Impact of fires on eutrophication in rivers (the Simmy River, the Bolon Nature Reserve)

G V Kharitonova¹, A V Ostrouhov¹, Z Tyugai², and V O Krutikova¹,³

¹ Khabarovsk Federal Research Center, Institute of Water and Ecology Problems FEB RAS, 680000 Khabarovsk, Russia
² Department of Soil Science, Moscow State University, 119991 Moscow, Russia
³ Institute of Tectonics and Geophysics FEB RAS, 680000 Khabarovsk, Russia

*Corresponding author’s e-mail: alex-im@mail.ru

Abstract. Compared to research on eutrophication in lakes, our understanding of eutrophication in rivers remains extremely limited. This is especially true of the impact of fires, which have become much more frequent in recent decades. Since the risks of eutrophication in rivers as a result of fires increase, it is important to timely assess the impact of fires on the state of rivers draining fire-prone territories. The aim of the study is to select and evaluate the reliability of criteria for impact of fires on eutrophication in stream on the example of the Simmi River (Bolon Nature Reserve, Far East, Russia). The tasks of the work are to assess the fire-prone of the territory from remote sensing data and and to identify markers of the impact of fires on the Simmi River. The fire-prone of the river watershed was estimated by the fire repeatability. The in situ study dealt with river bottom sediments. The sampling was carried out in in three month and the third year after the fire. To assess the impact of fires on eutrophication in the Simmi River, we used the P content in bottom sediments as a marker of the nutrient loading. The obtained results indicate high fire-prone and repeatability of fires the river watershed. In the first months after the fire, the response of the river system is the sequestration of P soluble compounds as a result of the binding of phosphate ions to vivianite. Vivianite is formed on the surface of clay microaggregates, which are removed by the stream over time. In three years after fire, vivianite-clay microaggregates were not detected. Flushing in flow system tends to reduce the scale of the fire impact.
1. Introduction

Compared to research on eutrophication in lakes, there has been significantly less work carried out on rivers despite the importance of the topic [1]. The concept of the eutrophication of a water body, i.e. a change from low to high productivity due to an increase in the input of inorganic nutrients, was established relatively early in the development of limnology [2]. Ohle W. [3] applied the term eutrophication to rivers as early as the mid-fifties, our understanding of eutrophication in rivers remains extremely limited. However, over the last decade, there has been a surge of interest to eutrophication in rivers. The research has been driven by the widespread both natural (floods, volcanic eruptions, fires, etc.) and anthropogenic impacts on aquatic ecosystems and the complexity of accounting for factors affecting eutrophication [1, 4, 5].

Eutrophication is a process not a state, requiring factors external to a system to act in order to bring about change within the system. In freshwater, this is the mainly syndrome associated with an excess of macro-nutrients derived from different natural and anthropogenic sources, which leads in turn to excess growth of primary producers and the exclusion of less competitive species. Primary producers need light, water, and carbon dioxide to photosynthesize and oxygen to respire. They also require micro-nutrients and macro-nutrients, with phosphorus and nitrogen being the key macro-nutrients. Biological assemblages are shaped by both natural environmental factors (physical, chemical and biological) and a number of ‘pressures’ from human activity (pollution, disturbance, species introductions, etc.) [4]. Nutrient enrichment may occur simultaneously with other pressures, and it is often, therefore, difficult to identify what exactly led to eutrophication.

Over the last decades, vegetation fires are amongst the most significant landscape disturbances and affect c.a. 4% of the global vegetated land surface annually [6]. This is due to increases in fire weather severity [7] and extended fire season in many regions [8]. Since the risks of eutrophication in rivers (and/or in lakes) as a result of fires increase significantly, it is important to timely assess the impact of fires on the state of rivers draining fire-prone territories. In this regard, studies of natural reserves are interesting, where the influence of one or another pressure can be neglected.

The aim of the study is to select and evaluate the reliability of criteria for impact of fires on eutrophication in stream on the example of the Simmi River (Bolon Nature Reserve, Far East, Russia). The tasks of the work are to assess the fire-prone of the territory from remote sensing data and and to identify relevant markers of the fire impact on the river. This work is a continuation of our studies of the Amur River and its main tributaries within the Middle Amur Lowland [9, 10].

2. Materials and methods

The studies were carry out on the Bolon State Nature Reserve (Far East, Russia), a strictly protected wetland area of international significance. Its area (103.6 ha) encompasses the lower reaches of the Simmi River, a small tributary of the Amur River, its basin, as well as the adjacent shore of Lake Bolon. This is the northeastern part of the Middle Amur lowlands of prevailing 22–26 m absolute heights. The lands are significantly waterlogged and swamped: swamps and waterlogged meadows occupy almost 80% of the study area. The
The state of ecosystems in the reserve is largely determined by the pyrogenic factor: high-intensity grass fires reoccur in the study area during relatively dry periods (spring and/or autumn) [10].

The fire-prone of the nature reserve territory and the watershed of the Simmi River was estimated by the fire repeatability for 36 years (1984–2019). Aster, Landsat 5, 7, 8 and Sentinel-2 satellite images at 30 m resolution were used for this purpose. The in situ study dealt with bottom sediments of the Simmi River. The sampling was carried out in May of 2018 (i.e., in the third year after the fire of 2016) and in July 2019 after a spring (March–April) fire (Figure 1).

**Figure 1.** Geographic location of the study area: 1 – Bolon Nature Reserve border, 2 – sampling sites, 3 – the main sampling area border.

