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Solar and Wastewater Effects on Zooplankton Communities of the Imandra Lake (Kola Peninsula, Russia), 1990 to 2003

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ABSTRACT
Both heliophysical and anthropogenic (wastewater) effects on zooplankton biomass and abundance of the Imandra Lake (the largest subarctic lake at Kola Peninsula, Russia) were investigated during the 1990 - 2003 period. We used different indexes of solar activity (sunspot numbers and UV- radiation values) as heliophysical factors. Information about UV- radiation values was derived from satellite data. As a parameter of anthropogenic pollution we used the information about wastewaters input in Imandra Lake by copper-nickel (Severonikel plant) enterprise and apatite-nepheline industry (AO Apatit). Besides we used the direct measurements of concentrations of the most important pollutants (Al, Ni, Cu) and biogenic components (N and P)in the Imandra Lake. It was shown that the correlation between heliophysical factors and zooplankton biomass and abundance was high and significant (r= 0.7- 0.8), and it was not significant between waste waters input volume and zooplankton productivity. According to the results obtained the main factor influencing zooplankton bioproductivity is solar UV-B radiation due to its damage effects. In addition for middle latitude Krasnoye Lake (Karelia, Russia; 1964 to 1984) and Lake Michigan (USA, 1984 to 1990) data we found nearly the same effect- anti-correlation between UV radiation level and zooplankton bioproductivity, but unfortunately the significance level was not sufficient. However, the effect at middle latitudes was some lower than at high-latitude Imandra Lake. Such discrepancy seemed to be associated with different day duration at high and middle latitudes. Our results seem to prove that solar forcing (mainly UV-B radiation) is significant factor governing zooplankton bioproductivity in subarctic lakes even in such polluted one like Imandra Lake.

Key words: *Imanda lake, solar, wastewater, zooplankton..*

INTRODUCTION

Dependence of zooplankton community on abiotic factors is widely known. The determination of phytoplankton and zooplankton abundance is one of methods to trace long-term changes in lakes on account of their high sensitivity to water quality conditions. Analysis of long-term plankton data sets seems to allow us to reveal man-made and natural perturbations of the lake ecosystems. Moreover, the influence of natural factors (including the solar activity) on zooplankton abundance dynamics in Arctic fresh- water systems had been studied insufficiently, while the main attention had been concentrated on study of influence of anthropogenic pollution.

The Arctic fresh- water systems are most strongly exposed to influence of human activity. The opinion that pollution of lakes by the wastewater inputs is generally accepted as the most dangerous factor for the biota communities (Moiseenko and Yakovlev, 1990; Andronnikova, 1996; Moiseenko, 1999; Vandysh, 2000). At the same time solar ultraviolet radiation, especially in UV- B wavelength band (280- 315 nm) reaching the Earth's surface is known to have damaging effects on plankton organisms (Smith and Baker, 1980; Diffey, 1991; Lubin *et al.*, 1992; Smith *et al.*, 1992).

However, UV- B variability effects on marine phytoplankton were analyzed only on a short time scales (less than one year)

(Smith and Baker, 1980; Smith *et al.*, 1992). In course of these studies a minimum from 6 to 12 percent reduction in primary phytoplankton production associated with ozone depletion was estimated for the duration of the cruise (Smith *et al.*, 1992). Unfortunately, a number of long- term (more than ten years) plankton data sets is available mainly at low and middle latitudes (Makarewicz Lewis and Bertram, 1994; Andronnikova, 1996; Kozhova and Izmestjeva, 1998) and practically absent at high latitudes (Vandysh, 2000).

The Murmansk region seems to be one of the most industrially advanced areas among all Arctic areas. The Imandra Lake is the largest lake at Kola Peninsula and is permanently polluted by the wastewater inputs from surrounding industrial copper-nickel enterprise (Severonikel plant) and apatite-nepheline industry (AO Apatit). Plankton is sensitive to water quality conditions, and thus respond to per-turbations of the lake ecosystem. Spatial and temporal effects of water pollution on plankton communities were studied earlier at the Imandra Lake (Kola Peninsula, North-West Russia) (Moiseenko and Yakovlev, 1990; Moiseenko, 1999; Vandysh, 2000). However, at the same time the role of natural factors in dynamics of zooplankton population is not appreciated enough. Therefore, the goal of this work is to reveal a possible influence of solar factors on zooplankton communities.

