Bioindication potential of conifers for environmental assessment

E Yu Aleksandrova¹, A A Trotsenko¹, E E Minchenok², T O Kovaleva² and A A Katansky³

¹Murmansk Arctic State University, Kommuny street, 9, Murmansk, 183038, Russia
²Murmansk State Technical University, Sportivnaya street, 23, Murmansk, 183010, Russia
³Rostov Institute for Protection of Entrepreneurship, Serzhantova street, 2/104, Rostov-on-Don, 344029, Russia

E-mail: trotsenko2007@yandex.ru

Abstract. The paper presents the results of a study of the state of the environment in the area of the Kola Mining and Metallurgical Plant using a bio-indicator of the Siberian spruce needles (Picea obovata). The following deviations in the morphometric parameters of Picea obovata needles were found: a decrease in the length and width, a reduction in the total surface, different types of damage and wilting. In areas with a more intense impact, a regular increase in the average percentage of damaged plants is observed compared to baseline samples. The state of the environment for the suppression of the Siberian spruce needles was assessed as “satisfactory” and “good”.

1. Introduction
One of the major problems of our time is the increase in anthropogenic pollution concentration. The biological benchmark of environmental pollution has acquired special significance, allowing us to evaluate the combined effect of various factors on the inhabitants of the planet. Currently, the concept of integrated environmental monitoring of the natural environment was developed, which includes biological monitoring using index organisms [1].

Higher conifers form an important group of biological indicators, which can be used to identify individual pollutants in various environments, as well as for a comprehensive assessment of the natural environment. The presence of contaminants in the soil continuum or atmosphere is accompanied by a variety of morphological reactions: discoloration (chlorosis, yellowing), premature wilting of needles, reduction of lifetime, and presence of necrotic spots. The shape and color of the necrotic spot is a specific reaction to a certain type of pollution, and the proportion of the affected surface of the needles can be used to quantify the response of the phytometer.

One of the largest metallurgical plants in Russia is the Kola Mining and Metallurgical Plant, which includes the Severonikel and Pechenganikel sites. The main activity of the enterprise is the extraction of sulfide copper-nickel ores and non-ferrous metals. The production sites of the plant are located on the territory of the Murmansk Region (Nikel, Zapolyarny, Monchegorsk). The main types of products
of the plant include cobalt concentrate, electrolytic nickel, and copper, carbo-nickel nickel powders, precious metal concentrates, etc.

It should be noted that the activities of the plant have a tremendous impact on the environmental situation in the area. The main polluting elements from the processing of copper-nickel raw materials are sulfur compounds and dust containing heavy non-ferrous metals, such as nickel and copper [2].

The purpose of the research was to analyze the state of the environment by deviations in the development of Picea obovata needles in the impact area of the Kola Mining and Metallurgical Company (Monchegorsk, Murmansk Region).

2. Materials and methods
We selected the Siberian spruce needles (Picea obovata) to conduct bioindication research. The Murmansk region has two representatives of the Picea genus: the Siberian spruce (Picea obovata) and the Finnish spruce (Picea fennica). Sometimes there are hybrid plants.

The target area of research was 140 km south of Murmansk. Needle samples were taken near Monchegorsk along a transect at different distances from the Kola Mining and Metallurgical Plant.

The samples were taken at about 2 km from the highway (in the forest zone) to minimize the influence of vehicles.

In 2018, we laid seven sites with a size of 10×10 m², and they included 5 test sites (a total of 300 samples) and two baseline sites (180 samples). Baseline samples were taken on the territory of 8 km around the Lake Chaika, East Bypass Road (60 samples) (Murmansk), and in the area of Lake Lapot (120 samples) (Kola District, the 20th km, along the Kola-Serebryansky HPP highway). All test trees were marked for easy counting.

In 2019, we collected samples from test and baseline sites laid down in 2018 (7 sites).

During the research, we selected trees of approximately the same age and size. Shoots were cut at the height of 1.5 m above the ground. Selected plants were approximately of one height and the same trunk diameter (measured in the field with a tape ruler).

Then, in the laboratory, we carried out a comprehensive assessment of each sample: we took 30 needles from each sample and measured their width and length and calculated the wilting type and the needle damage level [3 - 5].

To assess the state of the environment in the target area, we used a rating scale [6 - 9], which is presented in table 1.

We calculated the average percentage of damage and the prevailing wilting type to determine the state of the environment. Following the four wilting types, we distinguished four categories of environmental conditions: “good,” “satisfactory,” “unsatisfactory,” and “extremely unsatisfactory.”

The first category (“good”) corresponds to the average percentage of damage to the needles of not more than 5%; the first wilting type prevails with no damage. The second category (“satisfactory”) includes needles with 5-15% of damage, the second wilting type with black and yellow spots.

