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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 five 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, deaths 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.

LETTERS TO THE EDITOR

RAPID ECOLOGICAL CHANGE IN THE COASTAL ZONE OF LAKE BAIKAL (EAST SIBERIA): IS THE SITE OF THE WORLD'S GREATEST FRESHWATER BIODIVERSITY IN DANGER?

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 (Vereschagin, 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 UN 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 2,660 animal and more than 1,000 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 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 on-going 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" (MNRERF, 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 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 2007–2012, 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-[1], 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). Conclusions about changes to the macrozoobenthic communities (except for the sponges, see below) can be made only

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[1] 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 (SA = 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 2014–2015 are still being examined. Descriptions of seasonal and inter-annual dynamics will be presented in subsequent contributions.

after on-going 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.

1. <u>Changes in zonation and species composition of benthic macroalgae.</u> Significant, large-scale modifications of the benthic macroalgal community were observed by two independent groups of experts (ob. cit.) 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 0.5–10 m and an abundant late autumn bloom of *Stigeoclonium tenue* occurred in the shoreline zone (first algal zone; see Table 1 for normal zonation patterns), which is normally occupied by the green filamentous algae, *Ulothrix zonata*.

In 2013–2014, a mass bloom of *Spirogyra* was detected in autumn in the shallow water zone throughout much of the lake[2] (see caption to Figure 1 for the five criteria used to describe abundance patterns; Figs 2, 3). Also in 2014, the mass development of *Spirogyra* was noted on Ol'khon Island at two localities (i.e., the ferry harbor in Perevoznaya Bay and Shamanka Bay near Khuzhir Settlement on Ol'khon Island). 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). 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. 20^0C), was detected during

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[2] 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.

autumn (September–October) when water temperatures were 4–8 ^{0}C. Two of the sites (i.e., Listvennichnyi Bay in south basin and Tyya–Senogda coast in north basin) investigated to date were characterized by year-round mass blooms of *Spirogyra* spp. which sometimes included other filamentous algal species that are nontypical for Lake Baikal (ESM video 1). Dredge sampling, performed in the north basin (i.e., Boguchanskaya Bay and opposite the Tyya River mouth) in autumn 2013 showed *Spirogyra* spp. penetrating into the lake to a depth of 10–20 m. Algal wet biomass in 2013–2014 ranged from 100–1,500 g m^{-2}, which is similar or greater than that reported for native Baikalian algae inhabiting the first and second algal zones of Lake Baikal (Table 1, *sensu* Meyer, 1930). Also, a mass bloom event of *Stigeoclonium* on the rocks at the shoreline was seen each autumn in 2013–2015 in many areas of all three basins. Before these mass bloom events began occurring, *Stigeoclonium* was present in minor amounts during August–September at depths of 1–2.5 m and in some tributaries of South Baikal (Izhboldina, 2007).

2. Biomass increase of benthic macroalgae. In 2015, biomass of typical benthic Baikalian macroalgae increased significantly in some areas of the shallow water zone of Lake Baikal. For example, algal wet biomass within the first zone is normally dominated by the typical shoreline species, *Ulothrix zonata*. However, at some sites in Northern Baikal (north of Elokhin Cape), its biomass ranged from 3–5 kg m^{-2}, and this is 6 to 10 times greater than values recorded formerly (Izhboldina, 1990: maximum in June — 0.5 kg m^{-2}).

3. Mass development of benthic cyanobacteria. In several areas of the lake, cyanobacteria developed massively with some species growing prolifically on dying macroalgae (*Draparnaldioides* spp.) and sponges. Significant amounts of filaments of benthic Oscillatoriales and Nostocales were discovered by the first author in benthic dredge samples collected at depths of 10–15 m south of Peschanaya Bay (South Baikal) in the summers of 2013 and 2014. Mass blooms of benthic *Phormidium*, *Oscillatoria*, *Tolypothrix* species and others also occurred in the shallows of Bol’shie Koty and Barguzin Bays, etc. Earlier (2010–2012), similar Oscillatoriales and Nostocales were found on dying macroalgae of the endemic *Draparnaldioides* (Chlorophyta), near

the end of their vegetative season (Timoshkin et al., 2012a: p. 47–48). During the last 2 to 3 years, similar Cyanobacteria (predominantly belonging to *Phormidium* genus) developed massively on the dying Lubomirskiidae sponges. Therefore we began calling them "epizoic" cyanobacteria. According to our original data, collected in October 2014, at Bol'shie Koty Bay (5 m depth, syringe sampling), concentrations of orthophosphate in the water surrounding the dying sponge branches ranged from 0.213–0.97 mg l^{-1}, whereas in the near bottom water layer concentrations ranged from 0.038–0.045 mg l^{-1}. We hypothesize that the cyanobacteria preferentially colonize these dying organisms, because they are releasing nutrients. An additional change was detected in September 2015, when *Tolypothrix*, *Oscillatoria* species and other cyanobacteria developed abundantly on rocks within and near the shoreline, sometimes abundantly penetrating the most upper *Ulothrix zonata* zone and displacing this native filamentous green alga (Fig. 4A–F). Wet biomass of benthic cyanobacteria was very high, measuring up to 195.1 g m^{-2}. In years prior to these many ecological changes, *Tolypothrix* spp. were reported from the second and third algal zones only where their maximum total biomass was 87 g m^{-2} (Izhboldina, 2007). Such abundant blooming of Oscillatoriales and Nostocales within the first algal zone has never been detected before.

To check for the presence of neurotoxic cyanotoxins (i.e. — saxitoxin, STX and its analogues, termed paralytic shellfish toxins, PST), we analysed 12 benthic cyanobacterial samples collected in May, July, and September 2015, from the coastal zone of Bol'shie Koty Bay (Fig. 1: site 7) using an Abraxis Saxitoxin (PSTs) ELISA kit (Abraxis LLC, USA). Earlier, we had applied this method successfully to detect saxitoxin from planktonic cyanobacteria in Lake Baikal (Belykh et al., 2015a, b). The presence of STX and its analogues in the benthic cyanobacteria samples were also confirmed using another detection method, matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF-MS), as described in Belykh et al. (2015b). The following PST toxins were identified in the benthic cyanobacteria using the MALDI-TOF-MS method: saxitoxin (STX), neosaxitoxin (neoSTX) and gonyatoxin (GTX5), containing carbamoyl groups, decarbamoyl derivates of the saxitoxin (dcSTX), neosaxitoxin (dcNeoSTX) and gonyatoxin (dcGTX2/3, dcGTX1/4), and two compounds known as *Lyngbia wollei* toxins (LWTXs).