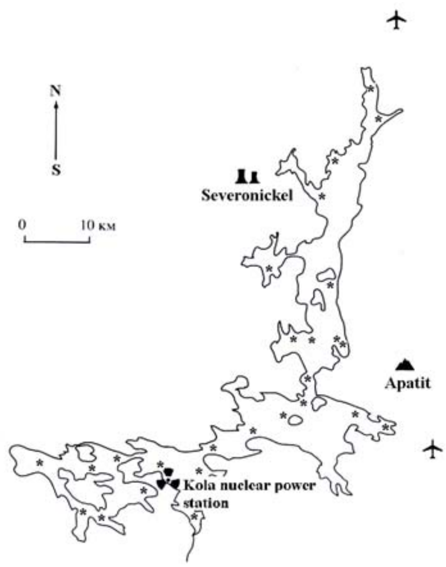

Fig 1. The Imandra Lake sampling stations, 1990-2003

MATERIALS AND METHODS

In this study we used long-term data sets of zooplankton collected by the Institute of the North Industrial Ecology Problems of Kola Science Centre RAS (Apatity, Kola Peninsula). Zooplankton was collected at 26 sites of the Imandra Lake (see Fig. 1) in the spring, summer and autumn from 1990 to 2003. To exclude the influence of seasonal factors only data from the summer are considered here (totally 284 samples). Totally 72 species have been identified in the Imandra Lake (Moiseenko and Yakovlev, 1990; Moiseenko, 1999; Vandysh, 2000). For the period studied, nearly 30 species were investigated from the Rotatoria, Cladocera, Copepoda.

A quantitative collection of zooplankton was made by a 6- liter water sampler from surface to bottom with 1-m intervals distinguishing the layers from surface to 2 m, 2 to 5, 5 to 10, 10 to 15, and 15 m to the bottom), and qualitative sampling was made by the Apshtein qualitative net (4% formalin was used as a fixator). The individual masses of organisms were evaluated using the equation of dependence between the length and the mass of planktonic copepods and rotifers (Ruttner- Kolisko, 1977). The zooplankton data were computerized. All computations and statistical evaluations were conducted using corresponding software (Vandysh, 2000).

Water temperature was measured simultaneously, and all data were corrected for a temperature. Temperature correction was made using Vant Hoff's temperature coefficient (Q_{10}= 2.2). We used also the information about wastewaters input in the Imandra Lake by Apatit and Severonikel plants for the period investigated. The data were obtained from the companies producing the pollution. Besides we analyzed our own measurements of concentrations of the most important pollutants (Al, Cu, Ni) and nutrients (N and P).

The mean, standard deviation (SD) and standard error (SE) values of zooplankton biomass B_t and abundance N_t were calculated for summer seasons. Student t-tests were conducted using a significance level of 5%. Zooplankton time series were compared with solar activity indexes (sunspot number W and MgII) water

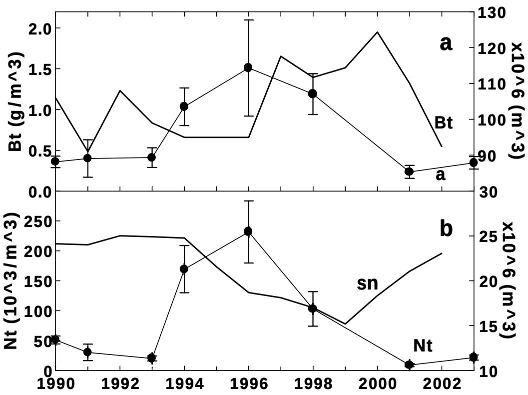

Fig 2. Yearly trends in zooplankton biomass (B_t) and abundance (N_t) (summer data only), and waste water inputs from "Apatit" (a) and "Severonickel" (sn) companies, Imandra Lake (1990-2003). 95% confidence intervals are shown by vertical bars.

