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THE RESPONSE OF LAKE DUROWSKIE ECOSYSTEM TO RESTORATION MEASURES

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Abstract. The Durowskie Lake situated in Wągrowiec (Poland) is the postglacial lake, used for recreation and sport fishing activities. Its surface is 143.7 ha and the maximum depth is 14.6 m. Few years ago it was strongly eutrophic with cyanobacterial water blooms. Restoration measures started in 2009 using three methods: oxygenation of hypolimnetic waters using wind aerators, phosphorus immobilization using iron treatment and biomanipulation measures – stocking the lake with pike fingerlings. The results of restoration measures were monitored during International Summer Schools, organized in July, as well as once every month during growing season, in years 2009-2011. Physico-chemical variables were measured and biological analyses were done every year with the same methods, making possible the evaluation of water quality and organism's composition changes during that time. The results of studies and evaluation of ecological state due to guidelines of Water Framework Directive indicated progressive improvement of water quality and ecological state of Lake Durowskie. The quickest improvement referred to physico-chemical variables of water quality, but they were highly variable during the seasons. Also phytoplankton changed quickly its composition and abundance, however, macrophytes and macroinvertebrates require longer time for reconstruction of their communities.

Key words: lake restoration, iron treatment, biomanipulation, phytoplankton, transparency, macrophytes, macroinvertebrates

1. INTRODUCTION

The Durowskie Lake is a postglacial lake, elongated in shape and situated in the direction northward-southward in the Wielkopolska Region (central Poland). Its coordinates are N 52°49'6" and E 17°12'1". Struga Gołaniecka River flows through the lake, supplying it with nutrients from the catchment area. Five other lakes situated on the river course above the Durowskie Lake are strongly eutrophicated, with cyanobacterial water blooms. The river catchment area is typically agricultural. Forests cover only 19% of its surface. Nevertheless, the Lake Durowskie is surrounded by forest from the north, but the town Wągrowiec is adjacent to the southern part of the lake. Its surface is 143.7 ha and the maximum depth is 14.6 m. It is used for recreation and sport fishing activities. Few years ago it was strongly eutrophic with cyanobacterial water blooms. To improve the lake water quality and restore ecosystem services, the local Authority decided to start restoration measures in 2009, using three methods: oxygenation of hypolimnetic waters using wind aerators, phosphorus immobilization using iron treatment, and biomanipulation measures – stocking the lake with pike fingerlings. The results of restoration measures were monitored during International Summer Schools, organized in July during three consecutive years.

The main aim of the study was to determine the ecological state of the lake according to the requirements of the Water Framework Directive, taking into account not only the physico-chemical variables of water quality and the chlorophyll-*a*, but also the qualitative composition and abundance of phytoplankton, macrophytes and benthic macroinvertebrates.

2. MATERIALS AND METHODS

The basic physico-chemical parameters of the water (temperature, conductivity, concentration of oxygen and water saturation with oxygen as well as the pH level) were directly measured near the two aerators in depth profile with the use of YSI multiparameter water quality probe during the summer periods of 2009-2011. Water samples were also taken for the analyses of nitrogen, phosphorus and chlorophyll-*a* content, from the epi-, meta and hypolimnion. They were spectrophotometrically analyzed with the use of ISO Standards (Elbanowska et al., 1999).

Phytoplankton samples were taken from the same stations near the surface (depth of 1m). The results of every single year were based on the data of 6 sampling periods. The samples for taxonomical analyses of algae were concentrated with use of plankton net (#10μm). Phytoplankton for the quantitative analyses were concentrated from the samples preserved with Lugol solution, from the volume of 1 l to 20 ml. Algae were counted using a chamber of 0.4 mm height and 22mm diameter. Biomass of phytoplankton was estimated from cell numbers and specific volumes (Rott 1981). The dominating phytoplankton species are defined as those which exceeded 10% of the total biomass. The species biodiversity index was calculated according to Shannon-Weaver (Pielou 1975, Kawecka & Eloranta 1994).

Submerged and emergent macrophytes were evaluated every summer. Patches of every association were classified using Brown-Blanquet phytosociological method (Matuszkiewicz 2001). Estimation of the shape of association's patches was done using Global Positioning System (GPS) positioning method, during boat inspections. Submerged vegetation was checked using the anchor. Data from the field research were transferred to the GIS program Mapinfo in which maps of plant associations were prepared and surface of every association measured.