The samples were collected using standard equipment and methodologies. The basic research methods were granulometric and bulk chemical analyses and scanning electron microscopy (SEM). The granulometric composition was determined using a laser diffraction particle size analyzer (SALD-2300, Shimadzu, Japan). The total composition was determined by X-ray fluorescence method (Pioneer S4, Bruker AXS, Germany). The SEM
analysis was performed using a VEGA 3 LMH Scanning Electron Microscope (TESCAN, Czech Republic). The elemental composition of the most representative sections was analyzed using an X-max 80 energy-dispersive spectrometer (Oxford Instruments, UK). The SEM and X-ray fluorescence analyses were performed at the analytical center of the Institute of Tectonics and Geophysics, Far East Branch, Russian Academy of Sciences (Khabarovsk).

3. Results and discussion
According to the analysis of both remote sensing and field data, the current ecological state of the reserve's landscapes is mainly determined by the pyrogenous factor. Only in the autumn of 2016, more than 80% of the reserve's territory was covered by fire. For a more detailed assessment of the fire impact, remote sensing data for 36 yr (1984–2019) were analysed, the time interval was determined by the availability of satellite data. The analysis of the results showed the scale and high repeatability of fires. Over the past 20 years, fires have covered the main part of the reserve's territory five or more times. Currently, there are no parts left in this territory that were not passed by the fires (Figure 2). The greatest repeatability of fires is characterized by the right bank of the Simmi River.

![Figure 2](image.jpg)

Figure 2. Spatial patterns of 36-yr (1984–2019) fire repeatability of the study area.

It should be noted that the timing of the passage and the nature of the fires (high speed and low depth of the fire front) contribute to minimizing their impact on the reserve’s
geosystems. Almost all fires are grass ones and occur in the spring (after the snow melts and before the beginning of the vegetation) and autumn (after the end of the vegetation) periods. According to field data, despite the periodically recurring impact of fires on the geosystems of the territory, the succession processes have a high intensity and are targeted at restoring the initial state of the landscapes. Nevertheless, the influence of permanent fires leads to an increase in the trophicity of swamp and meadow-marsh ecosystems and the proportion of species that are more demanding of mineral nutrition of soils.

To assess the impact of fires on eutrophication in the Simmi River, we used the P content in bottom sediments as a marker for the following reasons. The first, it is generally recognized that an increase in nutrient loading is a prerequisite of increased eutrophication in rivers. However, it has still not been unequivocally established which of the main nutrients is generally limiting in rivers. The second, enrichment by N tends to be associated with dissolved nutrients in the water column, whereas enrichment by P is associated with both bottom sediments and water column nutrients. The P in sediments is the main source of nutrient P in most rivers. The third, according to the Redfield ratio C:N:P 106:16:1, it can be roughly assumed that the production of primary producers is limited mainly by P, although nitrogen also plays an important role in this process.

The bulk analysis has shown that bottom sediments of the Simmi River feature elevated concentrations of both phosphorus (up to 2200 mg/kg P$_2$O$_5$) and iron (up to 6% Fe$_2$O$_3$). In addition, the presence of organic substances (up to 2.3%) makes it possible to assume that vivianite Fe$_3$(PO$_4$)$_2$·8H$_2$O is formed there. According to the SEM analysis, the increased iron content in sediments is determined by both accessory minerals (ilmenite, etc.) and clay microaggregates containing iron. As is well known, Fe (III) (hydroxy)oxides play an important role in the vivianite formation [11–13]. These compounds effectively precipitate phosphate ions and after microbial and chemical reduction serve as a source of Fe$^{2+}$ and orthophosphate; therefore, they can act as a precursor of the vivianite phase.

The formation of vivianite on surface of clay microaggregates was registered in all sampling points of 2019 (Figure 3a). The Fe:P atomic ratio in these microaggregates is 3:2 (Figure 3b). A slightly smaller quantity of vivianite–clay microaggregates at some part of sampling sites is determined by the presence of sulfate ions and sulfate-reducing bacteria in the bottom sediments, as well as the formation of framboid pyrite FeS$_n$. The share of the vivianite phase (i.e., the quantity of vivianite–clay microaggregates) in the sediments significantly decreases in sampling sites with higher flow rates. The vivianite–clay microaggregates were not detected in the samples collected in the third year after the fire of 2016; this may indicate their mobility in the water flow. It should be noted that the fire of 2016 was large-scale and affected 80% of the territory of the reserve. In 2019, the fire was less intense and affected mainly the right bank of the Simmi River. Consequently, flushing in flow system reduces exposure times to enhanced nutrient loads, thereby reducing the scale of changes.
4. Conclusion
The impact of fires on eutrophication in rivers was studied on the example of the Simmi River (Bolon Nature Reserve, Far East, Russia). The use of remote sensing techniques and field study have shown that the river watershed is characterized by high fire-prone and repeatability of fires. Only over the past 20 years, most of the territory has burned down 5 or more times.

Studies of the bottom sediments have shown that in the first months after the fire 2019, the response of the river system is the sequestration of P soluble compounds (the main nutrients of eutrophication in the rivers) that are formed as a result of "fire" mineralization. This occurs as a result of the binding of phosphate ions to vivianite, the solubility of which is extremely low in the absence of sulphates and sulfate-reducing bacteria. Vivianite is formed on the surface of clay microaggregates with a size of less than 100 microns, which are removed by the stream over time. Three years after a major fire in 2016, vivianite-clay microaggregates were not detected in the bottom sediments. So flushing in flowing system tends to reduce the scale of the fire impact.

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ORCID iDs
G V Kharitonova, https://orcid.org/0000-0002-7650-8500
A V Ostrouhov, https://orcid.org/0000-0002-1426-9639
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