STX concentrations ranged from 0.2 to 141.5 μg g^{-1} dry weight in all 12 benthic cyanobacterial samples from Lake Baikal as measured with the ELISA kit. Maximum toxin concentrations occurred in cyanobacteria collected from near shore rocks (Fig. 4B–F). Mean STX concentrations in benthic Lake Baikal cyanobacteria were similar to those reported for benthic cyanobacteria in New Zealand lakes (Smith et al., 2011, 2012), 10 to 6,000 times higher than those reported in an Arctic water body (Kleinteich et al., 2013) but much lower than those reported for pure cultures of benthic cyanobacteria isolated from New Zealand lakes (*Scytonema* cf. *crispum,* Smith et al., 2012) and a North American reservoir (*Lyngbya wollei,* Yin et al., 1997). At Lake Baikal, human exposure to intra-cellular saxitoxin in benthic cyanobacteria should be unlikely unless the toxin remains intact upon release into the water following cell death and lysis. The effects of ingestion of saxitoxin-containing cyanobacteria by freshwater benthic invertebrates, wildlife, dogs, or farm animals feeding or drinking at the lake's shoreline are unknown, but they are potentially severe, because STX is a potent neurotoxin.

4. <u>Large coastal accumulations of benthic algae and macrophytes.</u> Extraordinary coastal accumulations of rotting *Spirogyra,* Cyanobacteria, *Cladophora glomerata*, *Elodea,* and other aquatic plants, in which wet biomass sometimes exceeded 90 kg m^{-2}, were detected in 2013–2014 for the first time. These accumulations were located in the splash zone of the north basin (i.e., Tyya–Senogda beach) (ESM video 1), Chivyrkui (Monakhovo Settlement) and Barguzin (Maximikha Bay, sport camp "Rovesnik") Bays, Maloe More (Sakhyurte Settlement and Shide Bay) and the south basin (i.e., Kultuk coast) (Figs 1, 5A–B). Abundant coastal accumulations, mostly consisting of benthic cyanobacteria (*Tolypothrix* spp., etc.) were detected in Barguzin Bay (near Gorevoi Utyos Cape, Fig. 1: site 30) for the first time. The total wet weight of these coastal accumulations of cyanobacteria, occupying about 120 m^2, exceeded 1.2 tons. Light microscopy revealed that *Tolypothrix* spp., similar to that from Bol'shie Koty Bay (Fig. 4E–F), dominated the

biomass of these accumulations. Massive algal accumulations on the coasts are now occurring in the late summer or autumn seasons. However, one of these accumulations (consisting of typical macroalgae for this area) occurred unusually early — in June 2015 near Maloe More Strait (opposite Sakhyurte Settlement, Fig. 1: site 13), also for the first time. Evidently, the seasonal maxima of local algae development are now occurring earlier than before.

5. Mass mortality of snails. Billions of dead mollusks (mostly — representatives of the Lymnaeidae family) and their empty shells were found on the sandy beaches in the north basin between Tyya and Senogda in 2013–2014 (Fig. 6A–B). These "cemeteries" were located near the site influenced by sewage from Severobaikal'sk City and where prolific mats of *Spirogyra* were located. In June, 2015, less abundant accumulations of lymnaeid shells were found along the splash zone in Barguzin Bay off Maximikha Settlement.

6. Sickness and mass mortality of endemic Lubomirskiidae sponges. Several kinds of diseases of Baikalian sponges are occurring lake-wide, and they were first described in 2013–2014 (Bormotov, 2011; Timoshkin et al., 2014). All 3 growth forms of the sponges (branched, encrusting, globular) can be affected (Figs 7A–B, 8A–C; ESM video 2) according to observations made during more than 50 dives in 2014 and 40 in 2015. Depending on the local site, 30 to 100% of branched *Lubomirskia baicalensis* specimens were diseased, damaged, or dead. According to Dr. Ch. Boedecker's (Victoria University, Wellington, New Zealand) personal communication, this situation was confined to a depth of 15–20 m in most of the studied areas within the south basin (September 2014). The deeper living specimens of the branched sponges looked healthy. In June, 2015, however, branched sponges living at deeper depths appeared to be sick. Dr. A.B. Kupchinsky, who dove on October 28–29, 2014 opposite Chernaya River (south of Bol'shie Koty Bay, ca. 350 m from shore; Fig. 1: site 7), noted that 95% of the *Lubomirskia baicalensis* specimens were damaged or diseased at a depth of 5 m, while ca. 80% of the animals observed at depths of 6–14 m looked healthy.

As described earlier, the deterioration of the sponges is accompanied by mass development of epizoic *Phormidium* sp. (Fig. 8C; ESM video 3) (Timoshkin et al., 2014). The mobile filaments are comparatively large (3.8–7.5 μm in diameter), cherry-red, and exhibit slightly curved distal ends. Light-microscopic analysis shows that each infection patch on the particular sponge surface consists of 1–3 cyanobacteria species which dominate numerically by 90–95%. In most cases (50–80%), deformation and damage of the external surface of the sponge (in particular, oscula) happens before colonization and mass development of the cyanobacteria. According to preliminary data, the branched sponges dwelling in the south basin (Listvennichnyi and Bol'shie Koty Bays, off Chernaya River mouth) are most affected by the illness. For example, 100% of *Lubomirskia baicalensis* specimens, dwelling off Chernaya River mouth along our standard bottom transect (1 m x 10 m; at 3–12 m depths; June 2015; ESM video 2) were damaged, sick, or dead. Much less damaged or even healthy *L. baicalensis* specimens were found along the north-western coast (approximately located between Elokhin Cape and Bol'shie Ol'khonskie Vorota Gate). Remarkably, this particular coastal area was free of mass *Spirogyra* blooms in 2014–2015 and interestingly, the water column of this region of the lake exhibited the lowest summer phytoplankton concentrations of any place in the lake according to long-term data analyses of Izmest'eva et al. (2016).