Macroinvertebrates in Lake Durowskie were sampled at 14 stations divided into 3 different categories. Six of the sampling stations were situated in the profound zone (numbers 3, 5, 7, 9, 10 and 14), five in the littoral zone near the forest (no. 1, 6, 8, 11 and 13) and three in the littoral zone near the urban area (no. 2, 4 and 12). Two different core samplers were used for sediment sampling. The first one called 'Czapla' was used at the shallow stations in the littoral zone. Its diameter was 5.7 cm, so 17 samples were taken from each station. The second sampler called 'Kajak' with diameter of 7 cm was used for deeper parts of the lake and 10 samples were taken from each of these stations. Samples were washed on the sieve with mesh size of 0.4 mm and then were kept in plastic boxes filled with water. Organisms were separated from the sediments, dried, weighted and preserved with alcohol (70%) except of *Oligochaeta*, which were preserved with formaldehyde (4%). Number of individuals and biomass of organisms were calculated per square meter.

3. RESULTS AND DISCUSSION

Oxygen content in the metalimnion clearly increased from zero up to ca. 1 mg O_2 l^{-1} in subsequent years, especially at station I (Fig. 1). Changes in the epi- and hypolimnion oxygenation were not so distinct. In the upper water layer, oxygen saturation was over 100% due to oxygen supply realized by the phytoplankton. Near the bottom sediments there was oxygen depletion during the summer stratification period as a result of microbial oxygen demand. Water transparency clearly increased from 1m in 2009, to 1.5m in 2010 and up to about 2m in 2011 (Fig. 2). Water transparency was usually higher at station II than at station I. Mean chlorophyll-*a* values decreased during that time from above 50 μg l^{-1} in 2009 to 9 μg l^{-1} in 2010, and slightly increased in 2011 – up to 14 μg l^{-1}. It was connected with strong changes in phytoplankton composition, abundance and biomass.

Cyanobacteria domination in the phytoplankton of Lake Durowskie finished in 2010, despite their continuous inflow to the lake with water flowing from the upper lakes situated on the Struga Gołaniecka River (Stefaniak et al., 2005). The progressive reconstruction of phytoplankton community was noted (Fig. 3). In 2009, despite of Cyanobacteria domination (Fig. 4, Table 1), the dinophytes were subdominants (mainly *Ceratium hirundinella*). In 2010 phytoplankton was dominated by diatoms and dinophytes (mainly *Fragilaria ulna*, *F. ulna* var. *angustissima*, *Peridiniopsis cuningtonii* and *P. berolinense*). In 2011 chrysophytes were also very popular (*Dinobryon divergens*). Reconstruction of phytoplankton composition was towards the big species, not grazed by crustaceans, which number increased due to the biomanipulation measures. Lower primary production of phytoplankton in subsequent years led to decrease of fresh organic matter content in the bottom sediments and lower oxygen demand for its mineralization. However, it still not resulted in the increase of oxygen content in the hypolimnion, despite the use of two wind aerators. This means that the microbial demand for oxygen at the sediment-water interface was still higher than the supply of the aerators. Nevertheless, a decrease of the intensity of these processes provided an increase in the amount of oxygen in the metalimnion of the lake. This is a reversal of processes observed during the eutrophication, when loss of oxygen was progressing from the bottom sediments up to the metalimnion and in hypertrophic lakes even up to the lower part of epilimnion (Gołdyn et al., 2010).

