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Ecological studies of aquatic moss pillars in Antarctic lakes
2. Temperature and light environment at the moss habitat

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Abstract: To understand the environmental conditions, which control the growth of moss pillars in lake bottoms, water temperature and light in the moss pillar habitat in lake Kuwai Ike in Skarvsnes, Sôya Coast, East Antarctica, were continuously measured for about one year, February 1999 to January 2000. Limnological characteristics of surface water of the lake were investigated in summer 2000, and compared with those in four neighboring lakes. Low contents of ions, neutral pH and dissolved oxygen in saturation level in the surface water in lake Kuwai Ike were comparable to the values of the other oligotrophic freshwater lakes in Sôya Coast and Schirmacher Oasis, located in Queen Maud Land, East Antarctica. The temperature at the lake bottom showed uni-modal seasonal change, in the range 0–12℃. Several sudden temperature drops of >2℃ within a few hours were recorded in the ice-free autumn season; they may have been correlated with the wind-induced vertical mixing events which occurred before complete ice cover development on the lake surface. Light reaching the lake bottom showed clear diel and seasonal fluctuations, and the flux density was strongly affected by the attenuations of water, ice and snow: the photosynthetically active radiation (PAR) measured at the lake bottom was $<50\%$ of that at ground level even in ice-free autumn, and decreased further in ice covered seasons. The instantaneous PAR flux $<10\,\mu\mathrm{mol\ m^{-2}s^{-1}}$ was recorded for nearly 2 months in winter; however, daily fluxes over 1 mol $\mathrm{m^{-2}day^{-1}}$ were recorded for the other *ca.* 8 months, with $>100\,\mu\mathrm{mol\ m^{-2}s^{-1}}$ of instantaneous peak fluxes around noon.

key words: moss pillars, growth environment, water quality, bottom temperature, PAR

Introduction

Along the Sôya Coast, East Antarctica, there are many small oligotrophic freshwater lakes (Murayama *et al.*, 1981, 1984; Torii *et al.*, 1988; Ohyama *et al.*, 1992). In some of them, mosses in benthic algal-mats have been collected and reported as ‘submerged forms’ of terrestrial mosses that were growing near the lakes (Kanda and Iwatsuki, 1989; Kanda and Mochida, 1992). Recently, a unique structural moss community, the so-called ‘moss pillars’ has been discovered, and its abundant existence at several lake bottoms in the Skarvsness area has been reported (Imura *et al.*, 1999). Imura *et al.* (2003) summarized the recent progress of studies on the distribution of *Leptobryum* sp., one of the key species which constitutes the moss pillars, and noted that this species has not been found from terrestrial habitat in East Antarctica, but only on the bottoms of several freshwater lakes along the Sôya Coast, and well-developed moss

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pillars were only found on some of the lake bottoms in the Skarvsnes area (*e.g.* B-group lakes, see Fig. 1 Kudoh *et al.*, 2003). The reason(s) why they do not pillar-like structures in other areas, or on land are still unknown.

In order to determine the reasons why the moss achieves massive biomass and forms pillar-like structures at lake bottoms in the Skarvsnes area, growth environmental properties for the aquatic moss pillars have been studied since the JARE-36 party. In the present report, we describe the properties of the lake where typical aquatic moss pillars were found. Light and lake bottom (water) temperature were recorded by data-logging systems for nearly a year, and water characteristics such as ion (anions and cations) contents, pH, dissolved oxygen (DO) and electric conductivity were measured.

Methods

Study site

Lake Kuwai Ike (69°28.6′S, 39°34.8′E), one of the lakes where many aquatic moss pillars form on lake bottoms at 2–5 m depth (Imura *et al.*, 2003), is in western Skarvsnes (150 m in altitude) on the Sôya Coast. It is a small lake with a north-south axis (*ca.* 100 m) nearly twice as long as the east-west axis (*ca.* 50 m), and is surrounded by small hills. The depth measured with handy depth sonar at nearly the center of the lake was *ca.* 5 m. The lake has no major inlet or outlet of water; hence the lake water is primarily fed by precipitation and melt water supply from the surrounding water catchments basin, which balance the evaporation loss.