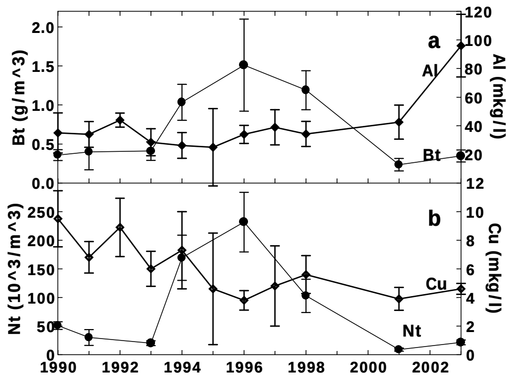

Fig 3. Yearly trends of zooplankton biomass (B_t) and abundance (N_t) (summer data only), and concentrations of Al and Cu, Imandra Lake (1990-2003). 95% confidence intervals are shown by vertical bars.

concentrations of the pollutants (Al, Cu, Ni) and nutrients (N and P) by Pearson correlation statistics (Glantz, 1994).

RESULTS AND DISCUSSION

Imandra Lake is the largest (length 109 km, average width 3.2 km, and water area with islands 880.5 km^2) and most polluted lake at Kola Peninsula. Wastewaters from copper-nickel plant Severonikel, apatite-nepheline industry Apatit, Kola nuclear power station and several other enterprises are discharged into the lake (Fig 1). Since the establishment of the companies (Apatit in 1931 and Severonikel in 1938) Imandra Lake is permanently polluted by their waste water inputs, where the most important pollutants are Ni and Cu(47- 67 and 6- 15µg/l respectively), suspended particles, finely dispersed mineral parts, biogenic elements and oil products. Zooplankton being a part of the lake ecosystem is sensitive to water quality conditions (Moiseenko and Yakovlev, 1990; Moiseenko, 1999; Vandysh, 2000). The increasing anthropogenic impact affects the living conditions of organisms. This causes changes in the species composition, quantitative indices, and the structure of zooplankton populations.

Fig 2 illustrates annual changes of zooplankton numbers N_t and biomass B_t, and as well waste water inputs from Apatit (a) and Severonickel (sn) companies. A considerable rise of zooplankton biomass and abundance occurred since 1994 with a maximal value in 1996 (more than 200%) and subsequent decrease (Fig 2). It is clearly seen that these changes in abundance and biomass do not appear to be connected to variations of waste water inputs. For example, increase in B and N occurred in 1994 while waste water input level was held approximately constant and began to decrease only in 1995 according to Severonickel data. As it is shown in Fig 2, over the three-year period (1994-1996), the lake-wide averaged summer zooplankton abundance ranged from 20 to 232 (x10^3) spec/m^3 and the zooplankton biomass ranged from 0.411 to 1.51 g/m^3. After 1996 B and N began to decrease and reached their previous level in 2000. However, taking into account that official data on wastewater input to Imandra Lake were obtained from the companies producing the pollution, we used our own data on the main pollutants and nutrients (Al, Ni, Cu, P, N). In Fig 3 are shown long-term changes in N_t and B_t together with Al and Cu concentration variations in the Imandra Lake. The important factor for zooplankton growth is availability of food (phytoplankton). Phytoplankton depends on nutrients such as N and P. Fig 4 shows variation of N_t and B_t in comparison with changes in water concentrations of nutrients (N and P) for the period considered. It should be noted that the correlation coefficients between all above mentioned water components and zooplankton parameters are rather low ($r \leq 0.35$) and insignificant. The lack of significance is related to the low number of data sets.

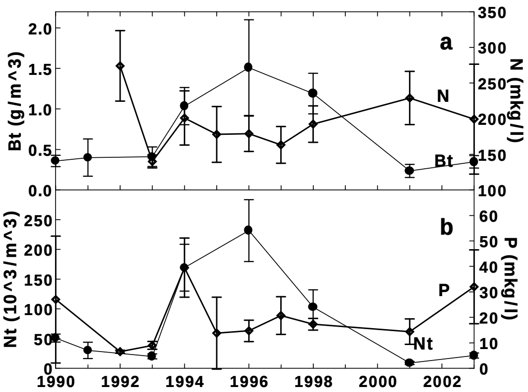

Fig 4. Yearly trends of zooplankton biomass (B_t) and abundance (N_t) (summer data only), and concentrations of N and P, Imandra Lake (1990-2003). 95% confidence intervals are shown by vertical bars.

