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Prediction of Lake Baikal ecosystem behaviour using an ecosystem disturbance model†

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Abstract

This paper combines predictions of the effects of anthropogenic impacts on the plankton of Lake Baikal with models of ecosystem disturbance. Increases in mineralization, non-toxic organic matter, nutrients, phenolic compounds, oil products and heavy metals were simulated. Significantly higher sensitivity of the community below the ice to external influences was demonstrated compared to the summer–autumn community, when there was no ice layer. Models of the distribution of aquatic pollutants demonstrate the occurrence of deviations from ecosystem state parameters in the bottom layer under the influence of pollutant input with precipitation and the distribution of perturbations over greater (up to 500 km) distances. Simulation of pollutant input at present levels shows that Lake Baikal is already perturbed. This is indicated by increases in bacterial and summer phytoplankton biomass and nutrient concentration, and by fluctuations in the zooplankton biomass.

Key words

anthropogenic impact, chemical pollution, disturbance models, ecological prognosis, Lake Baikal.

INTRODUCTION

Lake Baikal has recently become at risk from anthropogenic influence. States of economic activity in the lake region are:

1. Low economic use (e.g. deforestation for pastures, occasional forest fires, traditional agriculture, fisheries).
2. A gradual increase in economic use after the construction of the Irkutsk hydropower station in 1956.
3. Intensification of regional economic activities, following the construction of the Baikalsk Pulp and Paper Combine (BPPC) in 1966, characterized by intensive use of mineral fertilizers, the development of transportation, log rafting, mass tourism, population growth and an increase in coal consumption (Kozhova and Silow 1998a,b; Kozhova *et al*. 1998).

This risk has led to the need for monitoring, analysis and prognosis of Lake Baikal conditions. Mathematical modelling provides one way of achieving this (Joergensen 1997). Because a description of the natural behaviour of ecosystem components is difficult, we chose the method of deviation modelling. In this modelling the natural state of the ecosystem is imagined as 'zero', and deviations from the natural state are seen as decreases (shift to negative values) or increases (shift to positive values) in the concentration of components. A summary of results using this model has been published previously by Silow *et al*. (1995) for short-time experiments (up to 30 days), and by Silow (1999) for longer term experiments (up to one season). Recent work involves the application of a nine-component model with 21 chambers for medium-scale predictions (up to 3 years).

Model description

In the model, the water body of Lake Baikal is subdivided into 21 chambers: 10 surface (0–50 m depth); 10 intermediate (50–250 m depth); and one bottom chamber. This division is based on the characteristic features of the layers. In the surface layers photosynthesis occurs, and the layer is characterized by phyto-, zoo- and bacterioplankton, and is intensively mixed by winds. Water temperature in this layer varies from 0 to 10°C. The 50–250 m layer is barely illuminated, but zoo- and bacterioplankton are present. This layer is mixed mainly by autumn storms. The bottom layer contains bacterioplankton, has a constant temperature of 3.4°C,

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and is completely dark. The model does not include data on benthos as 95% of matter turnover and energy flow takes place in the plankton, fishes and seals and the model is based only on experimental data.

The deviations of components are described by:

$$dZ^i_k/dt = \sum_{j=1}^{N} Q_{ij}Z^i_k + (1/V_k)[\sum_{1\epsilon L}\{P_{lk}Z^i_l - P_{lk}Z^i_k + D_{kL}(Z^i_l - Z^i_k)\}] + U^i_k]$$

where Z(t) is the vector of deviation of parameters, and each Z^i_k represents the deviation of the parameter (component) i in the chamber k; Q is the matrix of the mutual influences of the components, and each Q_{ij} represents the change of the component i per unit of time at the change of component j by the unit of measure; V is the vector of the chamber volumes; P and D are the matrixes of

Table 1. The input of allochthonous substances into Lake Baikal from economic activity

Substance	Tributaries ($t\,year^{-1}$)	Atmospheric precipitation and coasts ($t\,year^{-1}$)	Wastewaters of BPPC
Sulfate	162×10^3	–	64×10^3
Nitrate	23	6	–
Phosphate	0.5	2	–
Organic matter	160×10^3	–	8×10^3
Phenolic compounds	160	40	2
Oil products	10.2×10^3	3.2×10^3	–
Cadmium ions	1.5	–	0.3

BPPC, Baikalsk Pulp and Paper Combine.