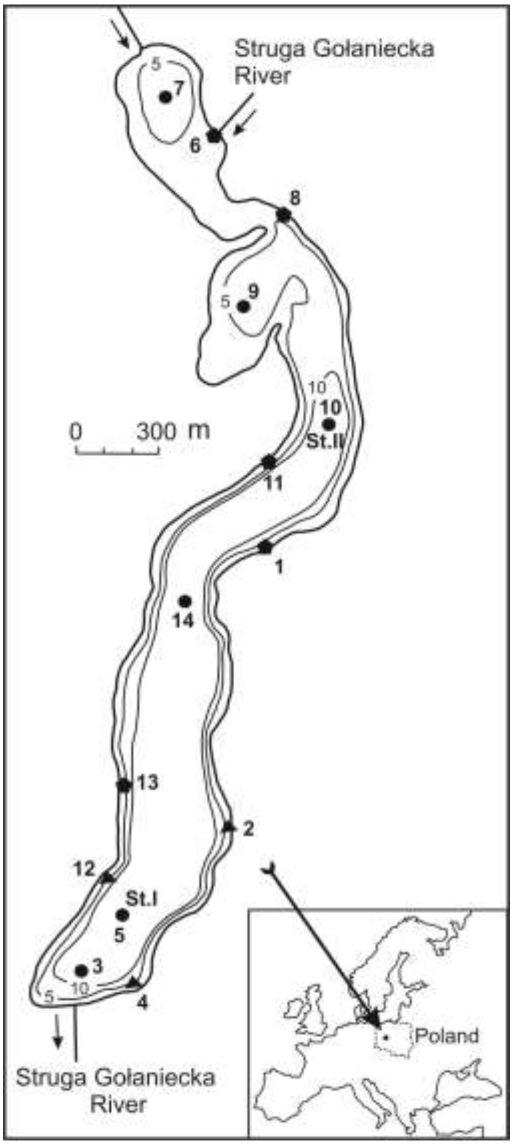

Figure 1. Map of Lake Durowskie with sampling stations for physico-chemical and planktonic analyses (St. I and St. II), as well as for macroinvertebrates in the profound zone (circles no 3, 5, 7, 9, 10 and 14), in the littoral zone adjacent to the forests (diamonds no 1, 6, 8, 11 and 13) and adjacent to the urban area (triangles no 2, 4 and 12).

Emergent macrophytes (helophytes) formed a belt along the shoreline, up to the depth of 1.5m. Its width was variable, depending on the slope of the bottom, ranging from a few to several tens of meters. Their total area decreased in the second year of restoration (2010) and increased again in the third year (2011) (Table 2).

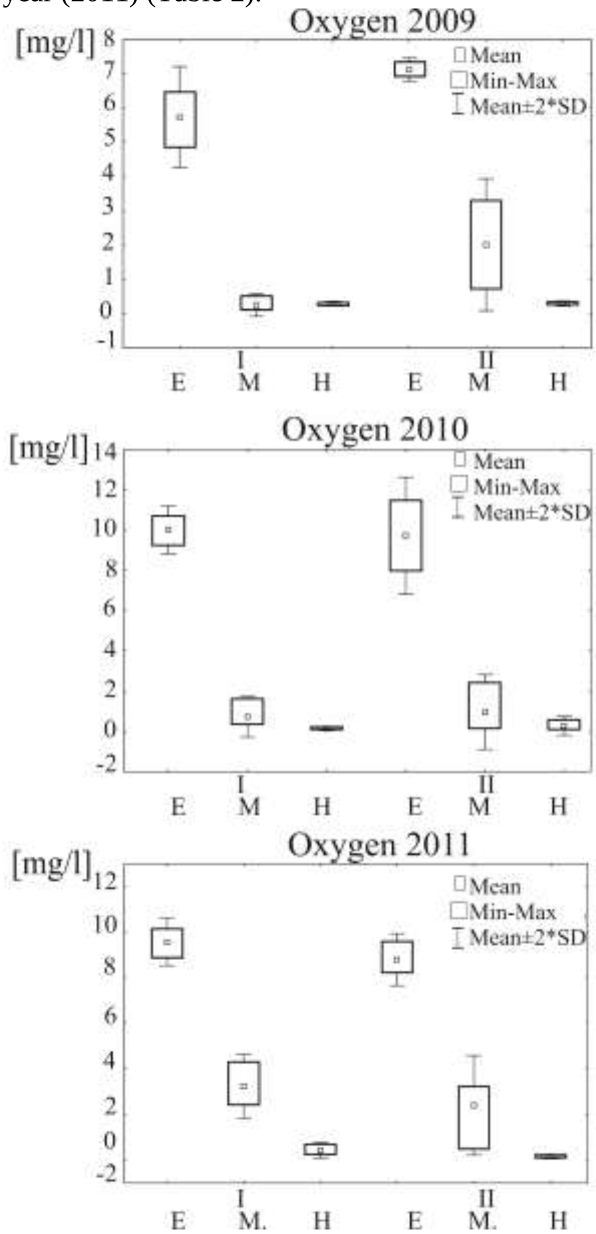

Figure 2. The concentration of oxygen in particular zones of the water column in Lake Durowskie (I – station I, II – station II, EPI – epilimnion, META – metalimnion, HYPO – hypolimnion; n=6).