Measurements of water characteristics

Conductivity, pH, DO and temperature were measured using a portable water quality checker (WQC-20A, Toa Co.) at *ca.* 0.5 m depth in the lake on 20 January 2000. The same parameters were measured at four neighboring lakes, B-1 Ike, B-2 Ike, B-3 Ike, and B-4 Ike (positions are shown in Kudoh *et al.*, 2003), in the western Skarvsnes area. At the same time, a few hundred m*l* of surface water was sampled with a small bucket from the lake shores for ion content. The surface water was stored in sealed plastic tubes under cool and dark condition for a few days until further analysis.

Anions and cations were column-chromatographically analyzed using an ion analyzer (IA-100, Toa Co.). The lower detection limit for each ion was *ca.* 0.1 mg/*l*.

Installation of data-loggers for light and water temperature

Photon flux density or photosynthetically active radiation (PAR) and water temperature were measured continuously by means of data-loggers with 2 and 30 min intervals, respectively. Two data-loggers (W400TL-TL, Little Leonard Co.), which were equipped with a hemi-spherical visual light sensor, were situated at 2.7 m depth (*ca.* 30 cm above the lake bottom) and a water temperature logger (NWT-SN, Nichiyu Co.) was set at the lake bottom using a mooring system that consisted of a bamboo float, nylon rope and a sinker (Fig. 1). The mooring system was deployed at 3 m depth position, nearly 30 m offshore from the northwestern shore, where many moss-pillars were visually observed by one of the authors on a rubber boat on 8 February 1999. At that time the lake surface was almost ice-free; only a small amount of ice floated on the

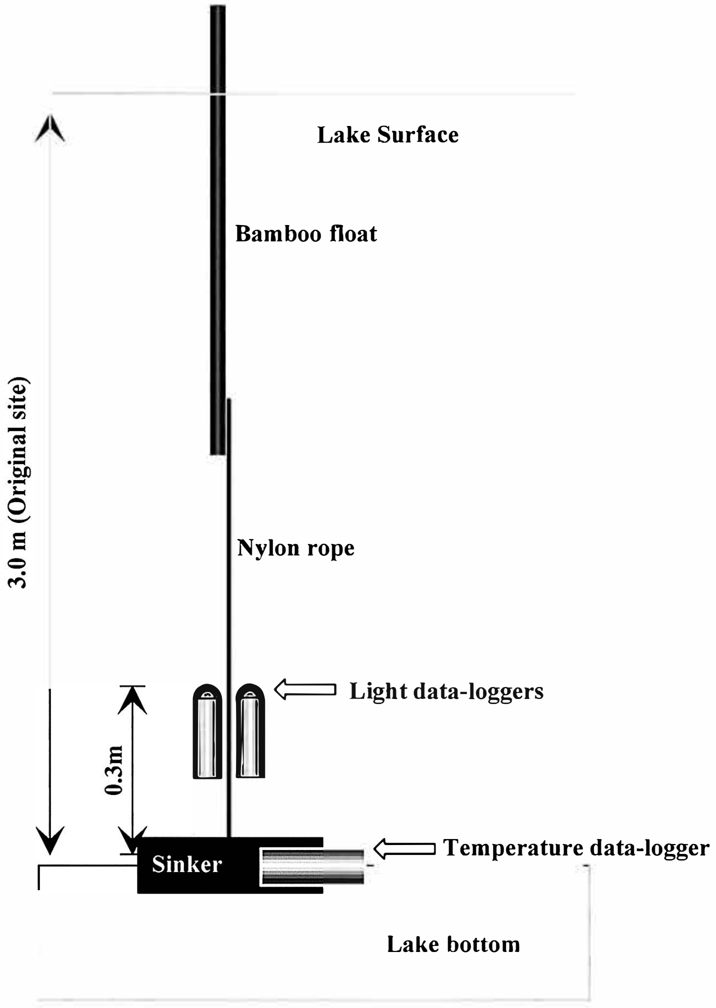

Fig. 1. Design of the mooring system deployed in lake Kuwai Ike.

southeastern shore side.

The mooring system was checked in early austral spring, 14 September 1999. By this time, the system had been moved *ca.* 50 m from the original mooring position of the northwest basin to the southwest shore side, probably due to surface ice movement when ice started to cover the lake surface after our deployment: partly developed ice-cover trapped the bamboo float, and the ice dragged the system to the southwest by wind-induced surface flow.