However in moderately polluted zones variations of zooplankton biomass and abundance not always can be interpreted in terms of water chemical content changes. Moreover, it should be noted that sublethal pollution reduces organism resistance and raises their sensitivity to other factor action.

Such variations in zooplankton biomass and abundance of the Imandra Lake observed in 1994-1996 may have other reasons, and it is necessary to consider natural factor influences on plankton community. Some studies have shown that enhanced levels of solar ultraviolet (UV) radiation may have damaging effects on marine (Smith and Baker, 1980; Smith 1989; Smith *et al.* 1992; Diffey, 1991; Hader *et al.*, 1998; Dattilo *et al.*, 2005) and freshwater (Kim and Watanabe, 1994; Halac *et al.*, 1997; Williamson, 1995; 1996) zooplankton communities. Note, that the UV radiation is subdivided into several spectral regions: UV-A (315– 400 nm) radiation; UV-B (280– 315 nm); and UV- C (200- 280 nm) (Diffey, 1991). Laboratory studies have supported findings that marine zooplankton are extremely sensitive to UV- B radiation (Dattilo *et al.*, 2005).

It is generally accepted that none of the solar UV radiation below 280- 290 nm reaches the Earth's surface (Diffey, 1991; Rottman, 1999; Madronich *et al.*, 1998; Floyd *et al.*, 2005). The quantity of UV radiation at the Earth's surface depends on the energy output from the Sun and the transmission properties of the atmosphere (ozone, clouds, air pollution). The most important variables influencing the Earth's radiation budget are ozone and cloudiness. Variations of solar (SCR) and galactic (GCR) cosmic rays appeared to be one of the main factors influencing the ozone layer, aerosols and cloudiness, especially at high latitudes (Shumilov *et al.*, 1995; 1996; Svensmark and Friis-Christensen, 1997; Veretenko and Pudovkin, 1997; Palle and Bago, 2000; Carslaw *et al.*, 2003; Kasatkina and Shumilov, 2005). On account of this, UV- B radiation reaching the Earth's surface appeared to be modulated by cosmic ray variation. There are some evidences that solar radiation reaching the surface experiences significant changes over the 11- year solar cycle (Veretenko and Pudovkin, 1997; Madronich *et al.*, 1998).

Biologically effective wavelengths in the UV- B range are absorbed efficiently by stratospheric ozone (O_3). Observations confirmed that reduced stratospheric O_3 results in increased flux of UV- B radiation and reduced phytoplankton productivity (Smith and Baker, 1980; Smith, 1989; Smith *et al.*, 1992). Unfortunately, all these studies were dealing with short-term (not more than one season) UV-B variations. It would be interesting to search for damaging UV-B effects on long-term zooplankton data sets taking into account the cycle variation of UV-B radiation. As it is known the total solar irradiance (TSI) varies by about 0.1% over the 11-year solar cycle and large changes (more than 10%) occur at shorter UV wavelengths (Lean *et al.*, 1997; Rottman, 1999; Tsioropula, 2005).

Shown in Fig 5 are long-term changes in total zooplankton numbers (N_t) and biomass (B_t) in the Imandra Lake, sunspot number (W), MgII solar activity index, and water temperature. The MgII index was first developed from Nimbus-7 SBUV irradiance data by Heath and Schlesinger (1986) and used as a proxy of solar UV-radiation (Rottman, 1999). All time series demonstrate similar behaviour. Zooplankton biomass and abundance show a clear anti-correlation with the 11-year solar activity cycle. The highest anti-correlation is between MgII and zooplankton abundance N ($r = -0.768$ $P< 0.1$). Whereas correlation coefficient between zooplankton biomass B and waste water input level from "Severonickel" (sn) is lower ($r = -0.62$) and insignificant. The low

