



Groundwater contamination by sewage causes benthic algal outbreaks in the littoral zone of Lake Baikal (East Siberia)

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ABSTRACT

Lake Baikal, an ancient lake in Siberia, contains more endemic species than any other lake in the world with most of them residing in the benthic littoral zone. Explosive growth of benthic *Spirogyra*, a filamentous green alga, began approximately in 2011 in localized coastal areas, with the most severe examples occurring near coastal towns that lack a wastewater treatment facility or have a malfunctioning system. At other sites (small settlements, harbors), however, the cause of its excess growth is less obvious. Multiple hypotheses have been offered including lake level fluctuations, climate warming, a relaxation of grazing pressure, and coastal eutrophication. We assessed these hypotheses using data on historical lake levels, water temperature, the spatial-temporal distribution of *Spirogyra* along inhabited and non-inhabited shorelines, and measurements of fecal coliform bacteria and nutrients in ground water, interstitial water, and lake water. These data suggest that groundwater contamination is the primary cause of coastal eutrophication. Most houses and buildings in small settlements around Lake Baikal lack septic tanks but use unlined cesspools to collect human waste. This untreated human waste enters groundwater via passive filtration through permeable soils and flows to the coastal zone where it drives excess growth of *Spirogyra*. Remediation — including installation of septic systems, modernization of existing sewage treatment plants in coastal towns, and the adoption of non-phosphate containing detergents — as well as a reconsideration of the federal monitoring system regarding the coastal zone is urgently needed to protect this extraordinary lake.

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Introduction

Anthropogenic eutrophication (excess nutrient enrichment from human activity) is one of the major problems afflicting lakes, rivers, and the ocean world-wide (Millennium Ecosystem Assessment, 2005). The vulnerability of freshwater ecosystems to anthropogenic eutrophication and the recovery of many of them following nutrient reduction by diverting sewage effluent or implementing advanced wastewater treatment have been investigated for nearly 6 decades (reviewed by Smith and Schindler, 2009). Notably, however, much of this research has focused on eutrophication of the water column. Yet, the benthic zone of coastal areas, particularly of large, oligotrophic lakes, may be the 'first responder' to nutrients entering from land-based activities (Rosenberger et al., 2008; Schneider et al., 2014). In such lakes, inordinate amounts of nutrients would be necessary to eutrophy the large

water column, but relatively smaller fluxes of nutrients to the substrate of the littoral zone could promote excess growth of benthic plants (Barton et al., 2013; Lambert et al., 2008).

Lake Baikal, the world's largest lake volumetrically, contains more endemic species than any other lake with most of these unique species residing in the benthic littoral zone (Timoshkin, 2011). Explosive growth of benthic *Spirogyra*, a filamentous green alga, began approximately in 2011 in localized coastal areas of this lake (Timoshkin et al., 2016) with the most severe examples occurring near coastal towns that either lack a wastewater treatment facility or have a malfunctioning system allowing excess nutrients to enter nearshore areas (Khodzher et al., 2017; Kravtsova et al., 2012, 2014; Timoshkin et al., 2016; Tomberg et al., 2017). At these sites, riverborne nutrients entering the coastal zone cause concentrations in nearshore waters to exceed background levels by as much as 20–60 fold (Khodzher et al., 2017; Tomberg et al., 2017).

At other coastal sites (small settlements, harbors) the cause of excess growth of *Spirogyra* is less obvious. At such sites, groundwater

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contaminated with nutrients may enter the substrate of the coastal zone and promote growth of *Spirogyra*. Indeed, results of hydrological research conducted in temperate zone lakes show that groundwater inputs often occur close to lake shorelines and decrease with distance offshore, but exceptions exist (Rosenberry et al., 2015). Groundwater can be a significant source of nutrients in oligotrophic lakes (Lewandowski et al., 2015), contributing to eutrophication (Meinikmann et al., 2015). Most investigations of the biological response to seepage and groundwater-born nutrients (particularly phosphorus and nitrogen) in lakes have focused on macrophytes, and these studies show enhanced biomass (Frandsen et al., 2012; Lodge et al., 1989), increased growth (Frandsen et al., 2012), and altered chemistry of leaf tissue (Sebestyen and Schneider, 2004). In contrast, the response of near-shore benthic algae and epiphytes to groundwater-born nutrients has seldom been investigated, but existing studies also show increased algal biomass (Hagerthey and Kerfoot, 1998; Périllon et al., 2018) and altered species composition (Hagerthey and Kerfoot, 2005).

In this paper, we use data on the spatial-temporal distribution of *Spirogyra* along inhabited and non-inhabited shorelines in Lake Baikal and measurements of fecal coliform bacteria and nutrients in groundwater, interstitial water, and lake water to answer the question: Does groundwater contaminated with human sewage and associated nutrients trigger excess growth of benthic *Spirogyra* in coastal areas? In addition, we

argue that warming waters associated with climate change, lake level fluctuations, and a relaxation of grazing pressure are, alone or together, unlikely to be the major drivers of the observed *Spirogyra* outbreaks. We conclude with management recommendations aimed at curbing excess growth of *Spirogyra* in nearshore waters.

Methods

Historically, the western coast of Lake Baikal has been investigated more thoroughly than the eastern coast, and therefore the former will be used predominantly as the model site for understanding the distribution of *Spirogyra*. Sampling localities are shown in Fig. 1.

Spirogyra sampling

Benthic algal sampling occurred, generally from June–October in 2013–2016, mostly along the western coast of Lake Baikal and around two islands, Ol'khon and Bol'shoi Ushkani Island (Fig. 1). Two dominant morphotypes of *Spirogyra* were identified in areas of its mass development (Figs. S1–S4), and their wet biomass (g m^{-2}) were quantified along transects (10–15 m long) perpendicular to the coastline at water depths of 0.5–1.5 m using quadrat sampling and the stone-unit method (Nakashizuka and Stork, 2002; Timoshkin et al., 2015).

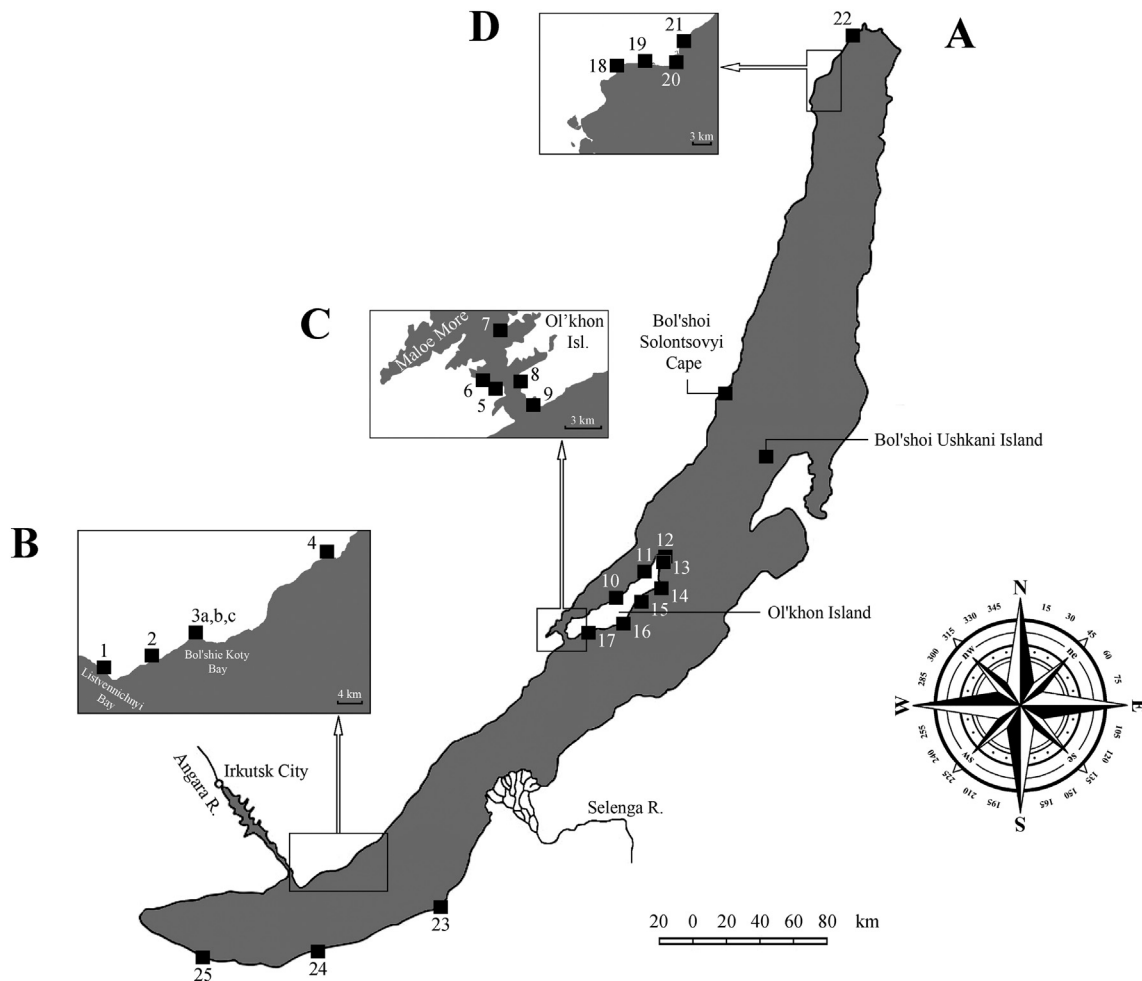


Fig. 1. Map of Lake Baikal with sampling localities: 1 – Listvyanka Settlement, 2 – Emelyanikha Bay, 3 – Bol'shie Koty Settlement and Bay (a, Chyornaya Stream; b, Zhilishche Stream; c, Bol'shaya Kotinka Rivulet), 4 – Bol'shoe Goloustnoe Settlement, 5 – Tutaiski Bay, 6 – Sakhyurte Settlement, 7 – Kharin-Irgi Cape, 8 – Perevoznaya Bay, 9 – Ushun Bay, 10 – Khuzhir Settlement and Shamanka Bay, 11 – Zantyk Cape, 12 – Khoboi Cape, 13 – Shunte Levyi Cape, 14 – Izhimei Cape, 15 – Khara-Khushun Cape, 16 – Ukhan Cape, 17 – Khalzyn Cape, 18 – Senogda Bay, 19 – Zarechnoe Settlement, 20 – Tyva River mouth, 21 – Severobaikal'sk City, 22 – Nizhneangarsk City, 23 – Babushkin City, 24 – Tankhoi Settlement, 25 – Baikalsk City. The Limnological Institute's Field Station (LFS) is located within the Bol'shie Koty Settlement and Bay between 3b and 3c in inset map B.