The system was retrieved on 20 January 2000. The ice covered nearly 50% of the lake surface at that time, and the float of the system was still trapped by thin ice. The system was located along the same southwestern shore as in spring. The depth was *ca.* 2 m, indicating that both light and temperature loggers were positioned at the lake bottom at 2 m after the system was moved.

Results and discussion

General limnological characteristics in lake Kuwai Ike and the neighboring lakes

Water quality of lake Kuwai Ike collected in summer showed comparable values to the values of typical oligotrophic freshwater lakes observed on the Sôya Coast as well as in Schirmacher Oasis in Queen Maud Land, East Antarctica; low in anions and cations, and small conductivity (Table 1, also see Murayama, 1977; Higano, 1977; Murayama *et al.*, 1988; Richiter and Bormann, 1995). All ion concentration measured by the present method in lake Kuwai Ike are smaller than in the other neighboring four lakes. Nutrients such as nitrate, nitrite, ammonium, and phosphate were also measured by ion chromatography, but the detection limit is larger than the natural concentration levels of those nutrients, therefore these could not detected at all ($<$0.1 mg/*l*). There are no terrestrial moss vegetations or bird colonies in water catchments surrounding the lake, suggesting that the nutrient supply from such organisms' activities is quite limited. The lake water is clear as one can visually see the bottom vegetation of aquatic mosses growing in the deepest basin (*ca.* 5 m) during ice-free autumn from surrounding hills, suggesting poor primary productivity by phytoplankton. A similar oligotrophic feature under almost no biological (include anthropogenic) impacts in East Antarctic lakes has been reported by Kaup (1988) and Haendel and Kaup (1995); they summarized their

Table 1. Water quality of several lakes where aquatic moss pillars were found, in the vicinity of Skarvsnes, Sôya Coast, East Antarctica. Positions of the lakes are drawn on the map in Kudoh *et al.* (2003).

Lake	B-1 Ike	B-2 Ike	B-3 Ike	B-4 Ike	Kuwai Ike
Anion (mg/*l*)					
PO_4	0	0	0	0	0
F	0	0	0	0	0
Cl	88.6	46.8	156.4	256.0	61.0
NO_2	0	0	0	0	0
Br	0	0	0	0	0
NO_3	0	0	0	0	0
SO_4	21.5	122.0	29.4	40.6	11.7
Cation (mg/*l*)					
Li	0	0	0	0	0
Na	50.5	263.0	80.6	137	34
NH_4	0	0	0	0	0
K	1.8	10.5	2.8	4.4	1.3
Mg	8.8	50.5	16.2	29.8	5.3
Ca	9.0	31.5	14.6	19	5.4
Other parameters*					
Conductivity (mS/m)	41.4	180.9	65.1	107.1	31.8
DO (mg/*l*)	10.1	11.7	11.2	12.0	12.2
pH	7.10	7.45	7.45	7.01	6.80
Temperature (℃)	7.6	4.8	5.0	3.7	5.2

*Measured on 20 January 2000 from the lake shores. Values are the data of surface lake waters.

limnological research in Schirmacher Oasis, and showed quite low nutrient concentration, inputs, and poor primary production in the water column.

All surface waters in the present five lakes showed neutral pH (*ca.* 7), and contained dissolved oxygen at nearly saturated concentration; those are also typical values of oligotrophic freshwater lakes in East Antarctica (Murayama, 1977; Murayama *et al.*, 1988; Richter and Bormann, 1995).

Seasonal changes of the lake bottom temperature and vertical water circulation in lake Kuwai Ike

The temperature in the moss pillar habitat showed dynamic fluctuations between mid-February and late-March (Fig. 2). During that period, the temperature suddenly decreased from >4℃ to <2℃ 4 times within a few hours. After that, the temperature gradually increased to 4℃ again in late-March, then it decreased slowly to 0℃ toward mid-June. The nearly 0℃ temperature recorded for *ca.* 50 days and the lowest temperature of <−1.0℃ detected for several days in early-October suggested that the lake bottom, where the temperature logger was positioned, started to freeze. The temperature was increased rather quickly to >12℃ with several fluctuations during November–December.