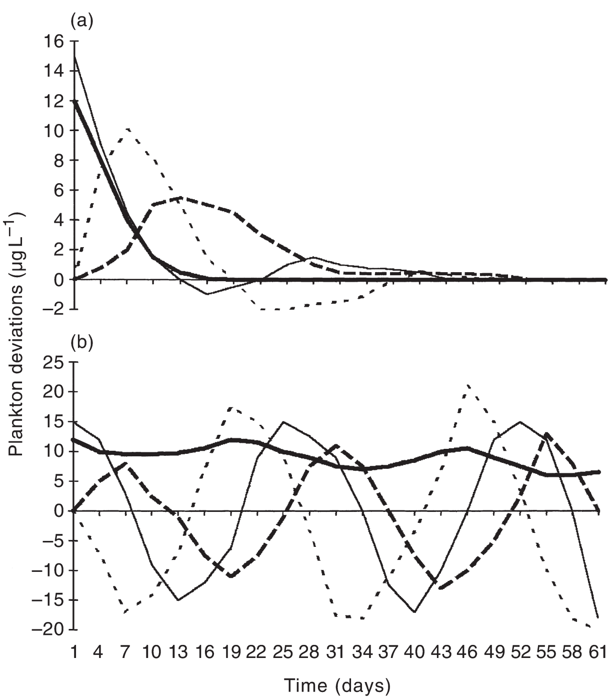

Fig. 1. Aggregated model of some components of plankton deviations under the action of (a) all pollutant inputs (atmospheric precipitation, inflow from tributaries and coasts) in summer and (b) tributaries input below the ice in ice-cover season. (–), Concentration of nutrients; (**–**), phenolic compounds; (– – –), phytoplankton; (**– – –**), zooplankton.

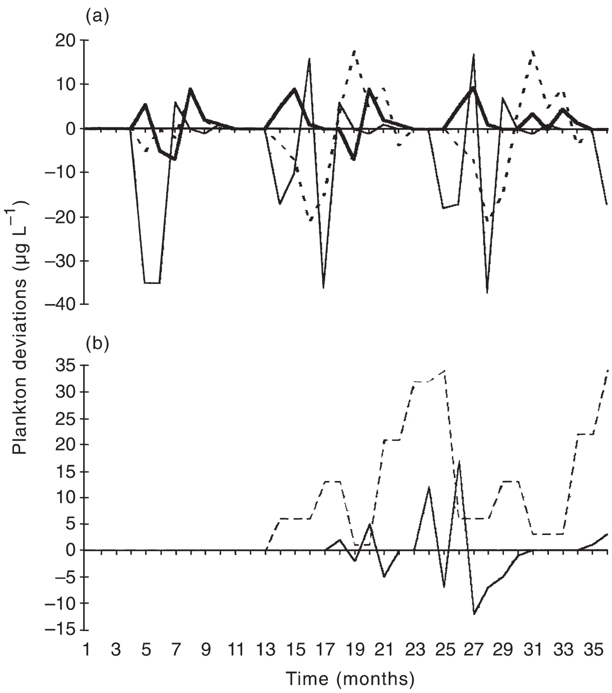

Fig. 2. Box model of some components of plankton deviations with pollutant inflow from atmospheric precipitation in (a) the upper layer and (b) the bottom layer of Lake Baikal. (–), Concentration of nutrients; (- - - -), phytoplankton; (**–**), zooplankton; (– –), bacterioplankton.

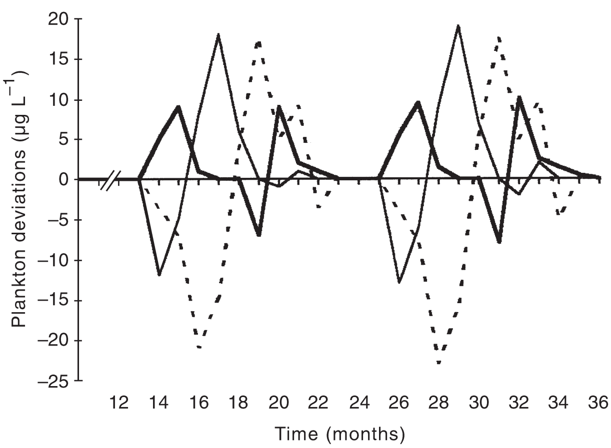

Fig. 3. Box model of deviations of some components of the plankton community in the northern part of Baikal with pollutant input from the main tributary, the Selenga River. (–), Concentration of nutrients; (– –), phytoplankton; (**–**), zooplankton.