Microbiological analyses

In 2015, abundances of Enterococci and *Escherichia coli* were quantified in lake water and in interstitial water of the beach in front of the Limnological Institute's field station (LFS) in the village of Bol'shie Koty (Fig. 1). In 2016, these same two groups of bacteria were quantified in groundwater only. Sampling in 2015 occurred once in June, August, and September. On each sampling date, triplicate samples (150-mL volume) of lake water were collected using a Janet syringe at the lake shoreline and again near the lake bottom but about 10 m lakeward of the shoreline. At the latter sampling site, the Janet syringe was connected to a 1.5 m long stick to facilitate bottom water sampling. In addition, three interstitial water samples (150-mL volume) were collected from the splash zone of the beach (1 m above the shoreline) on the same sampling dates. Specifically, one interstitial water sample was collected by syringe from water that accumulated in each of three pits (ca. 0.3-m deep, about 1 m from each other) dug into the beach's splash zone. In August 2016, triplicate groundwater samples were collected by syringe from a single lysimeter (described below) because groundwater collected in only one of the four lysimeters. In both years, all syringe samples were each poured into a separate sterile glass vial (250 mL) and placed in a cooler bag with refrigerants until laboratory analysis.

In the laboratory, total coliform bacteria (TCB) were quantified in each sample by membrane filtration (cellulose nitrate membrane filter, 0.45 µm) and cultured at 37 °C for 24 h (Federal Centre of Sanitary Inspection Ministry of Health of Russia, 2004; Federal Standard of Russian Federation, 2015). The bacteria were then subjected to the TCB strain test that assesses their ability to ferment lactose to gas and acid end products. The isolated coliforms were further tested biochemically to confirm their belonging to thermotolerant bacteria (TtC) (Federal Centre of Sanitary Inspection Ministry of Health of Russia, 2004). Generally, *E. coli* comprises the majority of TtC, and *E. coli* is a well-accepted indicator of fecal contamination. Thermotolerant *E. coli* was also identified by filtration and sample concentration using the selective agar HiCrome (Himedia production, No. M1571). Fecal enterococci were determined by membrane filtration and sample concentration using Slanetz and Bartley Medium (Himedia production, No. M612) as well as Bile Esculine Azide Agar (Himedia production, No. M493).

Nutrient analyses

Nutrient (nitrate, ortho-phosphate, and silica) concentrations were quantified in water samples collected in 2015 and 2016 in front of LFS in Bol'shie Koty, but the sampling design differed between years. In 2015, sampling occurred once in August and once in October at the lake shoreline within a *Spirogyra* patch and at a control site 10–15 m away where *Spirogyra* was absent. On both dates, a single sample of lake surface water (0.6 L) was collected each from the *Spirogyra* patch and the control site using a Janet syringe. Also, on both dates and at each site, 0.6 L of interstitial pore water was extracted at a depth 3–5 cm below the surface of the lake substrate using a syringe.

In August 2016, samples of groundwater, lake water, and interstitial water were collected along a transect extending from lysimeter No. 3 (described below) to the shoreline and shallow water zone (Fig. 2B). Specifically, single samples (0.6 L) of the following were collected: groundwater from lysimeter No. 3; water from each of two splash zone pits (i.e., holes No. 1 and 2, located 10 and 1 m above the shoreline, respectively); lake water from the shoreline; interstitial pore water, extracted at a depth 3–5 cm below the surface of the lake substrate, at a location ca. 10–15 m lakeward of the shoreline where water depth was 1 m.

Although replicate sampling for nutrients was not conducted in either 2015 or 2016, extensive sampling before and after the work reported here shows that coefficients of variation for lake water nutrient

analyses are typically <10% with high values ranging to 20% (Khodzher et al., 2017; Tomberg et al., 2012). Interstitial pore water, however, is more variable both in its mean value and coefficient of variation likely due to its groundwater origin.

Following collection, all water samples for nutrient analysis were filtered through polycarbonate membrane filters (0.45 µm) and analyzed immediately at the field station. NO₃[−] in the filtrates was quantified using high-performance liquid chromatography in micro-columns (Baram et al., 1999). Concentrations of PO₄^{3−} and Si were determined using colorimetric methods with a spectrometer (KFK-3, Russia). Colorimetric methods included the Deniges-Atkins method with stannic chloride as a reducer for PO₄^{3−} (ISO 6878:2004) and the silicomolybdic acid complex method for silica (Boeva, 2009). The precision levels of these methods were 0.01 mg L^{−1} for N(NO₃[−]), 1 µg L^{−1} for P(PO₄^{3−}), and 0.1 mg L^{−1} for Si.

Groundwater sampling and elemental analyses of groundwater, lake water, and soil

Sampling occurred May–August 2016 at the lake front of the LFS located in Bol'shie Koty (Fig. 1). At this site, the shore scarp (steep slope) is 3–3.5 m in height and composed of multiple horizontal layers typical of alluvial soils (Fig. 2B–D). The upper turf layer (0 – soil horizons; 10–15 cm) gradually transitions into a sandy-clay horizon with acute-angled, rock fragments. Its lower part contains a thin (3–5 cm) buried humus horizon that transitions into clay-pebble and sand-pebble sediments interlayered by a thin ochreous stratum. The beach, located below the shore scarp, is 8–10 m wide and its substrate is composed of boulders, pebbles, and sand (Figs. 2 and 3).

The shore scarp allowed ground water sampling 3.2–5.2 m below the soil surface. Lysimeters No. 1–3 were placed in 0.3–0.4 m deep holes at the base of the shore scarp (Fig. 2C, D). Lysimeter No. 4 (ca. 60 m S of lysimeter No. 3 and out of view in Fig. 2C, D) was located at the base of a 5.2-m soil profile. All lysimeters were a modification of an E.I. Shilova lysimeter (Kaurichev et al., 1996). Replicate ($n = 3$) groundwater samples from lysimeter No. 3 only were removed in both June and August using a plastic syringe. These samples were filtered (0.2 µm membrane filters) into polypropylene tubes and preserved with ultra-pure HNO₃ until elemental analysis.

Four samples of both lake water and water from the splash zone were collected on a single date in May, June, July, and August. These were filtered and preserved as described for groundwater samples. Lake water samples were collected 1 m lakeward of the shoreline, and a single splash zone sample was collected from each of four splash zone pits (e.g., hole No. 2 in Fig. 2B and three other similar pits) located 1 m landward of the shoreline.

For each soil or substrate sample, a granulometric fraction (<0.25 mm) was obtained by sieving. Subsamples were dried at 105 °C to constant weight and subsequently used for ammonium acetate extractions (CH₃COONH₄, pH 6.5) of mobile compounds of macro- and microelements (Suturin et al., 2013). The extraction agent was added to polypropylene vessels with the soil samples in a 1:10 ratio and shaken for 3 h. Then 14 mL of the collected suspension was filtered (cellulose acetate membrane filters 0.2 µm) into polypropylene test tubes.

Elemental composition of groundwater, lake water, and soil and substrate extracts was determined using ICP-MS. The analysis was performed using an Agilent 7500ce mass spectrometer (Agilent Technologies) with a quadrupole mass-analyzer at the Joint-Use Center 'Ultra-microanalysis' (Limnological Institute SB RAS). The instrument was calibrated by the standard solution "tune" (MECS-2A, Agilent) containing Li, Be, Al, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, As, Se, Rb, Sr, Ag, Cd, Cs, Ba, Tl, Pb, Th, and U. The accuracy of determinations was evaluated using a standard sample of Baikal deep water (Suturin et al., 2003) which was measured in each series along with the samples to be analyzed. The relative standard deviation (RSD) was 5% for Na, Mg, Al, Si, P, S, K, Ca, Mn, Fe, Cu, Zn, Sr, I, Ba, and U, and 5–10% for Co, Ni, Pb.