7. <u>The presence of fecal indicator bacteria in the coastal zone.</u> High concentrations of fecal indicator bacteria, exceeding government standards in the USA, Russia and Europe[3] (EPA, 1986; SRSR, 2000; Official Journal of the European Union, 2006), were detected at the end of the tourism season (September, 2014) in many localities, in surface and near-bottom water layers of the coastal zone as well as interstitial waters, especially under coastal algal mats in the splash zone near three settlements. Typical example of fecal indicator bacteria contamination is given in Fig. 9. For instance, water samples, collected near the Khuzhir Settlement exceeded USA government

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[3] No official regulations occur in the above cited documents for the interstitial waters of the beaches and the splash zone.

standards by 3.3 fold (*E. coli*) and 10.7 fold (enterococci), EU standards by 3.1 (*E. coli*) and 6.5 fold (enterococci), and Russian Federation standards by 6 fold (TCB only; enterococci are not regulated). Importantly, the three coastal settlements where the high concentrations of fecal indicator bacteria were found (Fig. 1: sites 4 (Listvyanka Settlement), 16 (Khuzhir Settlement) and 25 (Khakusy Bay, 10 km south of Ayaya Bay)) are each located in a different basin of the lake, and they have comparatively small permanent populaces. However, they are among the most popular sightseeing and recreational destinations at Lake Baikal. Furthermore, private houses and hotels in Listvyanka Settlement (ca. 2,000 permanent residents; ca. 300,000 visitors in 2014) are not equipped with wastewater purification systems. This is also true for Khuzhir Settlement (1,350 permanent residents; 500,000 visitors in 2014), the “capital” of the largest Baikal island (Ol’khon) which is a tourist mecca, and Khakusy Bay (ca. 20 permanent residents; > 1,000 visitors in 2014), a recreational center with hot springs used by residents of cities and settlements in Northern Baikal. These results suggest that intensification of tourism and recreational activities, coupled with inadequate wastewater treatment, are the main causes of fecal bacterial contamination of Lake Baikal’s coastal zone.

8. Organochlorine contamination of the coastal zone. The presence of organochlorine contaminants in the water and within organisms was established using high resolution chromato-mass-spectrometry with isotopic dilution (DFS HR, Agilent 7200 Q-TOF) based on methods 1668 and 1699 of the US Environmental Protection Agency (EPA, 2003). Preliminary analyses suggest the following:

Shallow water macroalgae have bioaccumulated lipophilic organochlorine substances, a process also reported in marine ecosystems (Malmvärn et al., 2008; Lupsor et al., 2009). Concentrations of some organochlorine pesticides (e.g., DDE, nonachlores, toxaphene) in the dried mass of filamentous green *Ulothrix* and *Spirogyra* algae were 1,000–5,000 times higher than in the water. Total concentrations of polybrominated diphenyl ethers (PBDEs) in native *Ulothrix* filaments, collected in all three basins of the lake (n=4), ranged from 0.13–4.4 ng g^{-1} of dry weight, while concentrations in *Spirogyra* filaments did not exceed 0.03 ng g^{-1} (n=3).

Endemic Baikalian sponges (*Lubomirskia* spp.) also bioaccumulated organochlorine pesticides. If we exclude from analysis sponge specimens with extraordinarily high concentrations of organochlorine pesticides and polychlorinated biphenyls (PCB's), the general pattern of contaminant bioaccumulation is compatible with that exhibited by the Baikalian macroalgae. Average concentrations of these organochlorine compounds in the sponges were approximately 9 ng g^{-1} (n=10). Several specimens demonstrated rather high total concentrations of PCB's, ranging from 250 to 1,000 ng g^{-1} of sponge dry weight. Therefore, the influence of organochlorine pesticides should be considered as one of the working hypotheses for explaining their mass mortality.

The concentration and chemical composition of organochlorine contaminants in the sewage of Severobaikal'sk City and the interstitial water of the neighbouring splash zone southwest of the city (i.e., area with the most intense *Spirogyra* bloom (Fig. 1: sites 21–23) and mass snail mortalities (Fig. 6)) differed significantly from that found in other basins of the lake. First, total PCB concentrations in the sewage (i.e., 28,000 pg l^{-1}) were one order of magnitude higher than that in the lacustrine surface waters. Second, pentachlorinated PCBs (such as PCB99, PCB101, PCB105, PCB118) are the typical isomers present in the water of all three basins of Lake Baikal presumably due to global aerosol transmission from remote sources, because they have never been used or synthesized either in the USSR or Russia. However, concentrations of 3- and 4-chlorinated PCBs, with remarkably high concentrations of 6-chlorinated PCBs, that are typical for those in technical liquids (e.g., transformer oils, condenser liquids, etc.), occurred in the sewage and interstitial waters of Severobaikal'sk City. This is evidence of a local source of PCB's. Evidently, it is related to the washing of train cars at depots of the Russian Railways company, which discharge their industrial effluents into the municipal wastewater treatment system of this city. This system was constructed for treating residential wastes only, and it is unable to treat industrial effluents properly.

Fortunately, present concentrations of organochlorine contaminants in the water column of the pelagic zone of Lake Baikal are below international regulatory standards. However, this masks an important problem. Biologists experimentally testing the toxicity of thousands of chemicals extracted from aquatic environments focus on concentrations of separate, individual contaminants. Yet in nature, organisms are exposed to “cocktails of contaminants”, where a mixture of organochlorine compounds, for example, consisting of individual chemicals at low, allowable concentrations, significantly harms aquatic communities (Kortenkamp, 2008; Relyea, 2009; Servan-Schreiber, 2014). Although the synergistic effect of multiple contaminants on fresh water ecosystems is beginning to receive scrutiny, it has never been examined using the unique and potentially sensitive communities of Lake Baikal. Therefore, the discharge of an “organochlorine cocktail” into the littoral zone of Northern Baikal via the failed wastewater treatment plant at Severobaikal’sk City could be dangerous.

CONCLUSION

Multiple severe changes have occurred recently in the coastal benthos of Lake Baikal and some changes, such as the mass proliferation of benthic macroalgae and the presence of toxic cyanobacteria, are strikingly similar to those reported recently in the Laurentian Great Lakes (Higgins et al., 2008; Steffen et al., 2014). In both the Laurentian Great Lakes and in Lake Baikal, these changes are, or have the potential to, impair economic activity and endanger human health. Importantly, the ecological deterioration of the nearshore habitat in Lake Baikal and the Laurentian Great Lakes is occurring while little change is happening offshore (Shimaraev and Domysheva, 2013; Hecky et al., 2004). This underscores the urgent need for coastal as well as pelagic monitoring of large lakes.