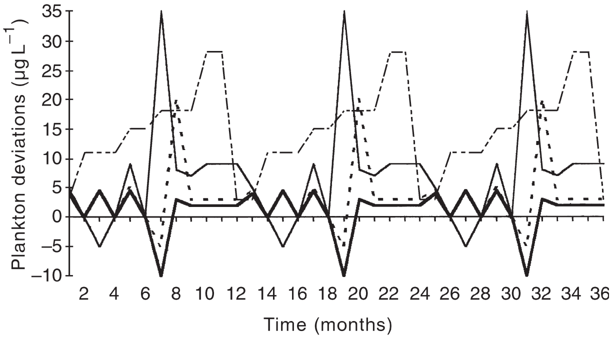

Fig. 4. Box model of deviations of some components of the plankton community in the upper water layer in the northern region of Lake Baikal. The pollutants come from tributaries, precipitation, shores and ice. (–), Concentration of nutrients; (– –), phytoplankton; (▬), zooplankton; (••–••), bacterioplankton.

Table 2. Representation of some parameters of the ecosystem state of Lake Baikal in the form of a linear regression $a + b \times$ (x–time in years), g m^{-3}

Parameter	a	b
Phenolic compounds	6.90×10^{-4}	7.3×10^{-5}
Oil products	7.46×10^{-3}	3.8×10^{-3}
Bacterioplankton biomass	0.21	0.013
Nitrate–nitrogen	0.02	3.8×10^{-6}
Phosphate–phosphorus	0.01	1.3×10^{-3}

turbulence and diffusion, respectively; L is the aggregate of neighbouring chambers; U is the vector of external influences; N is the number of chambers.

The following components were included in the model: bacterio-, phyto- and zooplankton, general mineralization of the water, and concentrations of non-toxic organic matter, nutrients (nitrate and phosphate), phenolic compounds, oil products and heavy metal ions.

There are very few examples of mathematical models based on field ecotoxicological experiments. The present model was developed by using data from experiments with mesocosms (see Silow *et al.* 1995 for details). Increasing mineralization was simulated by adding sodium sulfate, increasing nutrient concentration was simulated by adding sodium nitrate and potassium phosphate, increasing non-toxic organic matter by adding peptone, increasing phenolic compounds by adding 1,2-dehydroxyphenol, increasing oil products by adding diesel fuel and increasing heavy metals by adding cadmium chloride.

RESULTS AND DISCUSSION

Calculations were based on information of pollutant inflows to the lake, as summarized in Table 1 (see Kozhova & Silow 1998a). Calculations involving an aggregated model (Fig. 1) clearly demonstrate higher stability in the summer plankton community compared to the community below the ice, despite higher concentrations of pollutants in summer. Perturbations were introduced daily during the experiment and, in summer, included the pollutant inflow following ice melting (together with pollutant collected on the ice during the ice-cover season), constant inflow from precipitation, tributaries and shores. In winter, perturbation occurred under the ice with inflow from waters of tributaries. The absolute size of deviations is higher under ice. In summer, plankton components returned to their initial state after 30–40 days.

Results are presented for 3-year intervals for experiments performed using a box model. The importance of hydrology is clearly evident. The vertical transport of pollutants is reflected by the following results. In calculation experiments involving atmospheric pollutant inputs, the planktonic components in the upper layer react immediately after the ice melts (Fig. 2a). In the bottom layer, significant deviations of the concentration of bacterioplankton (from the start of the second year) and nutrient concentration (from the second part of the second year) under the influence of pollutants from precipitation are observed (Fig. 2b). With respect to the horizontal transport of pollutants, note that when pollutants are introduced from the main tributary Selenga River, deviations in planktonic components are observed in all chambers, even in the northern region of Baikal (500 km from the mouth of the Selenga River; Fig. 3).

In experiments simulating recent pollutant levels (Fig. 4), all components of the planktonic community (phyto-, zoo- and bacterioplankton) are disturbed. A total increase in nutrient concentration, bacterioplankton concentration and summer phytoplankton biomass also occurs.

These results accord well with time-series analysis for some parameters of the state of plankton in Lake Baikal (Table 2) over the last 20 years. The tendency of summer phytoplankton biomass to increase has been discussed in recent articles (Kozhova 1998; Izmest'eva & Kozhova 1998; Izmest'eva 1999).

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