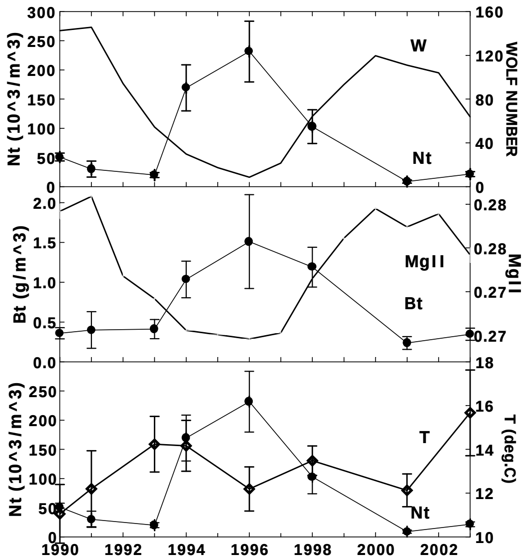

Fig 5. Yearly trends of zooplankton biomass (B_t) and abundance (N_t), and water temperature T (summer data only), Imandra Lake, MgII solar activity index, sunspot number W (1990-2003). 95% confidence intervals are shown by vertical bars.

relationship between variations in zooplankton parameters and water concentrations of main pollutants appears to be due to the parallel eutrophication, that develops because of high concentrations of biogenic elements (N and P), which input with wastewater and lower the toxicity of heavy and other metals (Moiseenko, 1999; Vandysh, 2000).

As it was mentioned above solar UV-radiation seemed to be one of the main factors influencing long-term changes in zooplankton. In this case GCR variations may affect zooplankton biomass and abundance indirectly, through cloudiness variation and modulation of UV- B reaching the Earth's surface.

As for middle latitude lakes Krasnoye (Karelia, Russia) (1964-1984) (Andronnikova *et al.*, 1996) and Lake Michigan (USA) (1983-1992) (Makarewicz Lewis and Bertram, 1994) data nearly similar trend was observed (some increase of zooplankton biomass and abundance during solar cycle minimum. However, no significant correlation between UV-radiation changes and zooplankton bioproductivity was found. This relationship is weak if ever occurs, as it is clearly seen from Fig. 6., where long-term (1964-1984) changes in zooplankton biomass and number in Lake Krasnoye and sunspot number variations are shown. This latitudinal distinction may be associated with different day lengths at high and middle latitudes, since some processes to repair UV-damaged molecules occur in the dark (Diffey, 1991; Lubin *et al.*, 1992). In addition, long-term and ozone-related short-term changes in UV radiation reaching the surface are most significant at high latitudes (Shumilov *et al.*, 1995; Hader *et al.*, 1998; Madronich *et al.*, 1998).

CONCLUSIONS

We have used long-term (1990- 2003) zooplankton data sets to determine solar activity and human-made effects on the Imandra Lake ecosystem. Our results seemed to demonstrate that solar forcing (mainly UV- B radiation) is an important additional (or may be sometimes dominant) factor that may act in combination with other human-made stresses that influence the zooplankton productivity in Arctic lakes, even in a such polluted lake as Imandra Lake. The influence of solar activity variation has to be taken into account during interpretation of results obtained in course of the study of production processes in fresh water ecosystems.

Results obtained are of particular concern for polar ecosystems where ozone- related UV changes are the greatest.

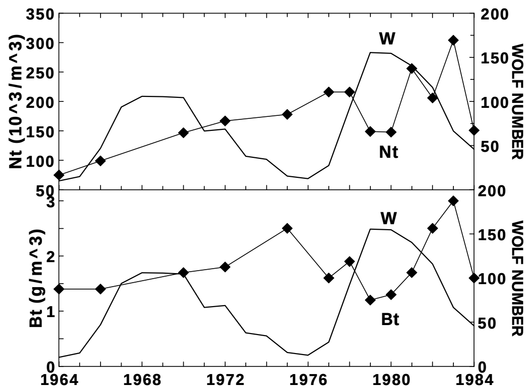

Fig. 6. Yearly trends of zooplankton biomass (B_t) and abundance (N_t), Krasnoye Lake (1964-1984) (summer data only), and sunspot number (W).

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