. Indeed, biomass degradation and cell lysis release organic matter in the liquid phase in the form of DOC along with some typical nutrients (K, P, Mn and Zn).

These processes, described above, are especially relevant for reconnaissance studies of the role of the spring period of snow melting and active rains on the formation and emission of greenhouse gases during flooding of the lichen cover of watershed areas. According to satellite observations in Western Siberia, the area subject to spring floods is 55–65% higher than the area of palsa in summer (Zakharova et al., 2014).

Conclusion

Thus, the conducted field experiments on setting up mesocosms with the addition of the dominant vegetation of flat-hilly frozen bogs (mosses and lichens) can serve as experimental models of the formation of the elemental composition and the formation of dissolved greenhouse gases in thermokarst subsidence during the decomposition of vegetation in the spring, when a large area of depressions is filled with thawed and rainwater.

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