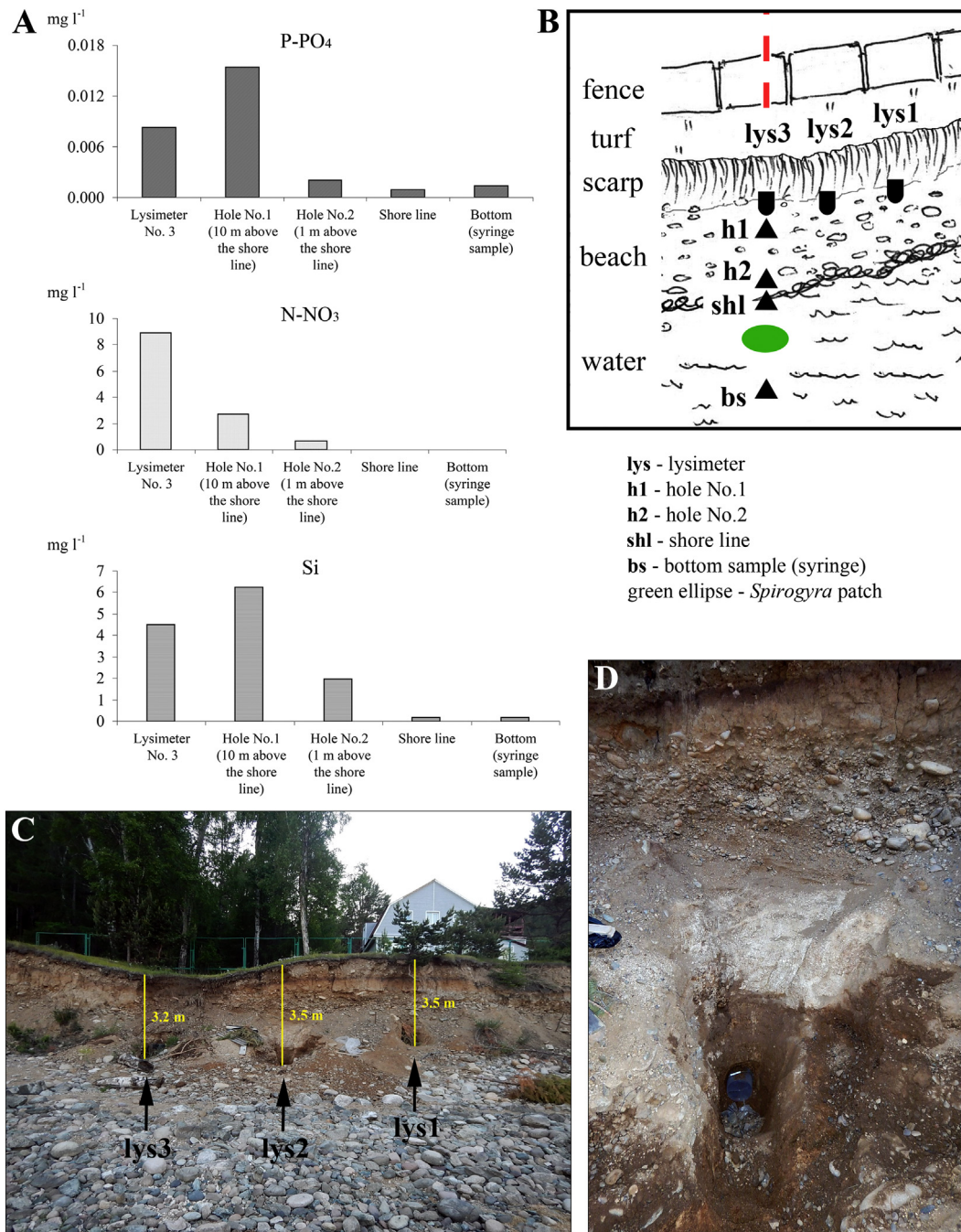


Fig. 2. Nutrient concentrations (A), a diagram (B) and photos (C, D) illustrating location of lysimeters and additional sampling locations for analyses of groundwater and nearshore lake water in front of LFS, Bol'shie Koty Bay, summer 2016. A – concentrations of $P(PO_4^{3-})$, $N(NO_3^-)$ and Si ($mg\ l^{-1}$) in single water samples collected along the transect from lysimeter No. 3 to the shoreline and shallow water zone, August 2016. X-axis, from left to right: lysimeter; pore water from holes No. 1 and 2 (“h1” and “h2” in Fig. 2 B); lake water from the shoreline (“shl” in Fig. 2 B); interstitial pore water collected from the lake bottom 10–15 m lakeward of the shoreline where water depth was 1 m (“bs” in Fig. 2 B; syringe was injected 3–5 cm below the surface of the lake substrate). C – location of three lysimeters, each in a separate hole (immediately above black arrows) and placed at the base of a soil profile (vertical yellow line), along the shore scarp in front of LFS. The fourth soil profile and lysimeter are out of view and to the left of lysimeter No. 3. D – a close-up view of an installed lysimeter. Additional explanation of sampling can be found in the Methods.

Water-level and temperature measurements

Extreme values (highest and lowest levels) of Lake Baikal's water level in a given year from 1960 to 2017, as well as average monthly air and surface water temperature ($^{\circ}C$) for the years 1940–2016, were obtained from ROSGIDROMET (Hydrometeorological Survey of Russian Federation, Irkutsk Branch). Temperature averages are for data collected at six hydrometeorological stations (HMS): the city of Irkutsk (60 km northwest of southern Lake Baikal) and five lakeshore stations including

the head of the Angara River, and the shoreline towns of Babushkin, Tankhoi, Bol'shoe Goloustnoe, and Listvyanka (Fig. 1). Values for May–September surface water temperature (lakeshore stations only) and their 5-year rolling averages were calculated from average monthly values for each station. As part of the study of *Spirogyra* development at the Bol'shie Koty field station, water temperature was also recorded every 30 min from July–October in 2015 and 2016 using a Tid-Bit Stow Away Logger placed 15 m north of a *Spirogyra* patch (see below) but at a water depth (0.2–0.3 m) equivalent to that in the patch.

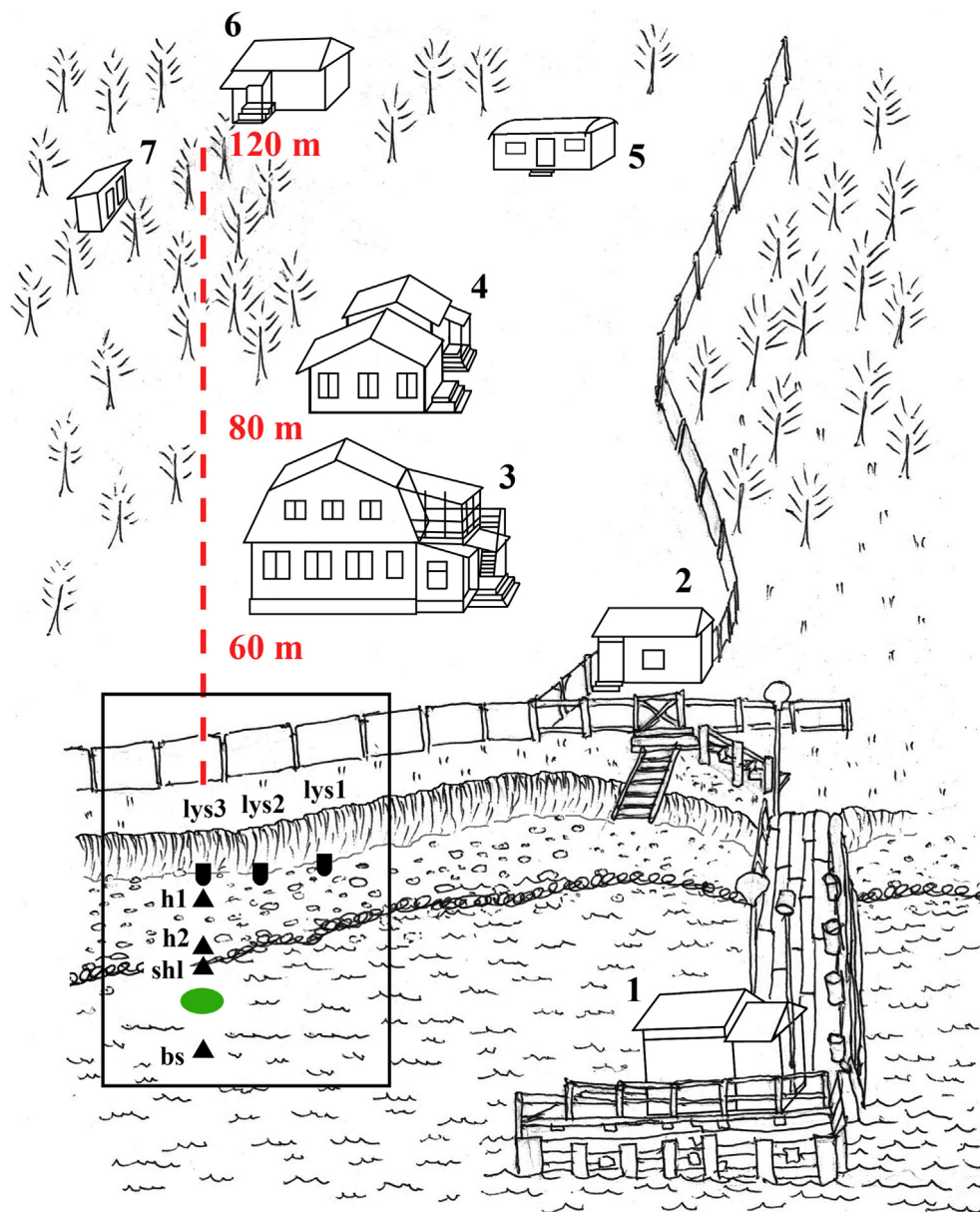


Fig. 3. Diagram of the Limnological Institute's field station (LFS) located 60–120 m from the beach: 1 – hydrometeorological laboratory, 2–3, 5 – living houses, 4 – kitchen, 6 – sauna and laundry washing apartment, 7 – toilet. Presumed route of groundwater flow (red dashed line) and the location of the 'LFS *Spirogyra* patch' (green oval). See Fig. 2 caption for definitions of abbreviations.

Water temperature values were averaged monthly. Also as part of this study, the director of LFS provided the number of person-days per month (May–October) in 2015 and 2016. Person-days were calculated by summing the number of days each person was present at LFS in a given month.

Results and discussion

Spatial-temporal distribution of Spirogyra along the west coast of Lake Baikal

The current spatial distribution patterns of *Spirogyra* in the coastal zone of Lake Baikal provide convincing insight for the cause of the recent *Spirogyra* outbreaks. The most abundant blooms of *Spirogyra* ('morphotype 1') occurred near coastal towns and settlements, such as Bol'shie Koty, Bol'shoe Goloustnoe, etc. (Fig. 1). The morphology, distribution and ecology of the dominant *Spirogyra* morphotypes 1 and 2

are described in the Electronic Supplementary Material (ESM Figs. S1–S4).

We have registered two types of *Spirogyra* patches in the coastal zone of Baikal depending on their size and development depths. The first type, large patches (50–1000 m and more in length) were typical for the coastal areas surrounding the settlements. As a rule, they occupied the depths 0.5–2 m. The second type, much smaller patches (0.2–2.0 m in length), were found near single houses and tourist camps near the shoreline, at the depths 0.2–0.3 m. Type 2 patches were detected only opposite the Limnological Institute field station (hereafter – "LFS patch") or in Emelyanikha Bay (see below).

Interestingly, the seasonal development and dynamics of *Spirogyra* ('morphotype 1') near settlements seem to be related to the seasonal influx of residents and visitors to these areas. We use the settlement of Bol'shie Koty as a representative example. This village has only 30 permanent residents. However, in summer (especially in July and August) the number of people increases significantly to include several hundred

