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Commentary

Rapid ecological change in the coastal zone of Lake Baikal (East Siberia): Is the site of the world's greatest freshwater biodiversity in danger?

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ABSTRACT

Ecological degradation of the benthic littoral zone is an emerging, urgent problem at Lake Baikal (East Siberia), the most species-rich lake on Earth. Within the last 5 years, multiple changes have occurred in the nearshore benthos where most of the lake's endemic species reside. These changes include proliferation of benthic algae, death of snails and endemic sponges, large coastal wash-ups of dead benthic algae and macrophytes, blooms of toxin-producing benthic cyanobacteria, and inputs of industrial contaminants into parts of the lake. Some changes, such as massive coastal accumulations of benthic algae, are currently shared with the Laurentian Great Lakes (LGLs); however, the drivers of these changes differ between Lake Baikal and the LGLs. Coastal eutrophication from inputs of untreated sewage is causing problems at multiple sites in Lake Baikal, whereas in the LGLs, invasive dreissenid mussels redirect pelagic nutrients to the littoral substrate. At other locations in Lake Baikal, ecological degradation may have different causes including water level fluctuations and the input of toxic industrial contaminants. Importantly, the recent deterioration of the benthic littoral zone in both Lake Baikal and the LGLs has occurred while little change has occurred offshore. This highlights the necessity of monitoring both the littoral and pelagic zones of large lakes for assessing ecosystem health, change and conservation.

The current ecological situation in the coastal zone of one of the greatest lakes of our planet—Lake Baikal (East Siberia, Russia)—has prompted us to write this commentary. We wish to inform the world's limnological community about the negative ecological processes which are increasing in Lake Baikal year by year. This glorious lake harbors an enormous quantity of pure drinking water and an unusual diversity of endemic life forms (Vereshchagin, 1940; Kozhov, 1963; Timoshkin, 2001). Specifically, Baikal contains one fifth of the total amount of unfrozen freshwaters of the globe. Fifteen years from now, according to projections of the United Nations, the human population will need 40% more drinking water than natural resources can provide (The United Nations World Water Development Report, 2015). This makes the lake strategically important both regionally and for all of humanity. But perhaps more important globally is that Lake Baikal is first among lakes in terms of its exceptional taxonomic diversity; more than 2660 animal and more than 1000 plant species and subspecies have been described, with ca. 60% of the animal species being endemic (Timoshkin, 2011). Therefore, the lake is an ideal natural laboratory for investigating questions regarding evolution and processes of endemic speciation.

Most of the biodiversity of ancient lakes is concentrated in their coastal zones (Kostoski et al., 2010; Vadeboncoeur et al., 2011; von Rintelen et al., 2012) as evidenced by Lake Baikal where greatest species diversity occurs on the substrate in shallow waters ranging in depth from 1 to 50 m (Timoshkin, 2001; Timoshkin et al., 2004; Semernoy, 2007). This habitat is currently experiencing rapid changes and modifications throughout the entire lake with some key changes similar to

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those occurring in the Laurentian Great Lakes. How will these negative processes in Lake Baikal, including the mass expansion and proliferation of the benthic filamentous alga of the *Spirogyra* genus, affect the primary and secondary consumers as well as the lake's water quality? Investigations are just beginning with questions being more numerous than answers. Scientists have not reached a consensus regarding the spatial scale, origin (natural versus anthropogenic), or causes of the ongoing processes. Interviews with scientists and papers in the popular press often contradict each other. To date, the international scientific society has very limited information.

Furthermore, the Ministry of Natural Resources and Ecology of the Russian Federation, responsible for the monitoring of Lake Baikal, in its annual State report titled "On the state of Lake Baikal and measures for its protection" (Ministry of Natural Resources and Ecology of the Russian Federation, 2014) states in the conclusion that "the state of the Lake Baikal ecosystem in 2013 did not undergo any significant changes. . ." (p. 362). This conclusion, based only on offshore sampling, is false. Interestingly, governmental monitoring in other countries also focuses on the offshore pelagic zone while mostly ignoring the nearshore zone. For example, a deficit of coastal monitoring in the Laurentian Great Lakes caused the USA and Canada, in their latest revision of the Great Lakes Water Quality Agreement (2012), to call for a "Nearshore Framework" that includes enhanced study and monitoring of coastal environments throughout the Great Lakes. As for Lake Baikal, scientists proposed a monitoring scheme for the coastal zone, based on the landscape-ecological approach (Timoshkin et al., 2005, 2009), and this proposal was supported by the world limnological community at the 2004 SIL meeting (Lahti, Finland). The lake's coastal zone was monitored from 2000 to 2003, but financial difficulties prevented extensive monitoring in subsequent years until 2010. Nevertheless, the coastal zone (including the splash zone) is still not included in the official monitoring scheme of Lake Baikal even in 2016.

As a result, citizens and non-governmental ecological organizations do not have a clear understanding of what is happening in the lake's coastal zone or what they need to do to protect themselves and the lake from these negative events. Therefore, it is critically important to inform everyone about the real situation and the presumed causes of the crisis. To this end, the goal of this contribution is to use results from recent systematic sampling to describe the current ecological situation in the coastal zone of the lake.