Sudden cooling with rather gradual recovery occurred between mid-February and mid-March, suggesting the occurrence of vertical water circulation which might be induced by wind. The density of freshwater is maximum at *ca.* 4℃; if cooling of the lake water starts at the surface under calm condition during the austral autumn as described by Ohyama *et al.* (1990), cooled water below 4℃ floats in the upper layer and forms reverse thermal stratification. However, if turbulence such as wind-induced vertical mixing or water movement (current) accompanied by water exchange is strong enough, the stratification may be destroyed, and cooled water can be transferred to a

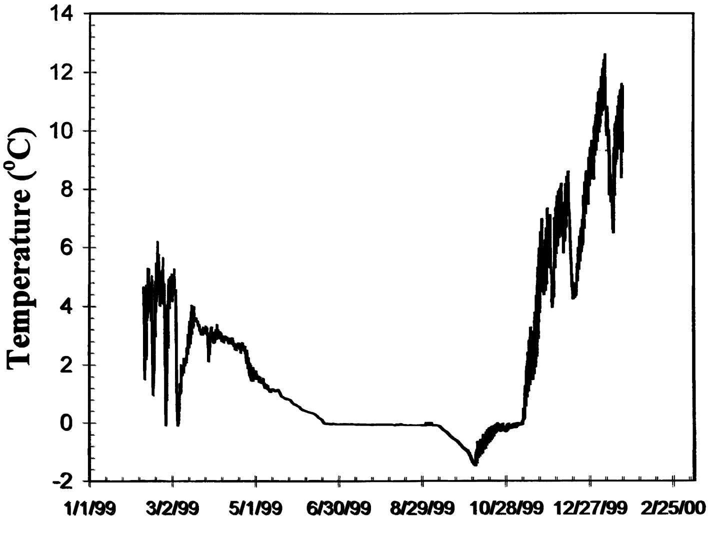

Fig. 2. Yearly seasonal change of the lake bottom temperature in lake Kuwai Ike.

deeper level. The present lake has no major water inlet or outlet, so that the current by water exchange should not be so significant. Therefore the sudden decrease of the temperature at the lake bottom recorded in autumn is thought to have been the result of wind-induced vertical mixing. After the water is mixed vertically and takes a uniform vertical temperature profile of <4℃, stratification is again produced if positive heat flux into the lake prevails under calm weather. Gradual increases after the sudden decreases in February and March indicate the occurrence of such a positive heat flux in this period. Wind-induced vertical mixing is suppressed after complete ice-cover development because the ice cover inhibits direct wind action into the lake water.

Sub-zero temperatures, which were momentarily recorded in late-February, indicate that the water temperature reached the freezing point and may indicate the start of ice formation at the lake surface. A gradual decrease of temperature toward 0℃ in mid-March to mid-June, without sudden changes as occurred in February–early March, was the result of gradual cooling of the water column without any turbulence, and hence the lake surface is thought to have been covered completely by mid-March.

As briefly mentioned in Method, the mooring system was dragged from the northwest original position (3.0 m depth) to the southwestern shore (*ca.* 2 m depth) by our visit in early spring (September), probably by the ice and wind actions. Caution should be taken in reading the data. This phenomenon likely occurred at the beginning of ice formation, since once ice completely covered the surface of the whole lake, the ice was hardly moved by wind action. In the present case, such an event likely occurred during late-February to early-March when wind-induced mixing seemed to be prevailing and the lake water started to freeze. Therefore, the data collected in the present mooring system after the dragging event might not have been taken in the center of the moss pillars habitat (2.7–3.0 m), but at the edge or outside of the habitat (2.0 m). According to previous studies in freshwater lakes on the Sôya Coast and in Schirmacher Oasis, the thickness of annual ice is *ca.* 2 m (Murayama, 1997; Murayama *et al.*, 1988; Ohyama *et al.* 1990, 1992; Richter and Bormann, 1995); then the original mooring position, 3.0 m depth in the lake, should never reach below the freezing point of water even in winter. The rather rapid increases observed during summer (November–January), are probably the result of the shallow lake bottom being directly warmed by solar radiation, and such rapid temperature changes might not occur in the deeper moss habitat. Ohyama *et al.* (1990) and Richter and Bormann (1995), reported that water-column temperature around 3.0 m depth never increased over 10℃ in other ice-covered freshwater lakes in East Antarctica; this observational evidence supports the above speculation. Further observations are needed for evaluation of the temperature changes of the moss pillar habitat.