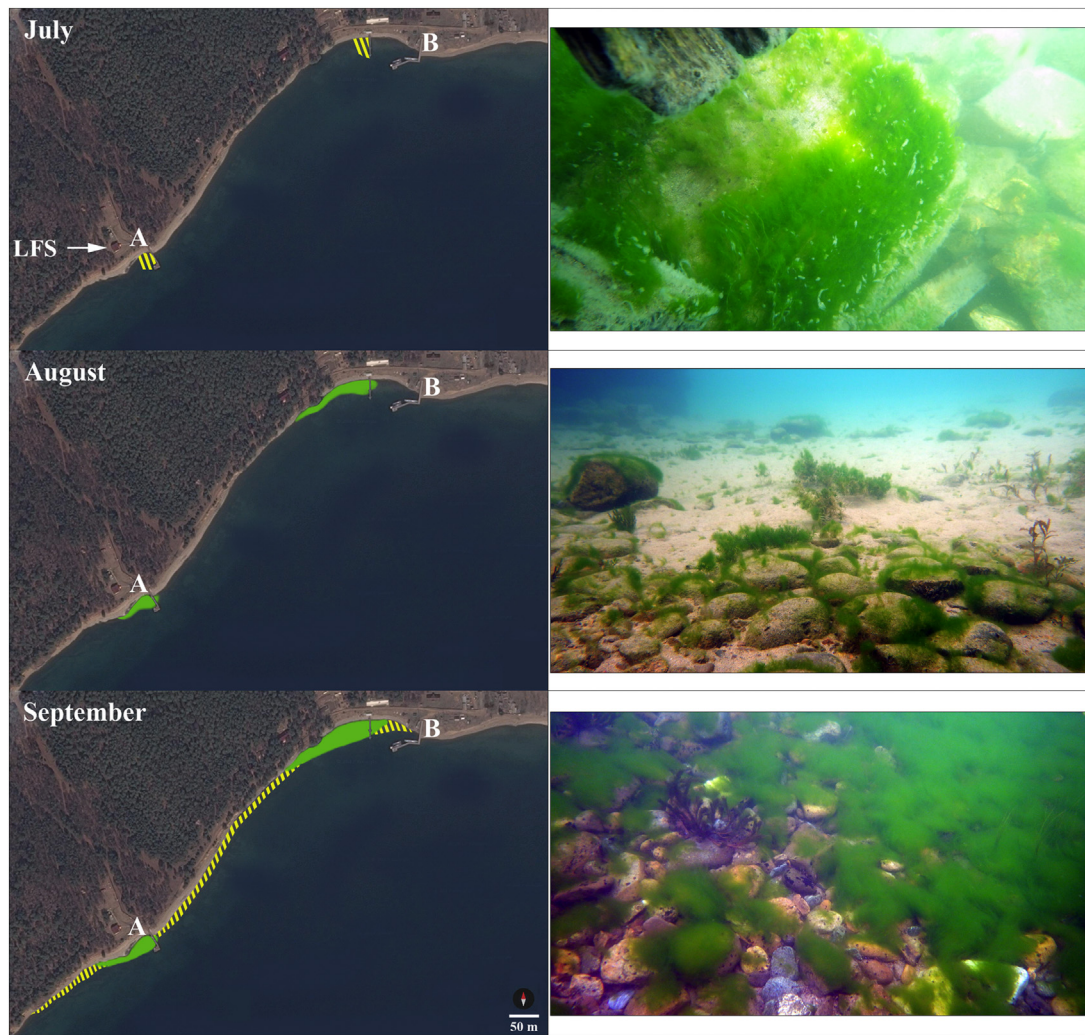


Fig. 4. Spatial and seasonal distribution of *Spirogyra* 'morphotype 1' in the coastal zone of Bol'shie Koty Bay, from July–August 2014–2016 (aerial images on left), and underwater photos of the algal blooms at the wooden dock A (upper right) and at the lake substrate, 1.5-m depth, near dock B (two lower right images). Green areas in the aerial images denote 80–100% coverage of the substrate by *Spirogyra* (wet biomass 300–500 g m⁻²), and yellow-black slashing indicates areas with wet biomass ≥100–200 g m⁻² (ca. 40–60% coverage). LFS — field station of the Limnological Institute SB RAS. Additional explanation can be found in the text.

students from Irkutsk State University who are completing their summer field studies, numerous students from regional and international summer schools, and thousands of tourists who visit this spectacular place. Unfortunately neither the East-Siberian Steamship line, which operates the regular jet foil connection between Irkutsk and Bol'shie Koty, nor the hosts of the numerous private hotels agreed to provide visitor statistics. Therefore their exact number cannot be estimated.

The seasonal dynamics and spatial distribution of mostly 'morphotype 1' in the Bay near the settlement are shown in Fig. 4, and ESM Figs. S5–S6. In June, macrophytes close to shore within zones 1 and 2 (for explanation, see Timoshkin et al., 2016) generally exhibit the typical Baikalian pattern (ESM Fig. S5A, B: mostly *Didymosphenia*, *Ulothrix*, Chrysophyceae spp.) (Izhboldina, 2007) and *Spirogyra* is almost absent. In July, a small amount of *Spirogyra* 'morphotype 1', limited to the underwater wooden parts of two boat docks, has appeared (Fig. 4, upper right photo). Both docks are located opposite two different field stations: LFS (Fig. 4, dock A) and Irkutsk State University's field station (Fig. 4, dock B). Both stations are used intensively from June through September but do not function (or function very rarely, five to seven persons per month) during the winter season. By August, the area of the alga distribution had increased, consisting of two well-defined patches, each 125–150 m in length along the coast line (bright green patches in Fig. 4, middle photos), in which the wet biomass of *Spirogyra*

was ≥100–200 g m⁻² and covered 80–100% of the benthic area within each patch at depths of 1–1.5 m (Fig. 4C, D). In September–October, the patches became connected, forming a solid area of *Spirogyra* extending 600–700 m along the coastline (Fig. 4, lower photos). *Spirogyra*'s wet biomass in the centers of the former patches increased to 500–600 g m⁻² (green areas in Fig. 4C, D), which was 1.5–2 times greater than the algal biomass between the patches and at their periphery (black-and-yellow shading, Fig. 4, left lower photo). From 2012 to 2016, no additional *Spirogyra* patches, other than those described, were observed in the vicinity of Bol'shie Koty.

In summary, intensive proliferation of *Spirogyra* 'morphotype 1' began in mid-summer with maximum development in autumn at both settlements during the ecocrisis period (2011–2016). During the same time period, mass *Spirogyra* blooms never occurred in areas to the north or south of these settlements. Importantly, neither settlement has a centralized wastewater treatment system. Instead, sewage effluent from private houses and numerous hotels, located 20–300 m away from the shoreline, is discharged into unlined cesspools, from where it presumably travels by passive filtration through the ground to enter the coastal zone of the lake where it appears to stimulate intensive blooms of *Spirogyra* 'morphotype 1'. In both cases, the spatial distribution of *Spirogyra* seems to reflect the coastal areas affected by wastewater. These blooms appear to be correlated with the person-days on shore

(see below), which usually reach their maximum in August but sharply decrease from October–November. A similar development of *Spirogyra* ‘morphotype 1’ occurs around most settlements with seasonal recreation activity; however, the alga remains relatively abundant year-round in several areas (Listvyanka Settlement, Baikal’sk City, near Tyva River mouth, Fig. 1) where nutrients enter the lake throughout the year.

Spatial distribution of *Spirogyra* around islands in Lake Baikal

We also tested the hypothesis that the spatial distribution of *Spirogyra* should be continuous and homogeneous along the coasts of two islands if water level and water temperature are the main drivers of *Spirogyra* blooms rather than nutrients from human activities. The two islands, Ol’khon and Bol’shoi Ushkani (Fig. 1), located only 74 km from each other, should experience similar water level fluctuations and water temperatures because of their relatively close proximity. Also, both islands are located a short distance (2 and 7 km, respectively) from the lake’s coastline, and these distances should not limit the dispersal of *Spirogyra* because it produces free-swimming filaments and zygospores. Recreational activity, however, differs greatly between these two islands. Ol’khon Island, the largest island (730 km²), receives ≥800,000 tourists annually, mainly in summer (Tokareva, 2016); however, since 2014 many hotels are occupied year-round (Petrova N.P., Personal Communication, Our Baikal Society, 2017). In addition, this island has 1651 residents distributed among nine small settlements with Khuzhir (Figs. 1, 5) being the largest with 1350 permanent residents (Ol’khon administration of Irkutsk District, 2016). In contrast, the smaller Bol’shoi Ushkani Island (9.4 km²) is part of a federal nature reserve with strict limits on the number of visitors. Only one family, that of the forest ranger who guards the archipelago, lives there permanently.

The sparsely populated Bol’shoi Ushkani Island remains free of *Spirogyra* blooms. In contrast, we have observed *Spirogyra* patchily

distributed along the coast of Ol’khon Island, and its wet biomass, seasonal development, and spatial distribution were similar to that described for Bol’shie Koty and Bol’shoe Goloustnoe (see above). The most abundant annual blooms in 3 years of observation on Ol’khon Island were detected in the small bay Shamanka that borders Khuzhir Settlement (100–210 g m⁻², 80–100% of projected area at depths of 0.5–1.5 m) and in Perevoznaya Bay where a ferry service connects the island to the mainland while the least abundant blooms occurred near Kharin-Irgi Cape (0–20% of projected area at the same depths), a popular area for tourist ships and vessels (Figs. 1, 5).

Another survey was performed in September 2016 when the coastal perimeter of Ol’khon Island was subdivided into ten stations (Fig. 5). Results from Khuzhir and Kharin-Irgi stations revealed an amount of algae (100–135 g m⁻²; Fig. 5, red circles) similar to that observed at Bol’shie Koty and Bol’shoe Goloustnoe while an insignificant amount of algae occurred at several remote stations (Zantyk on the western and Khalzyn on the eastern coasts; Fig. 5, green circles). Importantly, the northwestern and nearly the entire eastern coast of Ol’khon Island have been free of *Spirogyra* (Fig. 5, blue circles), and these areas are largely inaccessible to tourists and permanent residents do not live here. The seasonal development of *Spirogyra* observed in Shamanka Bay on Ol’khon Island from 2014 to 2016 was similar to that reported for Bol’shie Koty and Bol’shoe Goloustnoe in the south basin. Again we emphasize that in all above-mentioned areas, *Spirogyra* ‘morphotype 1’ dominated. The alga was largely absent in early summer but reached its maximum abundance in September. In summary, our observations of the *Spirogyra* distribution pattern along the coastlines of two islands do not support the water level and climate warming hypotheses as drivers of *Spirogyra* abundance as these factors would be shared among these sites. Instead, *Spirogyra* occurs mainly near settlements, harbors and centers of recreational activity, suggesting that anthropogenic eutrophication is primarily responsible for its proliferation.



Fig. 5. *Spirogyra* distribution and abundance at depths of 1 m (with the exception of *Sakhyurte, where water depth was 0.5 m) along the coast of Ol’khon Island, 2014–2016. Numbers describe abundance of benthic *Spirogyra* (g m⁻² wet biomass). Red circles represent sampling stations where *Spirogyra* was abundant (>100 g m⁻² wet biomass); blue circles are stations where *Spirogyra* has never been observed; and green circles indicate where *Spirogyra* abundance was insignificant (a few separate filaments). Yellow arrows indicate main directions of local water currents (according to Kozhov, 1972), which can help explain the *Spirogyra* distribution along the coast of Ol’khon Island.

In situ observations at Bol'shie Koty LFS and Emelyanikha Bay (west coast of South Baikal)

In 2015–2016, we observed the development of several small-sized *Spirogyra* patches near the lakeshore which supported our previous hypothesis that groundwater, contaminated by untreated sewage, flows into the shallow coastal zone of the lake where it fuels the growth of *Spirogyra*. Investigations of the nearshore phytobenthic communities, performed in 2015–2016 at Bol'shie Koty Bay, provided the strongest data for evaluating this hypothesis. A light green algal patch ('LFS patch'), round in shape and ca. 2 m in diameter, was discovered in late July 2015 on the lake substrate, approximately 5 m from the shoreline and at a depth of 0.3 m (Figs. 6–7, ESM Fig. S7). Microscopic analysis verified that the filamentous algae comprising this patch were predominantly *Spirogyra* 'morphotype 1' with small contributions of several other morphotypes. The samples of macrophytobenthos collected ca. 0.6–1.0 m to the north, east, south, and west of the patch contained hardly any *Spirogyra* filaments (Fig. 6C). Interestingly, a similar *Spirogyra* patch formed in nearly the same location in July–August 2016.