Significant changes in the structure and quantitative characteristics of the shallow water benthic communities were detected lake-wide during interdisciplinary studies of Lake Baikal's coastal zone (including the splash zone) (Timoshkin et al., 2014; most references, public lectures, and interviews of the first author on the crisis can be downloaded from www.lin.irk.ru and http://www.lin.irk.ru/hydrobiology/my-v-smi). From 2007 to 2012, sampling was performed sporadically, and it was restricted to two areas of the south basin (i.e., Bol'shie Koty and Listvennichnyi Bays only) due to a lack of financial support for more widespread lake sampling. Results of this sampling were published in 13 papers (for review, see Timoshkin et al., 2012a–c). Taxonomic composition and quantitative characteristics of macrophyto-, macrozoobenthos, and plankton communities, as well as hydrochemical, hydrological, and microbiological parameters of the interstitial, near-bottom, and surface waters in the shallow water zone were reported (Kulikova et al., 2012; Popova et al., 2012; Potapskaya et al., 2012; Rozhkova et al., 2012; Timoshkin et al., 2012b; Tomberg et al., 2012; Vishnyakov et al., 2012; Volkova et al., 2012; Zvereva et al., 2012; Sheveleva et al., 2013; Bondarenko et al., 2015). In addition, since 2013, several spring–summer and autumn sampling expeditions occurred annually throughout the entire lake.

When did environmental decline begin or when was it expressed most markedly? Due to a lack of lake-wide sampling surveys of the shallow water communities before 2010, only an approximate answer can be provided. Most likely, visible change in the benthic community began 2010–2011 with the most significant changes being detected in the macrophytobenthos communities (Kravtsova et al., 2012, 2014; Timoshkin et al., 2014, 2015). Macroalgae monitoring was performed using 1) "short" transects (0–1.5 m water depth; % cover and biomass by "stone-unit" (Nakashizuka and Stork, 2002) and quadrat (0.1 and 0.25 m^2) methods; underwater photo- and videorecording); 2) scuba diving (1.5 to 7–10 m depth); 3) dredging (20–25 m depth). Most samples from 2014 to 2015 are still being examined. Descriptions of seasonal and inter-annual dynamics will be presented in future publications. Conclusions about changes to the macrozoobenthic communities (except for the sponges, see below) can be made only after ongoing quantitative analyses are completed. A chronology and brief description of the unusual and/or negative ecological processes occurring between the years 2010–2015 are given below and give rise to our concern that the coastal environment is under increasing stress.

Changes in zonation and species composition of benthic macroalgae. Significant, large-scale modifications of the benthic macroalgal community were observed by two independent groups of experts in 2010–2011 in two local bays (Bol'shie Koty and Listvennichnyi) in the south basin. Specifically, filamentous green algae (*Spirogyra* spp. and *Stigeoclonium tenue*) at these two sites were growing prolifically in places and depths that are atypical for Lake Baikal. From late July through November, *Spirogyra* grew extensively at depths ranging from 0.5 to 10 m and an abundant late autumn bloom of *Stigeoclonium tenue* occurred in the shoreline or first algal zone, which is normally occupied by the green filamentous algae, *Ulothrix zonata* (see Table 1 for typical benthic algal zones in Lake Baikal).

In 2013–2014, a mass bloom of *Spirogyra* was detected in autumn in the shallow water zone throughout much of the surveyed portion of the lake (Figs. 1, 2, 3). It is easier to indicate areas where the alga was not found: Bol'shoi Ushkani Island, most of the coastline of Ol'khon Island (except for Perevoznaya Bay and a site near Khuzhir Settlement), and the northwestern coast stretching from Elokhin Cape to Maloe More Strait (Fig. 1). Interestingly, nearshore pelagic waters of this part of the northwest coast also exhibited the lowest chlorophyll concentrations of any area in the lake during summer (Izmest'eva et al., 2016), suggesting minimal anthropogenic influence. Even on Ol'khon Island which was largely free of *Spirogyra* in 2014, mass development of *Spirogyra* was noted at two anthropogenically influenced localities (i.e., the ferry harbor in Perevoznaya Bay and Shamanka Bay near Khuzhir Settlement). By 2015, mass growth of *Spirogyra* was reported at several new localities along the west coast of South Baikal (Emelyanikha Bay, Sennaya Bay, and a coast opposite Polovinnyi Cape) as well as Maloe More Strait (i.e., coastal zone off Sakhyurte Settlement and Kargante Bay; Fig. 1). In summary, *Spirogyra* spp. developed massively and even dominated the benthic macroalgal community along much of the eastern coast, and in many places along the western coast of Lake Baikal in autumn. Surprisingly, the maximum development of *Spirogyra*—a comparatively thermophilic algae (optimal temperature for growth is ca. 20 °C), was detected during autumn (September–October) when water temperatures were 4–8 °C. Two of the sites (i.e., Listvennichnyi Bay in south basin and Tyya–Senogda coast

Table 1
Under normal conditions, Lake Baikal exhibits a well-defined zonation of benthic algae. Each of the five zones or belts is usually dominated by 1–2 species, including endemics (Meyer, 1930; Izhboldina, 1990), and zones are most clearly defined during spring through autumn. Zones presented below begin with the zone closest to the water's edge and end with the deepest zone. The upper border of zone 1, occupied by the filamentous *Ulothrix zonata*, depends on water level fluctuations and is sharply defined by them during the open water season.

Zone	Depth (m)	Dominant benthic algal species
1	0–1.5	*Ulothrix zonata* (Web. et Mohr.) Kuetz. (green algae)
2	1.5–2.5	*Tetraspora cylindrica* var. *bullosa* C. Meyer (green algae) and *Didymosphenia geminata* (Lyngb.) M. Schmidt (diatoms)
3	2.5–20	*Draparnaldioides* C. Meyer et Skabitsch. (green endemic algae)
4–5	20–70	*Cladophora* Kuetz. (green algae with some endemic species)

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