The drivers of the current changes in Lake Baikal and those in the Laurentian Great Lakes differ. In the Laurentian Great lakes, current problems in the coastal zone, such as massive blooms of benthic *Cladophora*, are the result of invasive dreissenid mussels redirecting nutrients and energy from the pelagic to the benthic littoral zone (Hecky et al., 2004; Higgins et al., 2008) and increasing water clarity via their filtration activity (Malkin et al., 2008). In contrast, changes at Lake Baikal are not associated with invasive species. Instead, changes at many coastal sites are consistent with nearshore nutrient enrichment from human sewage (Kravtsova et al., 2014; Timoshkin et al., 2014), a situation reminiscent of the cultural eutrophication that occurred in the Laurentian Great Lakes from the late 1950's through the early 1970's. At that time, excessive inputs of phosphorus from sewage and P-containing detergents caused large blooms of *Cladophora* in the benthic coastal zone, but restrictions on point sources of total phosphorus loading largely eliminated these problems beginning in the 1970's and extending through the mid 1990's which is when the invasive dreissenid mussels triggered the reappearance of *Cladophora* blooms (Higgins et al., 2008). Thus, the mitigation of littoral zone eutrophication in the Laurentian Great Lakes during the 1970's through the mid 1990's suggests significant improvement of the near shore problems at Lake Baikal may be achieved by implementing wastewater treatment at multiple sites; however, the many endemic species in this oligotrophic lake's coastal benthos may have unique sensitivities necessitating more stringent controls on nutrient loading than in other freshwater ecosystems. Furthermore, ecological degradation of the nearshore zone at other sites in Lake Baikal may have different or multiple drivers including lake level fluctuations (Zohary and Ostrovsky, 2011), the input of toxic industrial contaminants (e.g., that can cause sponge die-offs) (Mamontov et al., 2000), and, possibly, climate warming (Moore et al., 2009).

Rapid identification of the causes of the severe ecological changes in Lake Baikal and the adoption of an appropriate coastal monitoring program are imperative to protect and preserve this great lake's unique biological wealth, water quality, and economic and cultural values. Study of the ecological changes in Lake Baikal's coastal zone is ongoing and will be presented in subsequent contributions.

Ethics. Sampling was conducted in accordance with national and provincial guidelines and permits.

Authors' contributions. O.A. Timoshkin conceived and designed the study and provided all photos except for those otherwise indicated. O.A. Timoshkin, V.V. Malnik, M.V. Sakirko, V.M. Domysheva, A.G. Lukhnev, O.V. Medvezhonkova, A.V. Nepokrytykh, A.E. Poberezhnaya, N.V. Potapskaya, N.G. Sheveleva, I.V. Tomberg, E.A. Volkova, E.P. Zaytseva, Y.M. Zvereva and A.B. Kupchinsky collected, treated and sorted phyto-, zoobenthic, microbiological, hydrochemical, etc. samples, including diving, and identification of organisms. M. Yamamuro provided the phototechnique and laboratory equipment for underwater investigations and edited the manuscript. O.I. Belykh, I.V. Tikhonova, G.A. Fedorova and A.V. Kuzmin performed the analysis of cyanobacteria, extracted and identified the cyanotoxins. D.P. Samsonov, A.I. Kochetkov and E.M. Pasynkova prepared, treated and analysed the samples for identification of organochlorine contaminants. A.A. Shirokaya prepared all figures with input from O.A. Timoshkin, N.V. Potapskaya and A.V. Nepokrytykh. O.A. Timoshkin wrote the article with major contributions from A.A. Shirokaya, M.V. Moore, V.V. Malnik, M. Yamamuro, E.M. Timoshkina, D.P. Samsonov, A.I. Kochetkov, E.M. Pasynkova and N.A. Bondarenko. All authors discussed the results and gave final approval for publication.

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Figure captions.

Figure 1. The abundance and spatial distribution of *Spirogyra* spp. in late summer–autumn, 2013–2015, and the abundance of algae and higher aquatic plants washed up onshore (pie charts) during the autumn seasons of 2013 and 2014 at Lake Baikal. Sampling sites: 1 — Kultuk Settlement, 2 — old Baikalian railway, 3 — Polovinnyi Cape, 4 — Listvyanka Settlement, 5 — Obuteikha Bay, 6 — Emelyanikha Bay, 7 — Bol'shie Koty Bay, 8 — Sennaya Bay, 9 — Bol'shoe Goloustnoe Settlement, 10 — Peschanaya Bay, 11 — Babushka Bay, 12 — Tutaiski Bay, 13 — Sakhyurte Settlement, 14 — Perevoznaya Bay, 15 — Shide Bay, 16 — Khuzhir Settlement, 17 — Kargante Bay, 18 — Ludar' Cape, 19 — Boguchanskaya Bay, 20 — Onokachanskaya Bay, 21 — Senogda Bay, 22 — Zarechnoe Settlement, 23 — Tyya River mouth, 24 — Nizhneangarsk City, 25 — Ayaya Bay, 26 — Amnundakan Cape, 27 — Davshe Bay, 28 — Maximikha Settlement, 29 — sport camp "Rovesnik", 30 — Gorevoi Utyos Cape, 31 — Babushkin City, 32 — Tankhoi Settlement, 33 — Baikal'sk City, 34 — Slyudyanka Settlement. Abundance of *Spirogyra* spp. under water at depth of 0.5–1.5 m: black circle — > 80–90% coverage of rocky substrate; white circle — small patches (3–10 cm dia.) on rocky substrate; black square — free-floating *Spirogyra* mats (1–30 m in length and 0.1–5.0 m in width, < 50% coverage of substrate) on sand; white square — small patches (3–10 cm dia.) on sandy bottom; diagonally hatched square — free-floating *Spirogyra* clouds (10–30 cm dia., < 50% coverage of substrate) among higher aquatic plants on sandy and/or silty bottoms. The solid black line represents coastal areas where sporadic *Spirogyra* (illustrated in Fig. 3) was detected under water. Pie charts describe the taxonomic composition and quantity of rotting algae and higher aquatic plants detected onshore.

Figure 2A–E. Mass development of *Spirogyra* (> 80–90% coverage of rocky substrate) in the coastal area of Lake Baikal in late September, 2014, at 0.5–1.5 m water depth. **A–B.** Bol'shoe Goloustnoe Settlement (Fig. 1: site 9). **C–E.** Near the Tyya River mouth (Fig. 1: site 23).

Figure 3A–F. Sporadic occurrence of *Spirogyra* in the coastal area of Lake Baikal. **A–B.** Free-floating clouds of *Spirogyra* (10–30 cm dia., < 50% coverage of substrate) among higher aquatic plants on sand. Tutaiski Bay (Fig. 1: site 12), August 15, 2013, 1.5–2 m water depth (frame side length = 33.3 cm, SA = 0.1 m^2). **C–D.** Free-floating mats of *Spirogyra* (1–30 m in length and 0.1–5 m in width, < 50% coverage of substrate) on sand. Near Zarechnoe Settlement (Fig. 1: site 22), June 2015, at 0.5–1.5 m water depth. **E–F.** Small patches (3–10 cm dia.) on sandy (**E**) and rocky (**F**) bottom. Bol'shie Koty Bay (Fig. 1: site 7), late August–early September 2015, 0.5–1.5 m water depth.