Because this single, isolated patch developed immediately in front of LFS (Figs. 1, 6, ESM Fig. S9), we hypothesized that wastewater from the toilets, sauna, kitchen, and other households on LFS property had traveled via groundwater to the coastal zone (Fig. 3). All these buildings are serviced by unlined cesspools that are not isolated from the surrounding soil. Concentrations of fecal bacteria provided important evidence supporting this hypothesis (Fig. 8). Extremely high fecal bacteria concentrations (Enterococcae — >12,000 CFU 100 mL⁻¹), exceeding those at non-polluted coastal sites by ca. 1000-fold, occurred in the interstitial waters of the pit in front of LFS in August 2015. For comparison, Enterococcae concentrations detected in the splash pit water samples of the remote and relatively virgin Bol'shoi Solontsovyi Cape in September 26, 2015 were 0 CFU 100 mL⁻¹ and in June 19, 2016, 10 CFU 100 mL⁻¹. By September, concentrations in front of LFS were six times lower than in August, but these concentrations (Enterococcae ca. 2000 CFU 100 mL⁻¹) were still nearly 3 orders of

magnitude higher than those observed for non-polluted coastal areas of the lake (e.g., 0–5 CFU 100 mL⁻¹ from splash zone pits at Bol'shoi Solontsovyi Cape during summer–autumn in 2015–2016; Malnik V.V., Personal Communication, Limnological Institute SB RAS, 2017; Timoshkin et al., 2012b).

Results of hydrochemical analyses of the surface and near bottom waters within the *Spirogyra* patch clearly showed that the local inflow of groundwater was enriched with nutrients (Fig. 6; Table 1). Importantly, groundwater and surface water of a small temporal stream within this particular valley are enriched with Si (Tomberg et al., 2012). Evidently, *Spirogyra* does not respond to Si-rich waters because we have never observed any *Spirogyra* patches in the coastal zone of Lake Baikal opposite the stream's mouth from 2010–2016, and small *Spirogyra* spots ('morphotype 2') were rarely observed in the lower part of the stream. Because the field station is supplied by groundwater from two drilled wells, each 20 m deep, these waters are also enriched with Si. Consequently, Si-enriched waste water from the field station can potentially flow via groundwater into the splash and shallow water zones of the lake. Indeed, Si concentrations in the interstitial water samples from the holes in the splash zone reached levels as high as 6 mg L⁻¹. Therefore, the high concentration of Si in the interstitial pore waters, taken from the center of the LFS *Spirogyra* patch (2.05 mg L⁻¹, Table 1) as compared to the low Si concentration, measured in the interstitial pore waters at the control site (0.14 mg L⁻¹) and at the shoreline (0.15 mg L⁻¹) strongly suggested that waste water discharge from the field station had moved into the bottom area, where the LFS patch developed. In August, 2015, Si concentrations in the syringe interstitial pore water sample, taken from the center of the LFS patch, were 15 times higher than that from the interstitial pore water of the control area lacking *Spirogyra* (several m away). Even shoreline surface water samples collected in August above the patch showed concentrations of Si that were 1.5 times higher than that in the water of the control site. Importantly, phosphate and nitrate concentrations in August in the pore waters of the *Spirogyra* patch were 1.5 and 5 times higher, respectively than

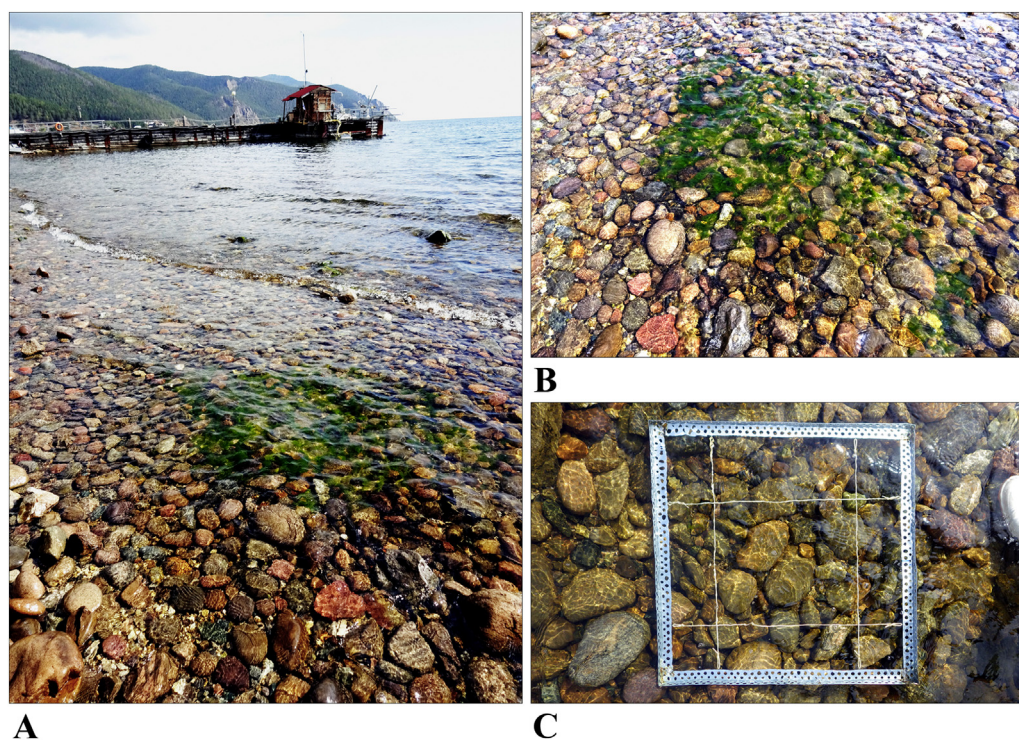


Fig. 6. *Spirogyra* 'morphotype 1' patch (ca. 2 m in diameter), in front of LFS, Bol'shie Koty Bay ('LFS patch'), aerial view, September 20, 2015. A, B — general view of the patch (wet biomass of *Spirogyra* >500 g m⁻²). C — typical view of the lake substrate outside the patch. *Spirogyra* was absent for at least 1 m in any direction from the outer boundary of the patch. Frame size: 50 × 50 cm.

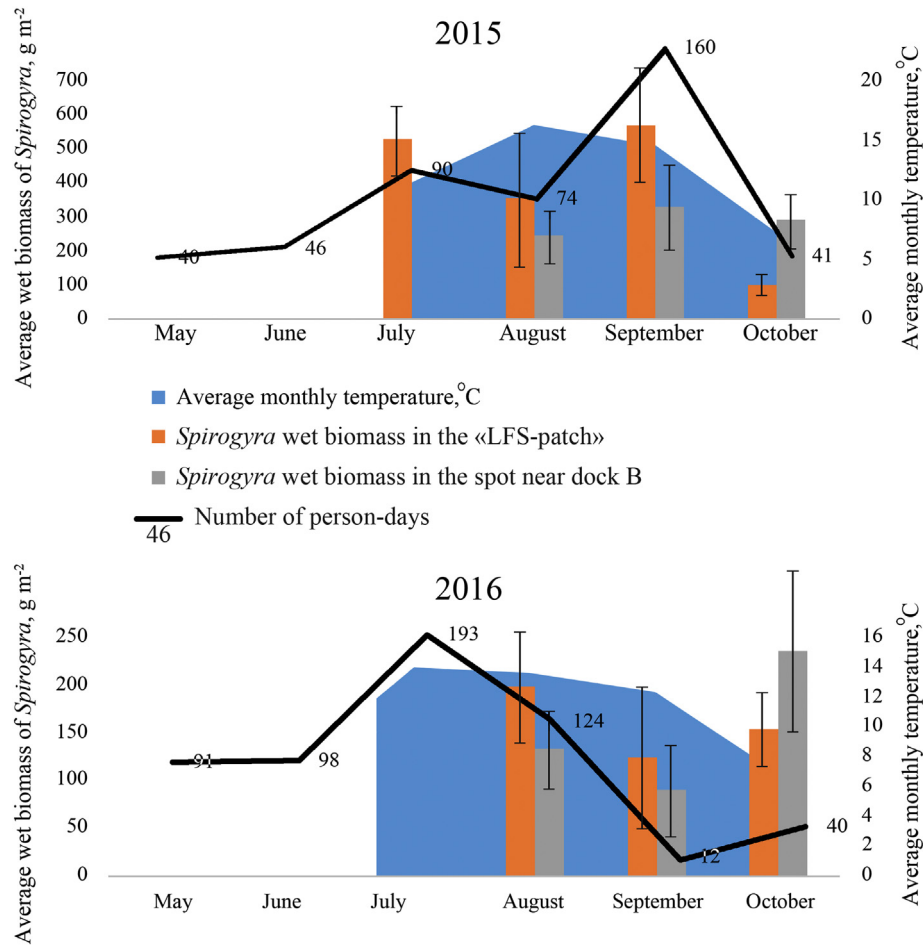


Fig. 7. Average wet biomass ($n = 3$, \pm SD) of *Spirogyra* 'morphotype 1' from May–October in 2015–2016 in the 'LFS *Spirogyra* patch' (Fig. 6), and *Spirogyra* wet biomass near dock B in Fig. 4. Average monthly water temperatures were calculated from readings recorded every 30 min at a site 15 m north of the LFS *Spirogyra* patch but at a water depth (0.2–0.3 m) equivalent to that in the patch. Number of person-days at LFS was calculated by summing the number of days each person was present at the station in a given month. A drop in lake level in October 2015 exposed the 'LFS *Spirogyra* patch' to air (Fig. S9) causing a significant decrease in biomass relative September 2015.

pore water values from the control area (Table 1). Even in October 2015, when the *Spirogyra* patch was above the shore line in the splash zone due to lake levels being naturally lower than those in August (Fig. S9), silica and nitrate concentrations were 1.6 and 2 times higher, respectively, in the pore waters of the patch than in pore waters of the control area (Table 1).

Interestingly, the spatial-temporal distribution of *Spirogyra* and its wet biomass values were similar in 'LFS patch', near dock B (Figs. 4, 7 and ESM Fig. S6C–F), 560 m north of LFS *Spirogyra* patch and opposite the settlement of Bol'shoe Goloustnoe (Fig. 1).

In addition, several patches with abundant blooms of filamentous green algae were detected in coastal puddles above the shoreline at a depth of 0.1–0.2 m on September 15, 2015 in Emelyanikha Bay (Fig. 1). The habitat of the patches was similar to that of the 'LFS patch', and the algal composition was identical, consisting of *Spirogyra* 'morphotype 1' which always attaches to stones (ESM Fig. S8A–C). Surprisingly, the coastal zone of the lake (from the shoreline, 0.5 to 1.5-m depth, ESM Fig. S8D–E) in this area of open Lake Baikal exhibited no mass development of *Spirogyra*. We could not explain this until we learned that this particular area of Emelyanikha Bay is a very popular place for hikers who tent camp here, but the area lacks any public toilets or washing facilities. To conclude, the *Spirogyra* 'morphotype 1' appears to be a very sensitive bioindicator of human waste because it develops massively in areas of recreational activity.