It was dominated by two plant associations *Phragmitetum communis* (W. Koch) Schmale and *Typhetum angustifoliae* Soó ex Pignatti. Hydromacrophytes with floating leaves (nymphaeids) formed patches close to the helophytes, at the water depth ca. 1.0-2.5m. Their total area increased over twice in the second year of restoration and slightly decreased in the next year (Table 2). Nymphaeids were only dominated by one association *Nupharo-Nymphaeetum albae* Tomaszewicz which, in most cases, only consisted of species *Nuphar lutea* (L.) Sm.

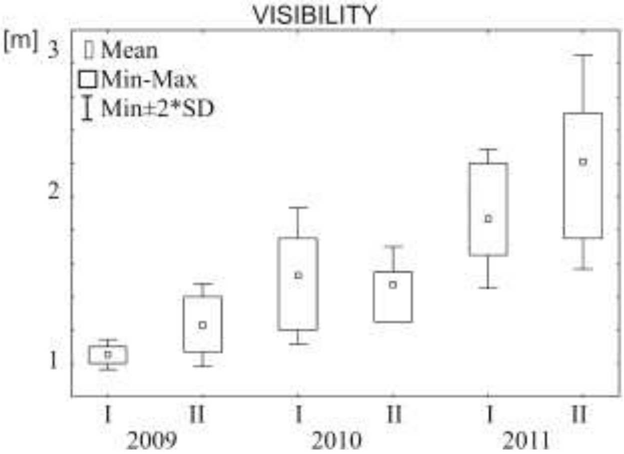

Figure 3. Changes of the water transparency in particular years in Lake Durowskie (I – station I, II – station II; n=6).

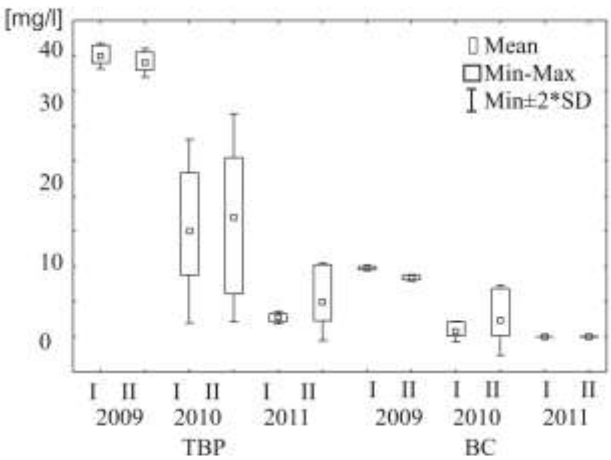

Figure 4. Changes of the concentration of total phytoplankton biomass and cyanobacteria biomass in Lake Durowskie in 2009-2011 (I – station I, II – station II, TBP - total biomass of phytoplankton, BC - biomass of Cyanobacteria; n=6).

Submerged macrophytes increased their surface from 185m^2 in 2009 up to 2550m^2 in 2011. However, this still is 0.18% of the total surface of the lake only. The association *Ceratophylletum demersi* Hild, which is an indicator of the bed ecological state, disappeared from the lake and *Potametum perfoliati* (W. Koch) Pass. spread in many parts of the littoral zone. Submerged macrophytes influenced the ecosystem by stabilizing the bottom sediments, creating refugees for macroinvertebrates, zooplankton and fish and accumulating nutrients in their tissues (Kuczyńska-Kippen et al., 2009).

Increased water transparency, due to restoration measures, improved the conditions for enhancement of submerged macrophytes growth since light climate is generally recognized as a key factor regulating their growth and distribution in eutrophic waters (Van Dijk & Van Donk 1991; Celewicz-Gołdyn 2010). However, changing light conditions caused delayed development of macrophytes in relation to the quick changes observed in phytoplankton (Søndergaard et al., 2007). Other reasons of delayed development of macrophytes are grazing by waterfowl or fish, lack of seeds and other propagules in the bottom sediments as well as unsuitable habitats (Bakker et al., 2013). One of the reasons may also be the slow decrease in the concentration of nutrients in the littoral zone sediments (Melzer 1999).