Figure 4A–F. Before and after the mass development of benthic cyanobacteria on stones in the shoreline zone of Lake Baikal (upper part of first algal zone), south basin (Bol'shie Koty Bay). **A.** Typical shoreline rocks covered with *Ulothrix zonata* and no cyanobacteria on July 20, 2010 before ecological change in the coastal zone began. **B.** Shoreline boulder showing the cyanobacteria, *Tolypothrix* spp. (reddish-brown flocks), and *Ulothrix zonata* (bright green filaments) on August 30, 2015 after ecological change started. **C–D.** Underwater (ca. 20 cm depth) (**C**) and above-water (**D**) images of *Tolypothrix* spp. flocks. **E–F.** Light microscope images of *Tolypothrix* (cf.) *distorta* filaments, the dominant cyanobacteria in the flocks. Scale bars: B — 3 cm, E — 360 µm, F — 60 µm. Photographs **B–F** were all taken on August 30, 2015.

Figure 5A–B. Large coastal accumulations of rotting aquatic plants. **A.** October 16, 2013, north basin (Senogda Bay). **B.** September 15, 2014, middle basin (Barguzin Bay: sport camp “Rovesnik”, west of Maximikha Settlement).

Figure 6A–B. Gastropod “cemeteries” along the western shore of North Baikal (Senogda Bay, May 29, 2014).

Figure 7A–B. **A.** Main stages of the illness and destruction of the dominant endemic species *Lubomirskia baicalensis* (Porifera) and an example of the mass proliferation of benthic *Tolypothrix* spp. (reddish-brown carpets on the rocks) and epizoic *Phormidium* spp. (dark-brown patches on the sponge branches) in the shallow water zone of South Baikal. September 28, 2014; Bol'shie Koty Bay, opposite the field station of the Limnological Institute SD RAS, 5.1 m depth (photo by S. Ihnken). From right to left: 1 — externally healthy branches with initial stages of the surface destruction, often concentrated near oscula; 2 — mass development of *Phormidium* cyanobacteria on sick sponges (ring-shaped flock); 3 — branches with completely dead areas with numerous *Hydra* spp. polyps attached. **B.** Healthy specimens of *L. baicalensis* from the same place and depth. June 6, 2006 (photo from the scientific archive of O.A. Timoshkin).

Figure 8A–C. A. Encrusting sponge *Baicalospongia* sp. with oscula and other areas covered by epizoic *Phormidium*. September 2014, Northern Baikal (photo by S. Ihnken). **B.** A sick branch of *Lubomirskia baicalensis* with the same foulings. **C.** *Phormidium* sp. filaments from the ring-shaped flock on *L. baicalensis* branch (light microscope image). September 30, 2014; south basin (Sharyzhalgai Cape, 10–11 m water depth) (photo by O.A. Timoshkin). Scale bars: B — 1 cm, C — 20.8 μm.

Figure 9. Counts of fecal indicator bacteria in the coastal zone of Lake Baikal in September, 2014 at three sites taken as an example (1 — Listvyanka Settlement, 2 — Khuzhir Settlement, 3 — Khakusy Bay). Pie diagrams depict counts (CFU 100 ml^{-1}) of colony forming units of bacteria in the interstitial (**A**), surface (**B**) and near-bottom (**C**) water layers (from left to right, respectively) at each sampling site. TCB — thermotolerant coliform bacteria.

ESM video legends, Timoshkin et al.

ESM video 1 (by O.A. Timoshkin). September 2014. Accumulations of rotting algae (97% *Spirogyra* spp.) along the coastline of Northern Lake Baikal, ca. 2 km west of Tyya River mouth. Severobaikal’sk sewage pipe discharges poorly purified waters about 1.5 km upstream from the river mouth (Fig. 1: site 23).

ESM video 2 (by A.B. Kupchinsky). June 28, 2015, standard video transect of sponges off Chernaya River mouth (Fig. 1: site 7). Notice the abundance of damaged and sick *Lubomirskia baicalensis* and *Baicalospongia* spp. (branched and encrusting sponge forms, respectively). Water depth is 15.8 m at the beginning of the videorecording and 3.1 m at the end. Numbers on watch face of diver’s hand: center — safe diving time remaining, minutes; upper left — present depth, m;

upper right — maximum diving depth, m; lower left — water temperature, °C; lower right — dive duration, minutes.

ESM video 3 (by O.A. Timoshkin). Light microscopy video of *Phormidium* (cyanobacteria) filaments which have colonized damaged sponge tissue. *Phormidium* has colonized sick or injured sponges, of both branched and encrusting species, throughout Lake Baikal. Scale bar dimensions defined in Fig. 8C. September 2014, opposite Urbikan Cape (east coast of north basin).