Ground water analyses

Cesspools receiving untreated wastewater in the Bol'shie Koty Settlement and LFS are usually 1.5–2 m deep and consist of a hole in the ground with no lining or cap. Consequently, household wastes are discharged into the C soil horizon, consisting of a gravel/sand/rock mixture with high permeability. Several cesspools located 60–120 m from the lake shoreline and associated with buildings of LFS were near where our groundwater samples were collected (Fig. 2). Groundwater regularly concentrated in lysimeter No. 3 only (Fig. 2B, C) in front of the presumed route of groundwater flow. All other lysimeters remained empty during the summer months of investigation. In May 2016 after the snow layer had melted, maximum concentrations of the mobile Na, Cl and S compounds in the lowest horizon of profile 3 were 2.5–238 times higher than those from soil profiles 1 and 2, located several meters north of profile 3 (Table 2). Effluent wastewater mixed together with snowmelt, rainwater, or both is the likely source of the high elemental composition observed as Na, Cl, and S compounds occur in high concentrations in urea and feces (Berezov and Korovkin, 1998; Zbarsky et al., 1965). High concentrations of the mobile Al, Mn, Co, Ni, Cu, Zn, I, and Ba elements also occurred in the lower horizon of profile No. 3 (Table 2). A similar tendency towards high elemental concentrations (except for well soluble Na, Cl, S, I compounds) was also detected in the soils of this profile in late August 2016. The elements P and K also significantly enriched the lower horizon of profile 3 by the end of the

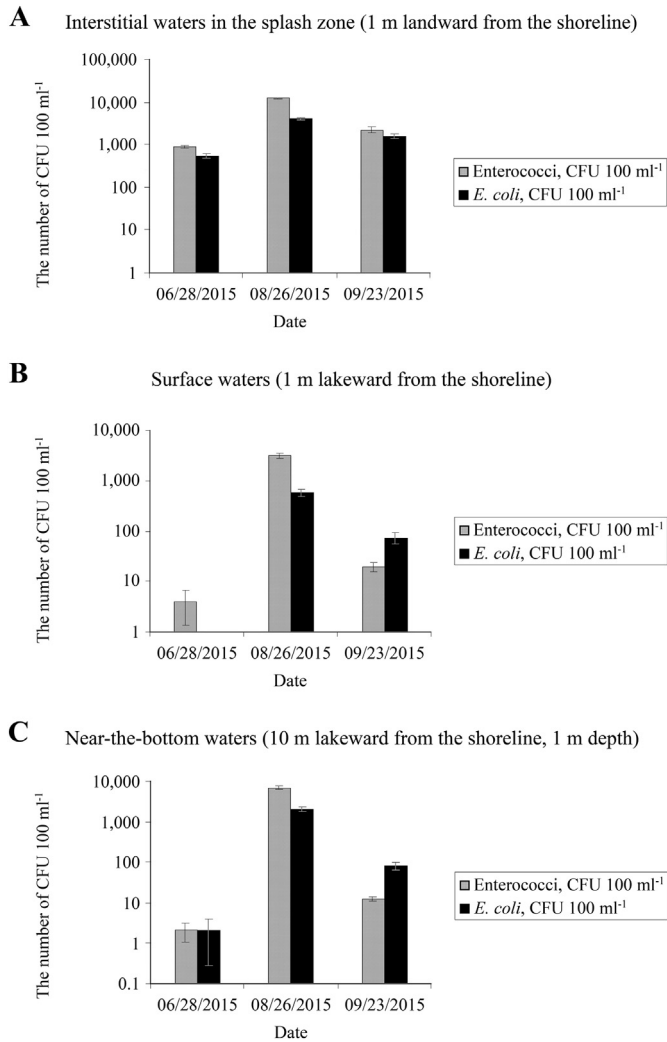


Fig. 8. Average abundance ($n = 3$, \pm SD) of colony forming units (CFU) of each of two groups of fecal-indicating bacteria (Enterococci, *E. coli*) in the lake surface, near-bottom, and interstitial waters in front of LFS in June–September 2015. Averages of interstitial water samples are based on a single sample extracted from each of three pits (0.3-m deep, 1 m from each other) dug into the splash zone of the beach (1 m above the shoreline).

summer season. Such changes demonstrate the intense Na, Cl, S, and I loading as well as the permanent inflow and adsorption of Al, Mn, Co, Ni, Cu, Zn, Ba, P, and K to fine soil particles. The Al, Si, Fe, Mn, Co, Ni, Cu, and Pb concentrations in the groundwater of profile 3 are one order of magnitude higher than that of the interstitial pore (splash zone pits) and nearshore waters. The groundwater is also significantly enriched with Cl, K, Zn, Ba, and P.

Sanitary microbiological and hydrochemical data further support these ICP-MS results and conclusions. High average concentrations of *E. coli* and Enterococcae (1580 and 2140 CFU 100 mL^{-1} , respectively)

were observed in the lysimeter samples in August 2016, after three consecutive days of rain. *Escherichia coli* survived after ca. 120 m travel underground from the putative source and reached the upper border of the beach (end of profile 3). Likewise relatively high concentrations of $\text{N}(\text{NO}_3^-)$ and $\text{P}(\text{PO}_4^{3-})$ were detected at the bottom of the shore scarp in lysimeter No. 3 and hole No. 1 but gradually declined towards the lake proper (Fig. 2B). Specifically, the phosphate concentration in the lysimeter water was 4–8 times higher than that in the lake's bottom interstitial and shoreline water, respectively, while NO_3^- was undetectable in the lake but 3 to 15 times higher in the lysimeter water than in holes No. 1 and 2 (Fig. 2A, B). The low nutrient concentrations in the nearshore zone of the lake suggest that *Spirogyra* 'morphotype 1' does not need a very high concentration of nutrients but instead a sustained inflow of sewage with relatively small amount of nutrients for mass blooming.

Several conclusions can be drawn from the lysimeter and *Spirogyra* data collected in front of LFS. Elemental, microbiological and hydrochemical analyses of water samples from the lysimeter suggest that an aquifer flows along or near the virtual transect (Fig. 3). The stream appears to flow at a depth of 3.5–4 m within the soil, and water collected from it was enriched with Na, Cl, S (typical of groundwater polluted by fecal wastes), Si (typical for ground waters of this area), and other elements. Nutrients and fecal-indicating bacteria exhibited high concentrations as well. The 'LFS *Spirogyra* patch' developed exactly at the terminal end of this transect where groundwater enriched by wastewater effluent discharged into the coastal zone of the lake. Our in situ observations, coupled with those of others, suggest that particular morphotypes of *Spirogyra* may be sensitive bioindicators of improperly purified wastewater (fecal pollution), elevated nutrients, or both (Hainz et al., 2009; Schneider and Lindstrom, 2011; Smith and Ludwig, 1968). The average wet biomass ($300\text{--}600\text{ g m}^{-2}$) and seasonal dynamics of this isolated patch were similar to that observed for larger patches (1–2 km long) in Bol'shie Koty Bay (Fig. 4) as well as in Listvennichnyi Bay and near Bol'shoe Goloustnoe Settlement.

Taken together, the spatial distribution and seasonal dynamics of the 'LFS *Spirogyra* patch', as well as its relationship to wastewater effluent entering the coastal zone through groundwater, should be considered as a model case for explaining the larger *Spirogyra* blooms observed annually near Bol'shie Koty proper, Bol'shoe Goloustnoe, and other settlements. At all sites, the abundance of *Spirogyra* begins to increase from July to August when visitors and tourists come to these settlements. Because most hotels and houses do not have septic tanks, a large volume of effluent from numerous buildings passively penetrates through the ground and discharges into the coastal zone of Lake Baikal, giving rise to patches of much larger areas of *Spirogyra* 'morphotype 1' with maximum development occurring in autumn.

In a broader sense, our work underscores how coastlines and the littoral zone of large aquatic ecosystems (e.g., large lakes, ocean) are 'first responders' to the most concentrated land-derived sources of contamination (Schneider et al., 2014), and it is here where eutrophication problems are most acute. Some Russian limnologists argued as recently as 1998–2002 that Lake Baikal was immune to eutrophication because its vast volume would dilute nutrients (Grachev, 2002; Kozhova and Izmetseva, 1998). A similar tacit assumption existed among marine scientists during the first half of the 20th century regarding the

Table 1

Nutrient concentrations (mg L^{-1}) in single surface and interstitial water samples collected from the 'LFS *Spirogyra* patch' and a control site lacking *Spirogyra* in 2015. Both the control and *Spirogyra* sites were located at the shoreline in front of LFS on the southwest coast of Lake Baikal in the village of Bol'shie Koty. Interstitial pore water samples were collected from a depth of 3–5 cm below the surface of the lake substrate. Additional explanation of sampling can be found in the Methods and in Fig. 2A.

Water samples	Si,		$\text{P}(\text{PO}_4^{3-})$		$\text{N}(\text{NO}_3^-)$	
	August	October	August	October	August	October
Control – shoreline surface water	0.15	0.39	0.002	0.003	0.02	0.04
Control – interstitial pore water	0.14	0.41	0.004	0.006	0.01	0.03
'LFS patch' – shoreline surface water	0.23	0.32	0.005	0.002	0.02	0.03
'LFS patch' – interstitial pore water	2.05	0.67	0.006	0.005	0.05	0.06

Table 2
Elemental concentrations ($\mu\text{g L}^{-1}$) (average values \pm SD) from lysimeter samples, Lake Baikal coastal zone water, and acetate-ammonium extracts (AAE) from the soil and lake substrate in front of LFS during May–August 2016 (n = number of samples). Concentrations obtained using an ICP-MS Agilent 7500 CE mass spectrometer.