Table 1. Dominating taxa of phytoplankton of the studied Lake Durowskie water in 2009-2011.

2009	2010	2011
Limnothrix redekei (Van Goor) Meffert *Planktothrix agardhii* (D.C. ex Gom.) Anagn. et Kom. *Ceratium hirundinella* (F. B. Müller) Bergh *Peridiniopsis cunningtonii* Lemm. *Peridiniopsis elpatiewskyi* (Ostenf.) Bour. *Fragilaria ulna* (Nitzsch) Lange-Bertalot	*Fragilaria ulna* (Nitzsch) Lange-Bertalot *Fragilaria ulna* var. *angustissima* Sippen *Peridiniopsis cunningtonii* Lemm. *Peridiniopsis berolinense* (Lemm.) Bour. *Ceratium hirundinella* (F. B. Müller) Bergh	*Ceratium hirundinella* (F. B. Müller) Bergh *Peridiniopsis cunningtonii* Lemm. *Asterionella formosa* Hass *Fragilaria crotonensis* Kitton *Dinobryon divergens* Imhoff

Table 2. Area (in m^2) covered by macrophytes in Lake Durowskie in the years 2009-2011.

Type of vegetation	2009	2010	2011
Helophytes	78401	53918	62900
Nymphaeids	1048	2301	1872
Submerged macrophytes	185	2507	2550

Biodiversity of benthic macroinvertebrates had a growing trend all the years studied and was the highest in 2011. In 2009, 15 taxa occurred, in 2010 there were found 19 taxa, and in 2011 up to 26. In 2011, as many as 4 species of mussels (Bivalvia) were stated: *Anodonta anatina* (L.), *A. cygnea* (L.), *Unio pictorum* (L.) and *U. tumidus* Phil. These organisms, as filtrators, contributed to the efficient improvement of water quality.

The highest number of benthic organisms in 2011 was found at station 13 – 6279 specimens m^{-2}, mainly due to the presence of the invasive New

Zealand mudsnail *Potamopyrgus antipodarum* (Gray) and of chironomids (Chironomidae, Diptera). In Poland this mudsnail was first noted in 1933 and since then a rapid expansion into various freshwater habitats has been observed. In some places it occurred at very large densities, reaching above 100 000 specimens m^{-2} (Głowaciński et al., 2011). The average density of macroinvertebrates in 2011 in Lake Durowskie was 1658 specimens m^{-2}. In 2009 and 2010 the average density was 980 and 1276 specimens m^{-2}, respectively. So, the permanent increase of macroinverebrate abundance was noted in subsequent years. This increasing trend was stated both in the profound zone and at the littoral stations adjacent to the forest. In the profound zone, the density grew from 199 specimens m^{-2} in 2009 to 238 specimens m^{-2} in 2010 and 318 specimens m^{-2} in 2011 (Fig. 5). In the littoral zone, near the forests, it increased from 691 specimens m^{-2} to 2032 specimens m^{-2} and 2482 specimens m^{-2}, respectively (Fig. 5). This trend was not observed in the urbanized area of the lake littoral. Due to human impact, the changes were unpredictable and abrupt there.

The highest biomass of macroinvertebrates was stated in 2011 at station 12 – nearly 855 g m^{-2}, mainly due to the presence of three species of mussels (Bivalvia). The biomass of benthic organisms, as in the case of density, was growing in each successive year of the study, both in the profound zone and at the littoral stations adjacent to the forest. In the profound zone it was the lowest and only consisted from one species *Chaoborus flavicans* (Meig.). There was an average of 1027 mg m^{-2} in 2009; it rose to 1316 mg m^{-2} in 2010 and up to 38 299 mg m^{-2} in 2011. This increase in 2011 was mainly due to the value stated at station 7, as at few other stations it was even higher in 2010 (Fig. 6). In the littoral zone near the forests it was first close to 100 g m^{-2}, increased to more than 134 g m^{-2}, and next to 318 g m^{-2}, respectively in subsequent years. There were large differences among the stations, almost up to 3 orders of magnitude (Fig. 6). The smallest biomass was in the northern part of the lake, near the inflow of polluted Struga Gołaniecka River. The biomass of benthic macroinvertebrates in the urbanized zone of the lake littoral was the highest and did not linearly grow in the subsequent years of the study (Fig. 7).