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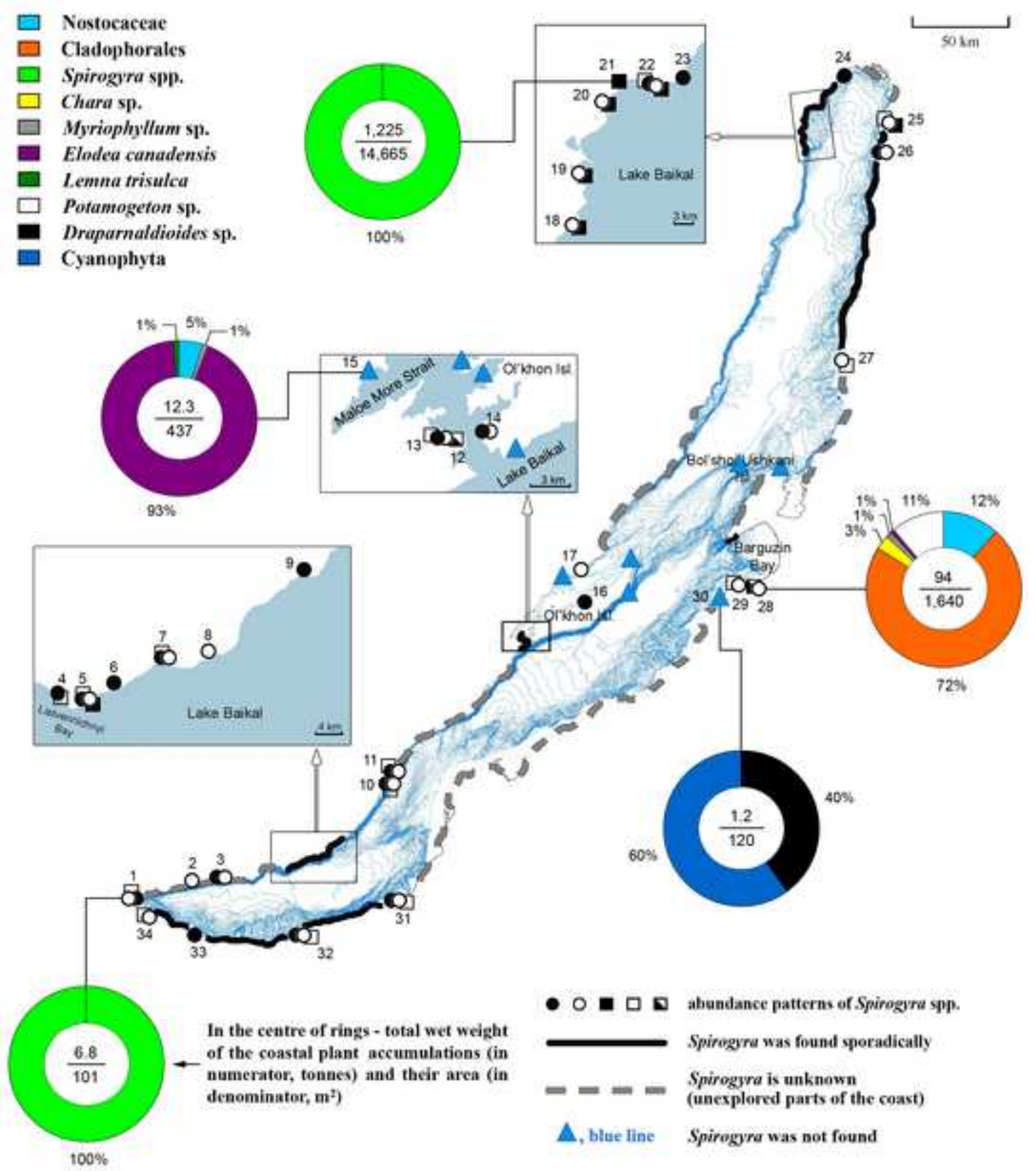
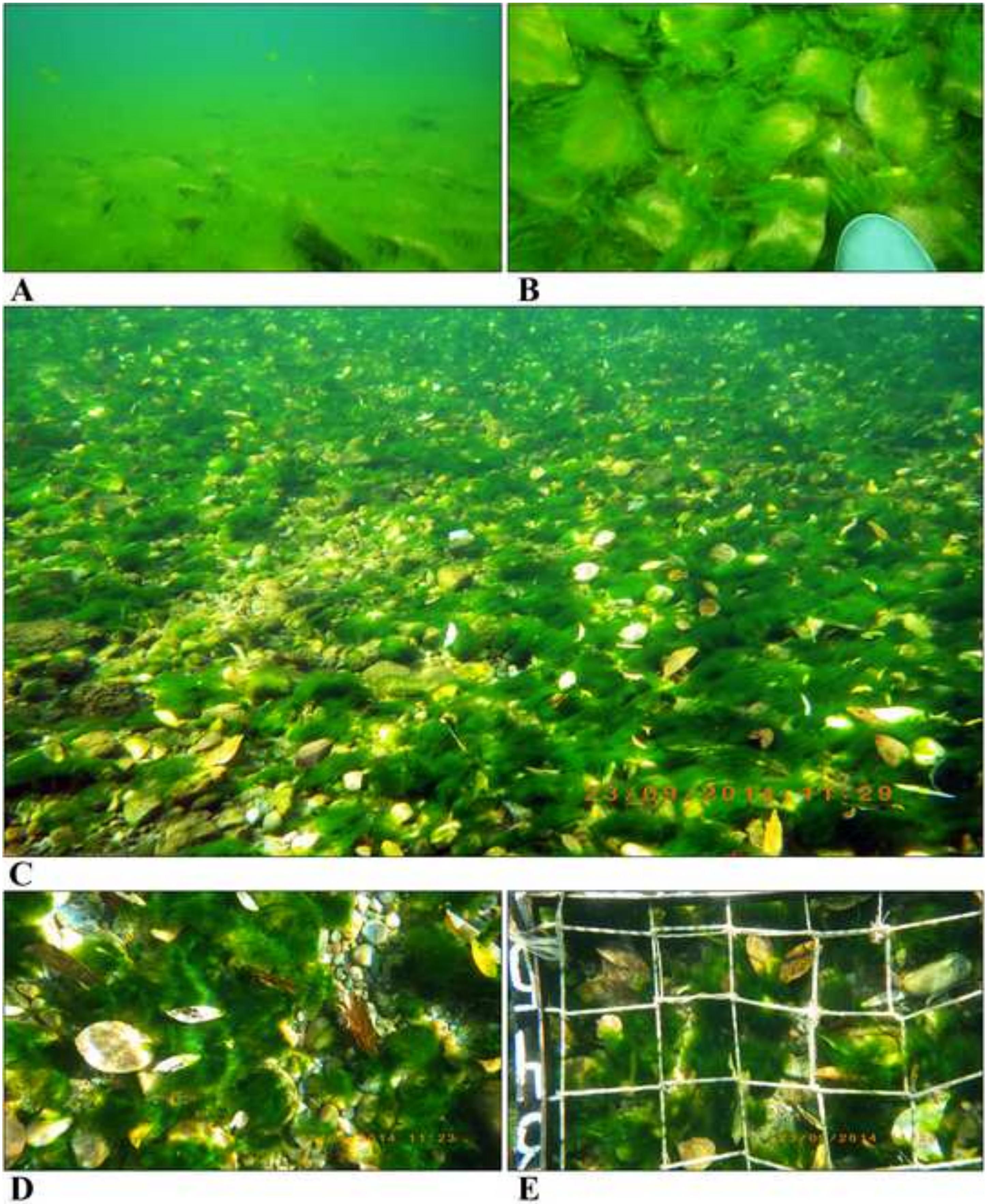
Table 1. Under normal conditions, Lake Baikal exhibits a well-defined zonation of benthic algae. Each of the five zones or belts is usually dominated by 1–2 species, including endemics (Meyer, 1930; Izhboldina, 1990), and zones are most clearly defined during spring through autumn. Zones presented below 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)