Element	05/26/2016		08/28/2016				Lysimeter water samples n = 3		PW ^a n = 1	AAE from soil, splash zone pits n = 5	Water, splash zone pits, n = 16	Lake water, 1 m beyond shoreline n = 16	AAE from lake substrate (1.5-m water depth) n = 3
	AAE from soil (n = 1) ^b												
	Soil profile identity number						Profile no. 3						
	1	2	3	2	3	4	06/30/2016	08/28/2016					
Na	1530	1670	4100	1030	980	2500	1570 ± 370	1670 ± 60	5100	880 ± 280	3150 ± 200	3540 ± 100	875 ± 210
Mg	38,000	41,000	46,000	30,000	50,000	53,000	2670 ± 60	4600 ± 60	8500	30,000 ± 9000	3050 ± 900	3220 ± 60	20,750 ± 700
Al	4.2	4.20	10.8	5.30	13.6	1.67	170 ± 10	1500 ± 90	1200	1.89 ± 0.33	160 ± 30	6.50 ± 0.10	5.55 ± 1.7
Si	1510	980	1100	2000	1380	2200	3800 ± 60	5900 ± 60	7800	1080 ± 300	2200 ± 400	390 ± 120	1070 ± 320
P	<7	<7	12.3	<7	57	12.9	98.3 ± 3.5	53.0 ± 10	<30	10.3 ± 3.85	<30	36.0 ± 1.8	40 ± 20
S	600	<500	21,000	<500	<500	1110	2160 ± 270	1230 ± 60	9900	<500	2000 ± 200	1580 ± 90	630 ± 130
Cl	<40	60	9300	107	106	55	1720 ± 420	1600 ± 60	8800	<40	<1000	<1000	40 ± 20
K	3800	6200	4100	4400	11,000	4000	1740 ± 400	2100 ± 230	1400	4600 ± 1800	1030 ± 100	890 ± 90	2900 ± 800
Ca	320,000	240,000	200,000	190,000	210,000	340,000	7100 ± 200	11,000 ± 300	21,000	186,000 ± 60,000	12,950 ± 400	14,600 ± 1200	164,500 ± 6000
Mn	41	72	460	31	660	200	320 ± 10	54.0 ± 10	25.0	84.0 ± 30	2.58 ± 0.75	0.23 ± 0.05	160 ± 90
Fe	48	47	48	47	60	46	690 ± 10	1420 ± 90	930	49.0 ± 14.1	110 ± 30	45.0 ± 4.2	48.5 ± 2.5
Co	0.87	0.95	3.60	0.66	2.90	0.96	4.33 ± 0.12	0.87 ± 0.08	0.82	0.67 ± 0.15	0.091 ± 0.03	0.033 ± 0.010	1.01 ± 0.27
Ni	1.24	3.50	10.8	1.70	8.2	6.9	4.70 ± 0.26	4.50 ± 0.20	3.60	1.70 ± 0.40	0.29 ± 0.06	0.32 ± 0.03	2.15 ± 0.50
Cu	1.32	2.50	4.20	1.63	5.00	1.59	6.90 ± 1.10	6.70 ± 0.30	5.60	1.53 ± 0.60	1.19 ± 0.34	0.58 ± 0.06	3.35 ± 0.50
Zn	0.56	1.29	2.40	0.55	1.80	<0.4	13.9 ± 7.1	11.8 ± 0.80	5.20	<0.4	2.01 ± 0.70	1.60 ± 0.55	<0.4
Sr	2100	1790	940	2600	1840	2200	49.3 ± 1.2	78.0 ± 0.6	125	1400 ± 300	75.0 ± 9.0	100 ± 10	1610 ± 650
I	2.9	3.80	14.5	4.60	4.7	4.4	4.57 ± 0.06	2.00 ± 0.06	8.70	5.50 ± 0.77	2.70 ± 0.25	1.62 ± 0.27	4.90 ± 0.90
Ba	830	570	1740	860	2100	940	8.13 ± 0.12	25.0 ± 0.47	11.5	910 ± 320	9.30 ± 0.85	9.10 ± 1.77	1310 ± 500
Pb	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.29 ± 0.08	1.48 ± 0.09	1.39	<0.05	0.13 ± 0.06	0.050 ± 0.020	<0.05
U	1.33	1.14	0.73	1.81	0.72	0.74	0.17 ± 0.003	0.12 ± 0.06	0.32	1.80 ± 0.60	0.34 ± 0.05	0.54 ± 0.09	0.78 ± 0.26

^a PW – water that had percolated through the beach deposit layers and collected under lysimeter No. 2 (Profile 2).

^b Soil samples collected 130–150 cm below the beach surface at the base of soil profiles.

vulnerability of the oceans to eutrophication and other forms of pollution. Although never formally stated, this sentiment was similar to the frequently repeated slogan, “Dilution is the solution to pollution.” Now, however, coastal eutrophication and the resultant dead zones in the ocean are well recognized globally (Diaz and Rosenberg, 2008; Rabalais et al., 2002), and oceanographers working offshore beyond the continental shelf acknowledge that no place is immune to the effects of human-derived nutrients (Karl and Tien, 1997; Van Dover et al., 1992). The same is true for Lake Baikal.

Alternative drivers

Results shown here and elsewhere (Khodzher et al., 2017) clearly point to nutrient loading as the primary factor driving the explosive growth of *Spirogyra*. This increase in loading is most likely caused by the intensification of tourism and illegal building construction near the shoreline (Chernova, 2017; MacFarquhar, 2017). The rising inputs of nutrients could be interacting synergistically with some alternative drivers, particularly rising lake temperature described below. Historical data and information from the literature suggest that contributions from other potential drivers are unlikely. Among these, we address specifically lake level fluctuations and a reduction in grazing pressure.

Climate warming

An increase in lake water temperature attributed to contemporary climate change has been documented in the offshore pelagic zone of Lake Baikal by multiple groups of scientists (Hampton et al., 2008; Katz et al., 2011; Shimaraev and Domysheva, 2013; Shimaraev et al., 2002; Sizova et al., 2013; Troitskaya et al., 2003), and some researchers

established a positive relationship between surface water temperatures in May–October and the biomass of Baikal phyto- and zooplankton (Afanasyeva and Shimaraev, 2006; Shimaraev et al., 1994). However, these are long-term temperature trends, and the time span of the last 10–13 years is the most relevant for clarifying the relationship between *Spirogyra* biomass and temperature. Surprisingly, the trend for surface water temperature in the south basin near areas of abundant *Spirogyra* blooms (Listvennichnyi Bay, Bol'shie Koty Bay, Bol'shoe Goloustnoe Settlement) was negative at all three meteorological stations along the west coast from 2000 to 2016 (i.e., -0.2 to -0.3 °C per 10 years) (Fig. 9). In contrast, trends in surface water temperature at the east coast stations were positive (i.e., 0.6 to 1 °C per 10 years) (Fig. 10). Such variation may be associated with local factors such as extensive shallow water zones, close proximity of the Selenga River delta (east coast), coastal upwellings, etc. In summary, there appears to be no consistent relationship between trends in surface water temperature and the spatial pattern of *Spirogyra* mass development. Additional information and arguments are given in ESM (Fig. S10).

Lake level fluctuations

As water levels rise and fall, typically about 1 m annually due to changes in lake inputs (i.e., precipitation and stream flow) relative to outflow (evaporation and flow associated with the hydroelectric plant at Irkutsk), nutrients from either offshore via boundary mixing and seiche activity (Zohary and Ostrovsky, 2011) or from above the shoreline by the 'Birch effect' (Jarvis et al., 2007; i.e., high rates of mineralization upon re-wetting of organic substrates) can be moved into the littoral zone. However, historical lake level data for Lake Baikal refute the claim that lake level fluctuations are driving the current blooms of

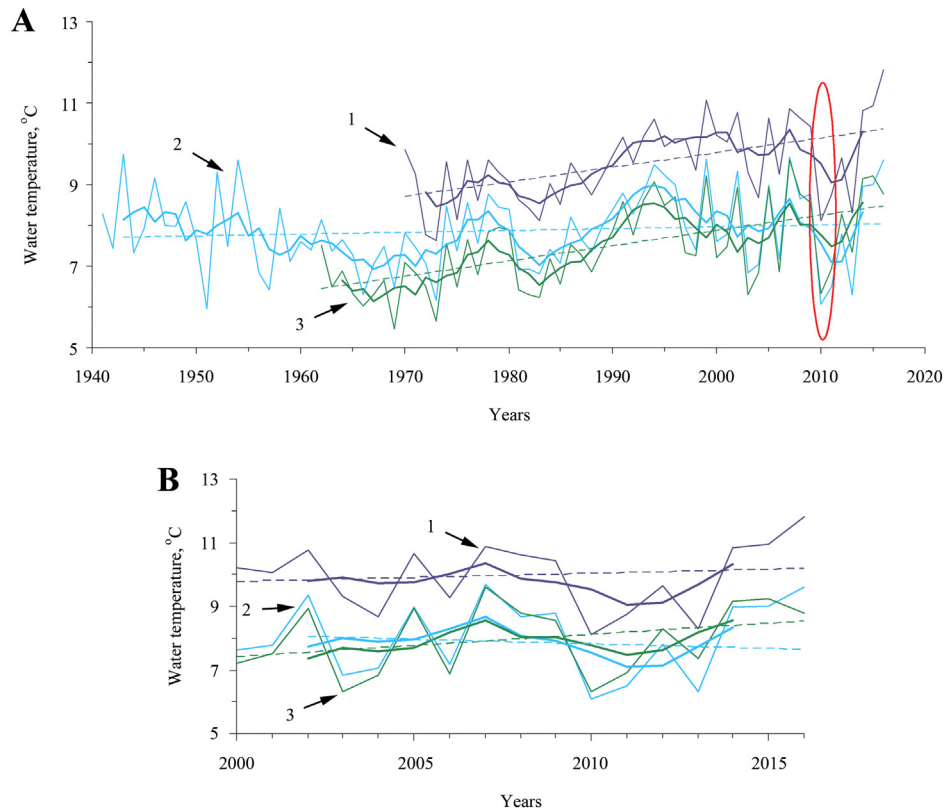


Fig. 9. Average surface water temperatures for May–September (thin lines), their trends (dashed lines) and 5-year smoothed data (thick lines) for stations in the littoral zone (0–3 m from the shoreline) on the west coast of Southern Baikal: Bol'shoe Goloustnoe (1), Listvyanka Settlement (2) and a mouth of the Angara River (3) from the beginning of measurements to 2016 (A) and from 2000 to 2016 (B). The red ellipse indicates the year in which the coastal crisis began.

Spirogyra. Lake level varied by as much as 3 m from the period 1730 (when the first measurements were made) until the late 1950s (Galazyi, 1987). After the construction of the Irkutsk hydroelectric dam on the lake's sole outlet, the Angara River, the water level of Lake Baikal increased in 1963 by 1.36 m but decreased gradually to 0.8 m. Variation in the lake's water level also decreased to within 1 m (Fig. 11), as required legally by the Russian Federation (Resolution of the Government of Russian Federation, 2001). Nutrient enrichment of the coastal zone probably happened during and shortly after construction of the dam; however, no harm to the lake ecosystem such as the current mass proliferation of algae and mortality of sponges was observed during that period (Timoshkin et al., 2016) or in subsequent years before the *Spirogyra* outbreaks began 5–7 years ago. Furthermore, water level fluctuations occur throughout the lake, but our hydrochemical measurements from 2007 to 2014 for interstitial, near-bottom, and surface waters (Timoshkin et al., 2012b; Tomberg et al., 2012) showed concentrations of macronutrients varied greatly along the lakeshore with nutrients most frequently being highest where human activity onshore is greatest (Khodzher et al., 2017; Tomberg et al., 2016).