Photon flux density (PAR) at the lake bottom (2–2.7 m depth)

Photon flux density (PAR) at the lake bottom showed very dynamic daily and seasonal changes during the mooring observation period (Figs. 3, 4). The maximum flux of PAR (*ca.* 1100 μmol m^{-2}s^{-1}) during the observational period was recorded three days after the mooring system deployment in the moss pillar habitat. The PAR decreased gradually toward mid-winter (Fig. 3) with diel fluctuations, and reached below 10 μmol m^{-2}s^{-1} around noon in June (Fig. 4). Such dim light condition con-

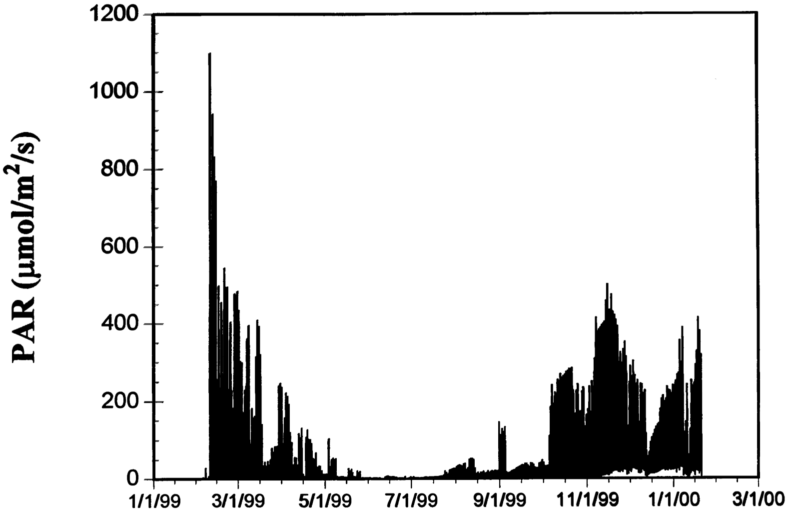

Fig. 3. Yearly seasonal change of photon flux density (photosynthetically active radiation, PAR) measured at 2–2.7 m depth of lake Kuwai Ike.