Nostocaceae
Cladophorales
Spirogyra spp.
Chara sp.
Myriophyllum sp.
Elodea canadensis
Lemna trisulca
Potamogeton sp.
Draparnaldioides sp.
Cyanophyta
50 km
1,225
14,665
100%
21
22
23
20
19
18
Lake Baikal
3 km
24
25
26
27
1%
5%
1%
12.3
437
93%
15
Maloe More Strait
Ol'khon Isl
13
12
14
Lake Baikal
3 km
Bol'shoi Ushkani
1%
11%
12%
1%
3%
94
1,640
72%
Barguzin Bay
17
16
Ol'khon Isl
30
29
28
9
7
8
6
4
5
Listvenichnyi Bay
Lake Baikal
4 km
11
10
1.2
120
40%
60%
1
2
3
34
33
32
31
6.8
101
100%
In the centre of rings - total wet weight of the coastal plant accumulations (in numerator, tonnes) and their area (in denominator, m²)
abundance patterns of Spirogyra spp.
Spirogyra was found sporadically
Spirogyra is unknown (unexplored parts of the coast)
, blue line
Spirogyra was not found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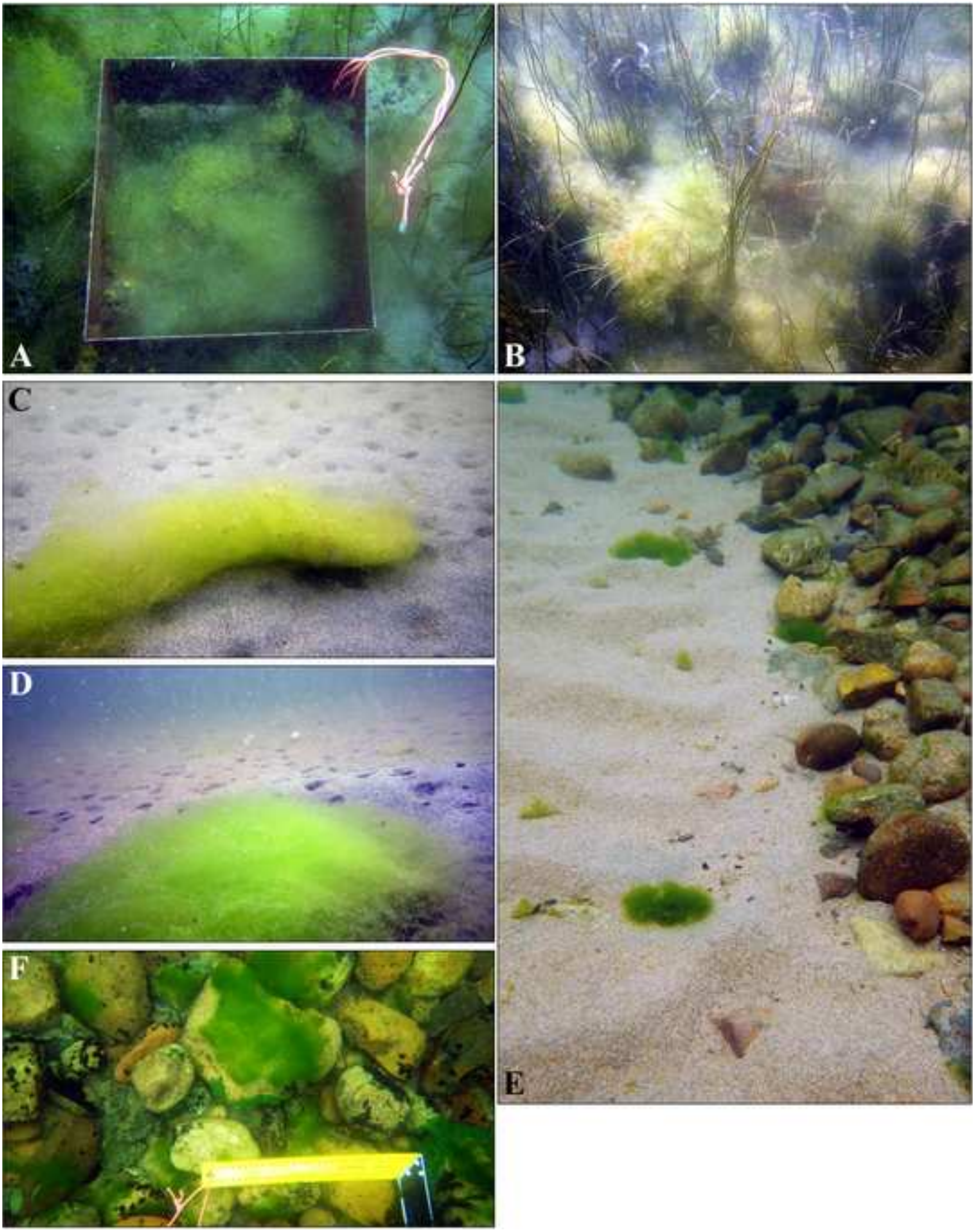
B
23/09/2014 11:29
C
14 11:22
D
09/2014
E