Some authors have suggested that the proliferation of *Spirogyra* was linked to the unusually low water level (ca. 455.9 m) observed in 2015 which was caused by low precipitation. However, the lake's water level was 0.6 m lower in 1980–1982 than in 2015 (Fig. 11), with no observed negative effects on the coastal communities. Lastly, the current outbreaks began as early as 2010–2011 when the lake's water level was normal and fluctuations low.

Reduction in grazing pressure

Herbivores can be very effective in controlling benthic algal biomass as demonstrated by results of a meta-analysis of 865 experiments (field

and laboratory) that investigated grazer control of periphyton biomass in lotic, lentic, and marine ecosystems. Hence, a relaxation of grazing pressure can intensify benthic algal blooms. Most lake grazers, however, are not capable of consuming large filamentous algae (e.g., *Spirogyra*) (Cattaneo, 1987), and there is no obvious cause for a reduction in benthic grazers or grazing pressure that might have allowed vigorous growth of *Spirogyra* at the locations in Lake Baikal where the outbreaks are centered. A reduction in grazing pressure might *secondarily* be associated with the blooms of *Spirogyra* if herbivores leave *Spirogyra*-infested areas because of poor food quality or avoidance of oxygen depletion associated with decaying *Spirogyra*. However, the prolific production of *Spirogyra* in outbreak areas requires substantial nutrient inputs regardless of grazing pressure. Thus, a reduction in grazing pressure may be a secondary outcome that exacerbates the problem, but it is unlikely to be the primary cause.

In summary, the data for alternative drivers do not support the hypothesis that any of them are primarily responsible for the recent outbreak of *Spirogyra* at the lake, but these data also do not reject the hypothesis that warming water temperature may be acting synergistically with nutrient additions, and possibly secondary loss of grazers, to cause dangerous ecosystem change. What is particularly worrisome is that *Spirogyra* blooms are now occurring year-round at a minimum of three localities in the coastal zone of the lake (Listvennichnyi Bay, Baikal'sk City in the south, and near Severobaikal'sk City in the north, Fig. 1) suggesting that these blooms have become a permanent condition. If nutrients continue to pour into the coastal region of this oligotrophic lake, a permanent state change in the coastal ecosystem could occur and be sustained by the lake's long residence time (377–400 years). The only means currently available to stop this 'cancerous' growth is to starve the 'cancer' of wastes and nutrients.

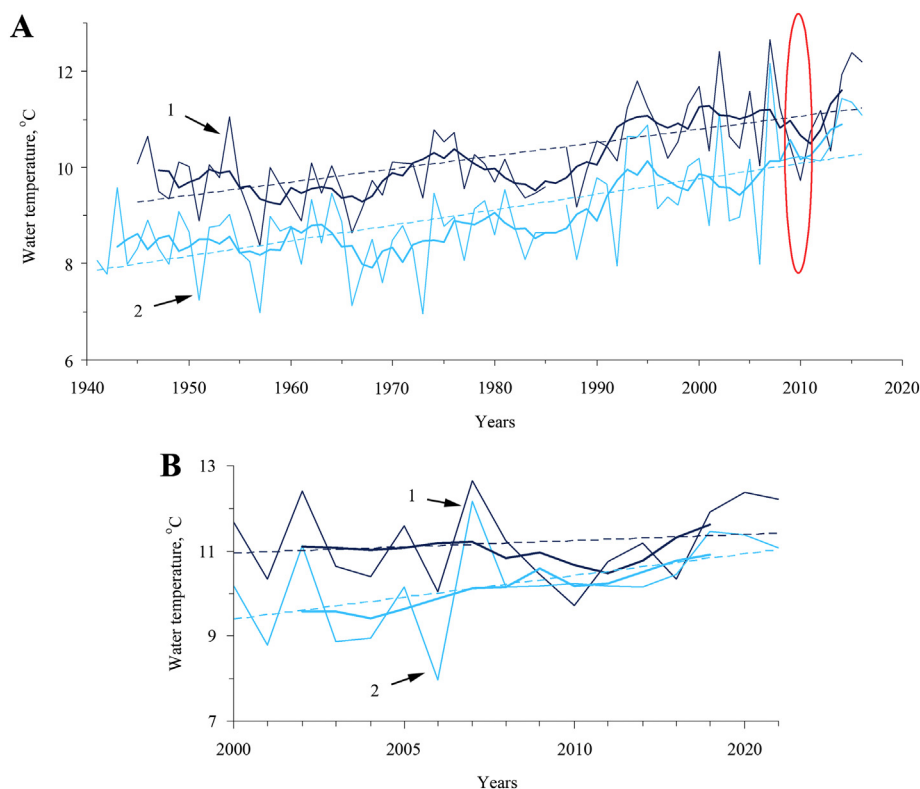


Fig. 10. Average surface water temperatures for May–September (thin lines), their trends (dashed lines) and 5-year smoothed data (thick lines) for stations in the littoral zone (0–3 m from the shoreline) on the east coast of Southern Baikal: Babushkin (1) and Tankhoi (2) from the beginning of measurements to 2016 (A) and from 2000 to 2016 (B). The red ellipse indicates the year in which the coastal crisis began.

Conclusion and recommendations

Our interdisciplinary approach which included multi-year comparisons of the 1) spatial-temporal dynamics of *Spirogyra*; 2) chemical and microbiological analyses of groundwater as well as interstitial, near-bottom, and surface waters; 3) surface and near-bottom water temperature; 4) water level fluctuations supports the hypothesis that anthropogenic eutrophication is the main driver of the *Spirogyra* blooms in Lake Baikal. *Spirogyra* 'morphotype 1' appears to be a sensitive bioindicator of wastewater entering the coastal zone via groundwater from surrounding settlements in Lake Baikal. During autumn, the period of its maximal development, the alga significantly influences and changes the composition of native Baikalian benthic communities

(Rozhkova et al., 2016). In areas where *Spirogyra* proliferates massively (e.g., near Severobaikal'sk City at the northern end of the lake), giant amounts of rotting algae have accumulated annually at least since 2013 along the coasts (Timoshkin et al., 2016; Fig. S3). These masses, in turn, contribute to poor water quality and secondary water contamination by nutrients and bacteria (Tomberg I.V. and Malnik V.V., Personal Communication, Limnological Institute SB RAS, 2017), as well as changes in the coastal plankton communities (Sheveleva et al., 2017).

The process of benthic eutrophication and contamination by waste waters of the coastal zone of Lake Baikal must be halted immediately. We have made previous urgent recommendations (Timoshkin et al., 2014) which we reiterate and expand upon here. First, an assessment of the current ecological situation of the Lake Baikal ecosystem, based

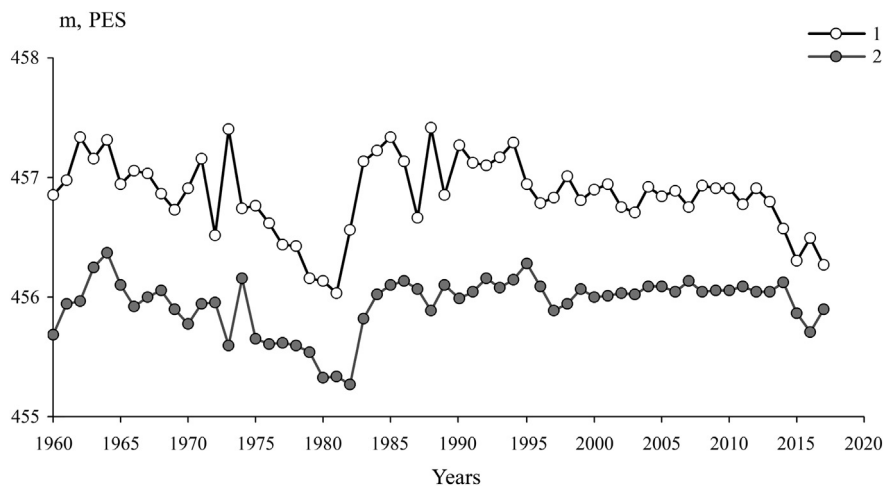


Fig. 11. Average highest (1) and lowest (2) values of Lake Baikal's water level in a given year from 1960 to 2017. Water level was recorded daily at 8 stations, located in all 3 basins of Baikal using an automatic water level recorder maintained by ROSGIDROMET (Hydrometeorological Survey of Russian Federation, Irkutsk Branch). PES — Pacific Elevation System.

exclusively on scientific data and arguments, must be presented in detail to the Russian federal government. A common language is needed to facilitate communication among all stakeholders including scientists, officials of state agencies, and members of the general public. Specifically, we strongly recommend: 1) a reduction in nutrient loading (nitrogen and phosphorus) to the lake's coastal zone by incorporating appropriate wastewater treatment systems in coastal settlements and towns, including modernization of existing wastewater treatment systems using new technology that produces P and N concentrations in the effluent that are comparable to those of uncontaminated Lake Baikal water; 2) strict control over the functioning of wastewater treatment facilities and the discharge of bilge water from ships; 3) an information campaign promoting the use of nonphosphate-containing detergents by permanent residents, tourists, and hosts of hotels within the lake's central ecological zone (for explanation of term, see Antipov et al., 2007); and 4) the acceptance of a ban on the production of phosphate-based detergents across Russia which would be similar to that which exists in Japan for Lake Biwa (Lake Biwa Comprehensive Preservation Initiatives, 2012) and the Laurentian Great Lakes (Litke, 1999). Finally, it is vitally important to expand the existing monitoring scheme for the Lake Baikal ecosystem which currently focuses almost exclusively on the pelagic zone. Interdisciplinary monitoring of the coastal zone, including the splash zone, near-bottom waters, and benthic communities should be adopted by the federal monitoring system. Such a monitoring program, approved by the World Limnological Congress, Lahti, 2004, in combination with a monitoring design for the Lake Baikal splash zone (Timoshkin et al., 2012b, 2012c), is available and can be used as a guide (Timoshkin et al., 2005, 2011, 2012a, 2012b, 2012c).

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jglr.2018.01.008>.

Authors' contributions

The first author conceived and designed the study and provided the photos for Figs. 2, 4–6 and S1–S9. O.A. Timoshkin, N.N. Kulikova, V.V. Malnik, V.M. Domysheva, I.V. Tomberg, A.E. Poberezhnaya, and E.P. Zaitseva collected and treated samples. M. Yamamuro provided the phototechnique and laboratory equipment for underwater investigations and edited the manuscript. A.A. Shirokaya prepared all figures and provided sources of literature. O.A. Timoshkin wrote the article with major contributions from M.V. Moore, A.A. Shirokaya, N.N. Kulikova, V.V. Malnik, M.N. Shimaraev, E.S. Troitskaya, V.N. Sinyukovich, M. Yamamuro, and E.M. Timoshkina (review of the literature, statistical analysis, and so on). All authors discussed the results and gave final approval for publication. The comprehensive editing of the text was made by a native speaker, M.V. Moore.

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