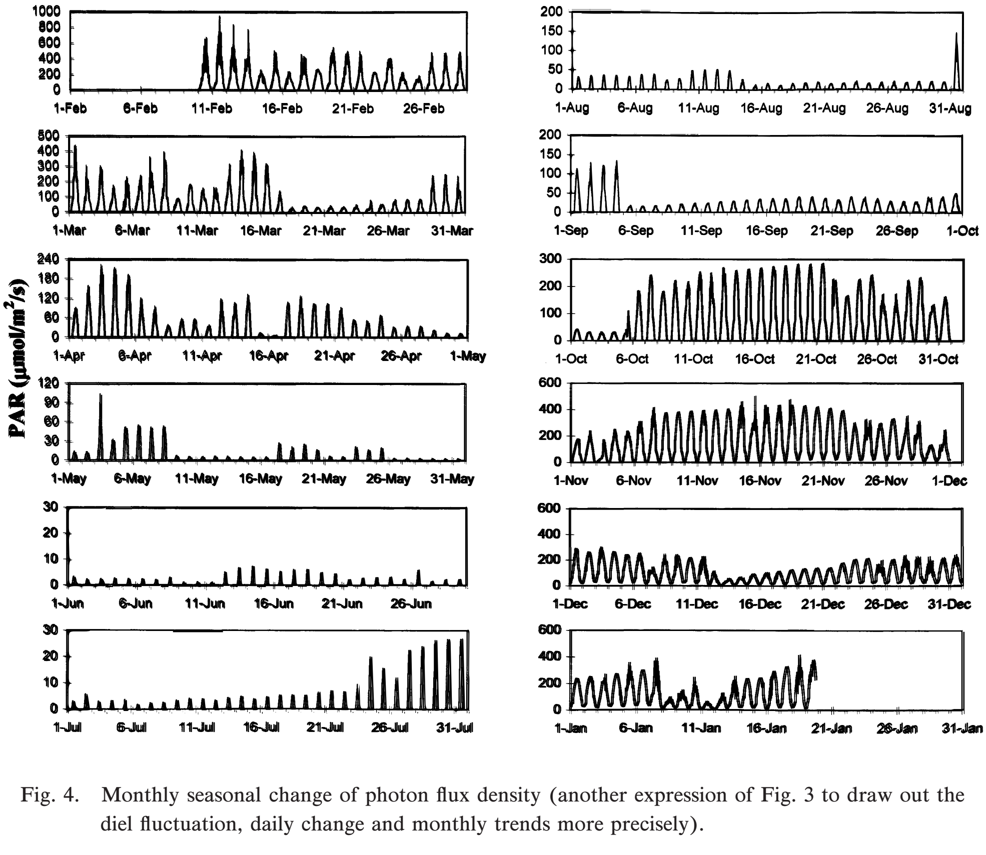

Fig. 4. Monthly seasonal change of photon flux density (another expression of Fig. 3 to draw out the diel fluctuation, daily change and monthly trends more precisely).

Table 2. Monthly data of PAR and lake bottom temperature in lake Kuwai Ike.

	1999											2000
	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.
PAR (μmol/m^2/s)												
Average	129	49.6	19.4	2.90	0.38	1.24	6.09	11.8	76.1	153	96.8	119
Maximum	940	434	221	103	7.18	26.7	145	133	284	500	301	413
Minimum	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	4.73	3.41
Daily flux (mol/m^2)	11.2	4.28	1.67	0.25	0.03	0.11	0.53	1.02	6.58	13.23	8.36	10.31
Temperature (℃)												
Average	3.73	2.89	2.57	1.06	0.18	−0.05	−0.07	−0.41	−0.57	2.67	7.00	10.2
Maximum	6.19	5.27	3.36	1.79	0.56	−0.02	−0.01	−0.01	−0.01	7.33	10.54	12.60
Minimum	−0.08	−0.08	1.47	0.56	−0.43	−0.06	−0.08	−1.02	−1.47	−0.18	4.27	6.52

tinued for *ca.* 2 months, then the PAR flux increased gradually from late-July to mid-November. The daily maximum PAR in November–December was not so large as recorded in mid-February, however, the daily-integrated flux of PAR was larger in November than in February due to the difference of day length (Fig. 4, Table 2).

Photon flux, or simply solar radiation at ground level at Syowa Station showed a minimum and a maximum in mid-June and mid-December, respectively, and showed a rather gradual seasonal change between these periods (Antarctic Meteorological Data, 2000); however, the present PAR data recorded at 2–2.7 m depth occasionally showed sudden changes in mid-March, mid-May, late-August, early-September, early-October and mid-December (Figs. 3, 4). PAR at the lake bottom should be affected by the day/night cycle, seasonal changes of sun angle and weather condition, as well as reflections, scattering and absorption of water, ice cover and snow on the ice cover. Since the albedo of annual ice on freshwater lakes is 17–48% and that of snow nearly 90 % (Richter and Bormann, 1995), according to measurements in lakes in Schirmacher Oasis, attenuation by the ice and snow seems to create the unique PAR flux variability at the present lake bottom. For example, the maximum PAR was recorded in ice-free mid-February (late summer) in 1999, instead of ice-covered November–December when the solar radiation peak was recorded on the ground, and several sudden changes in PAR at the bottom were probably caused by the appearance/disappearance of snow on the lake ice.

PAR at Syowa Station (data not shown), which was occasionally measured for another research purpose, was sometimes over 2000 μmol m^{-2}s^{-1} in perfectly clear mid-summer daytime (November–December); however, the records obtained at the lake in the same season was *ca.* 400 μmol m^{-2}s^{-1} (Fig. 4). This suggests that at least 75% or more of PAR was attenuated by water, ice and snow even in summer because the lake was covered by ice. The albedo of an open water surface is known to be 6–20% at sun elevation angles between 70° and 10° (Hutchinson, 1957); therefore, the ice-free autumn (January–February) in the present lake might be the lightest lake bottom environment recorded in the present study.

The lake bottom habitat is a rather shady environment compared to the terrestrial habitat for mosses; however, the monthly PAR data listed in Table 2 indicate that more than 1 mol $m^{-2}day^{-1}$ of daily integrated PAR flux with $>100\ \mu mol\ m^{-2}s^{-1}$ of instantaneous peak values ($>12\ \mu mol\ m^{-2}s^{-1}$ on daily average), which is sufficient for positive growth for shade-adapted aquatic plants and algae (*e.g.,* Ikushima, 1970; Van *et al.*, 1976), was incident on the lake bottom at least for 8 months.

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