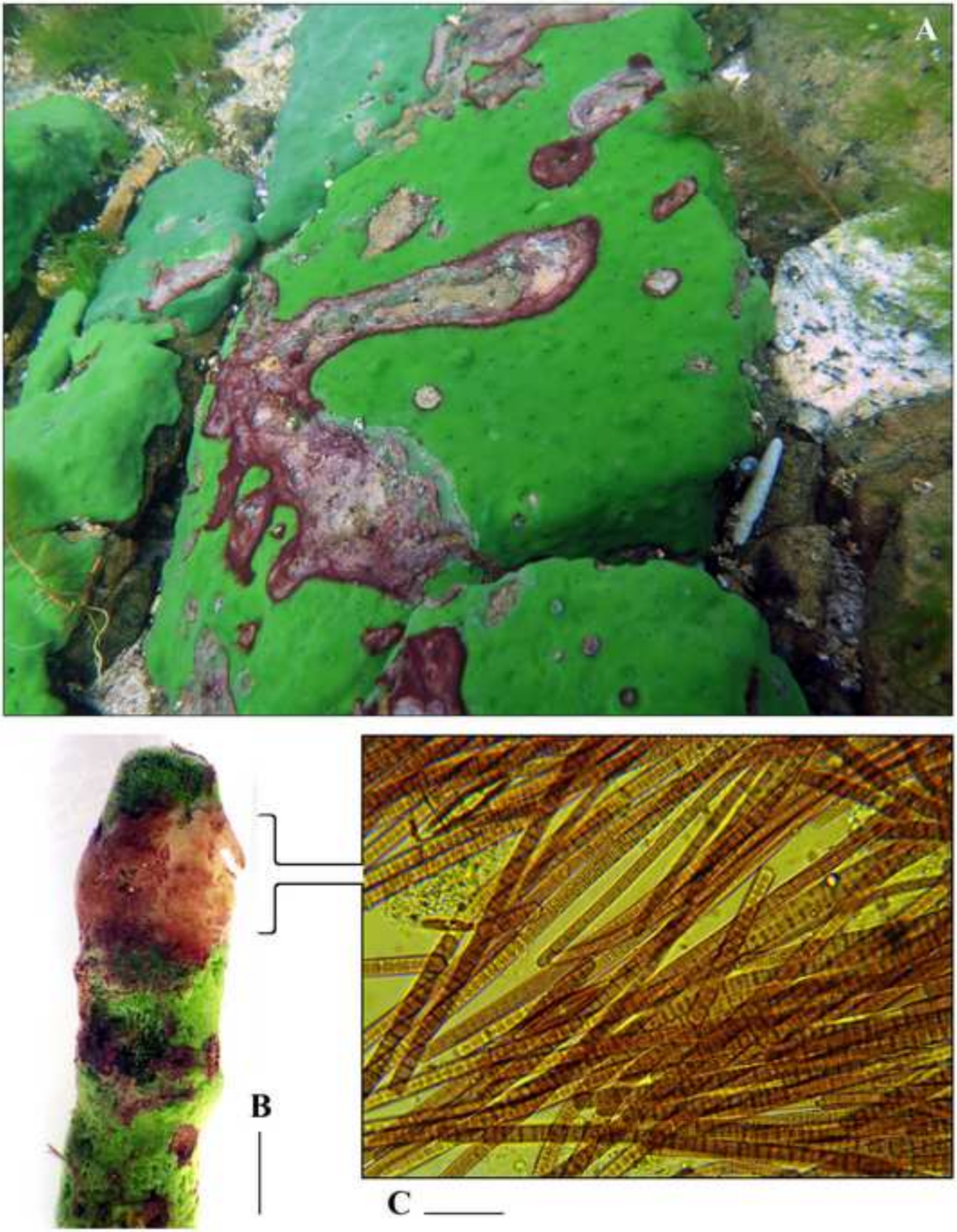

A
B
C
D
E
F

Figure

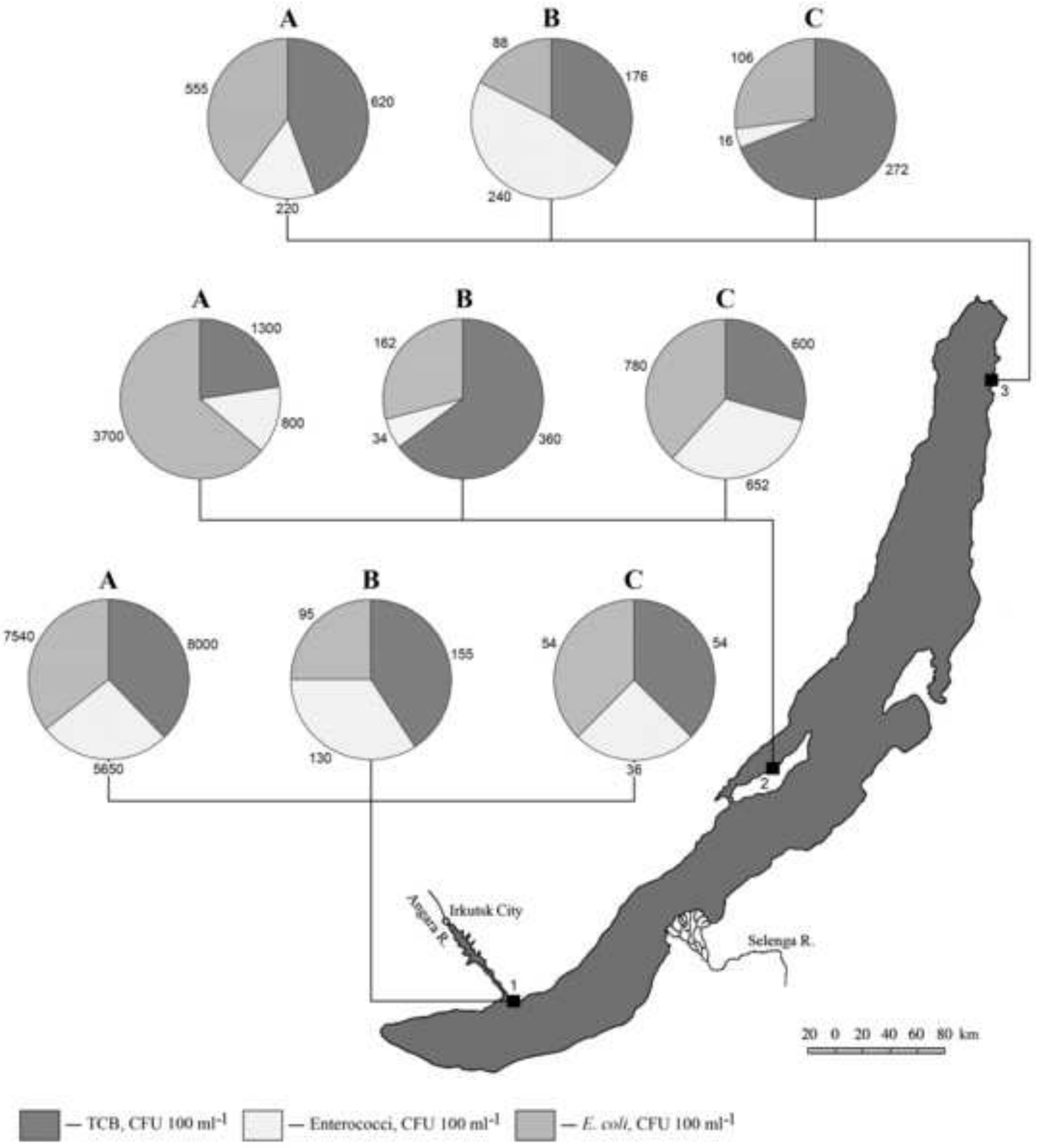

A
B


A
B


A
1
2
3
B


A
B
C

Figure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C
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800
3700
B
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780
600
652
A
7540
8000
5650
B
95
155
130
C
54
54
36
1
2
3
Irkutsk City
Angara R.
Selenga R.
20 0 20 40 60 80 km
— TCB, CFU 100 ml-1
— Enterococci, CFU 100 ml-1
— E. coli, CFU 100 ml-1