Steady increase of both density and biomass of benthic organisms in the profound zone of the lake, was due to the improvement of oxygen content at these places. This is related to the oxygenation of lake hypolimnion by the two aerators. Organisms have occurred at all stations in 2012, while in the past were not everywhere present, due to the presence of toxic hydrogen sulfide (Kraska et al., 2006; Obolewski 2011).

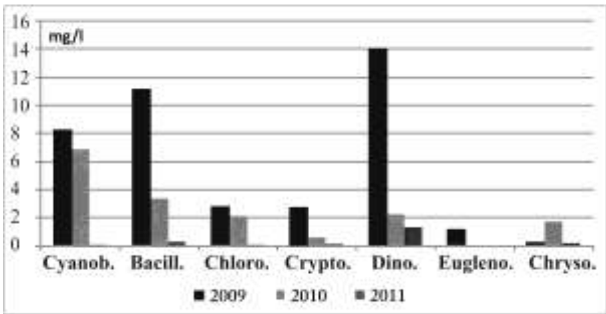

Figure 5. Changes of the average biomass concentration of particular algae groups in Lake Durowskie in 2009-2011 (Cyanob. – *Cyanobacteria*, Bacill. – *Bacillariophyceae*, Chloro. – *Chlorophyta*, Crypto. – *Cryptophyta*, Dino. – *Dinophyta*, Eugleno. – *Euglenophyta*, Chryso. – *Chrysophyta*).

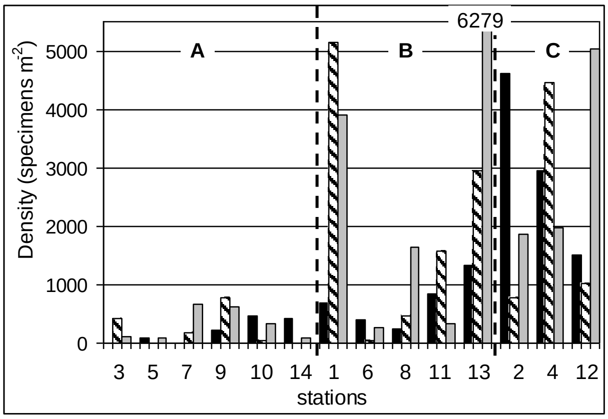

Figure 6. Spatial and temporary variability of the density of benthic macroinvertebrates in Lake Durowskie (A – profundal zone, B – littoral adjacent to the forests, C - littoral adjacent to the urban area

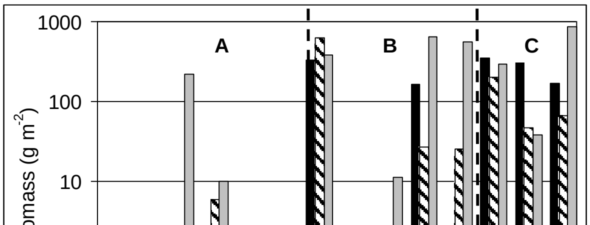

Figure 7. Spatial and temporary variability of the biomass of benthic macroinvertebrates in Lake Durowskie (explanations – like in Fig. 6)

4. CONCLUSIONS

Water transparency increased to more than 2 m, indicating a good state of the lake according to the Water Framework Directive.

Low level of chlorophyll-*a* also indicated a good state of the lake. Saturation of water with oxygen slowly improved, but needs more time to fit the WFD expectations.

A quick response of phytoplankton to the restoration measures was stated: the disappearance of cyanobacteria and growth of dinophytes, diatoms and chrysophytes. Abundance and biomass of planktonic algae decreased significantly.

Submerged macrophytes increased their surface, creating habitats and refugees for fish and macroinvertebrates, however, their total area was still very small, being only 0.18% of the entire surface of the lake.

Macroinverebrates increased their diversity, abundance and biomass. Very important was the growing density of bivalves, due to their capacity of phytoplankton filtration.

Restoration of the lake is a long-term process. Response of phytoplankton and some of physico-chemical variables is very quick, but other components of ecosystem need much more time for the reconstruction of species composition and colonization of new territories.

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