Table 1. Rating of environmental condition based on morphometric indicators for Siberian spruce needles.

| Category of environmental condition | Average percentage of damage | Prevailing wilting type | Damage description |
|------------------------------------|------------------------------|-------------------------|--------------------|
| Good                               | Not more than 5%             | 1                       | No spots           |
| Satisfactory                       | 5-15%                        | 2                       | Black and yellow spots |
| Unsatisfactory                     | 15-25%                       | 3                       | Partial wilting of needles |
| Extremely unsatisfactory           | Over 25%                     | 4                       | Wilting of needles  |
The third category ("unsatisfactory") includes needles with damage level not exceeding 15-25%; the third wilting type prevails with partially dried needles.

The fourth category includes the "extremely unsatisfactory" state of the environment with damage level over 25%, with the prevailing fourth wilting type (wilting of more than 50% of the area of needles).

Mathematical and statistical analysis of the research results, generalization, and interpretation of the data obtained, the formulation of conclusions, and the estimation of the results are more reliable when using the \( \phi^* \) - the Fisher test at a significance level of \( p \leq 0.001 \) and the Spearman correlation analysis.

3. Results

Within the framework of this research during 2018 and 2019, we measured the length and width of spruce needles. During their examination it was discovered that the length of the needles at the test sites ranged from 5 to 21 mm. The maximum length of the needles was found at the maximum distance from the Kola MM and varied in the range from 14 to 21 mm.

The width of the needles at the test sites ranged from 0.5-1 mm. We also noticed the thickening of the needles from areas with a lower anthropogenic impact (0.9-1.3 mm), which confirms the bioindication potential of conifers for registering divergence of environmental parameters.

We calculated the hemispherical and total surface of needles based on the measurements of morphometric parameters (length and width of needles). The largest hemispherical surface of the needles (22.23 mm\(^2\) and 19.98 mm\(^2\)) was recorded at the most remote site (No. 5, 12.5 km from the MMP), and accordingly in the baseline zones (8 km of the East Bypass Road (the Lake Chaika area) and the Lake Lapot area). The total surface of the needles ranged from 13.95 mm\(^2\) to 36.38 mm\(^2\). The largest surface was recorded at measurement points with minimal pollution.

The obtained statistical data indicate the significance of differences between the baseline and test sites and a slight difference between sites located close to each other.

During the analysis of data from test-sites located near the Kola Mining and Metallurgical Plant, a decrease in the hemispherical surface of the needles (8.52 mm\(^2\) - 11.96 mm\(^2\)) and the total surface area (13.95 mm\(^2\) - 19.59 mm\(^2\)) were noted.

At the first site (at 2.5 km from the territory of the Severonikel plant), we took 30 samples. The length of the needles in 2018 varied from 4 to 16 mm (the mean of sample was 10.08 mm). The maximum width of the needles was 1.2 mm; the minimum was 0.4 mm (the mean of sample was 0.91 mm). In 2019, there are no significant changes in the morphometric indicators of the examined needles: the length of the needles was from 6.3 to 12 mm, the maximum width was 1.2 mm, the minimum width was 0.5 mm, the mean of sample was 0.87 mm.

The percentage of damage at site No. 1 in 2018 ranged from 3 to 100% (the mean of sample was 62.53%); the prevalence of the second and third categories of damage was noted (the mean value is 2.53). In 2019, the average damage indicators amounted to 60.5%, the prevalence of the second and third categories was also noted.

The calculation of the wilting type showed that the second and third types prevailed in 2018-2019, the average indicator in 2018 was 2.67, in 2017 - 2.57. The radius of the needles varied in the range from 0.42 to 0.47 (the average value is 0.43) in 2018, from 0.35 to 0.47 in 2019. Also, according to formula 1, we calculated the hemispherical side of the needles, which in 2018 ranged from 8.52 mm\(^2\) to 22.22 mm\(^2\) (the average value is 12.61), in 2019 - from 5.49 to 20.72 mm\(^2\) (the average is 12.77 mm\(^2\)).

The average value of the total surface in 2018 was 20.63 mm\(^2\) (value range: from 13.95 mm\(^2\) to 36.38 mm\(^2\)), in 2019 - 20.91 mm\(^2\) (value range: from 8.93 mm\(^2\) to 33.92 mm\(^2\)).

The analysis of indicators for sample 1 (2.5 km from the Kola MMP) allows us to classify its status as satisfactory in 2018 and 2019 (table 2).

At the second site, we selected 30 needles from three trees of the same age (with the same trunk circumference) and branches of the same age (the age was determined by the number of whorls). The
distance from the site of the Severonikel plant was 5 km. The analysis showed that in 2018 the needles with length of 4 - 11 mm prevailed (the average value is 7.81 mm). The maximum width of the needles was 1.1 mm; the minimum was 0.5 mm (the average is 0.87 mm). In 2019, there were no significant changes in the morphometric parameters of the needles: the length of the needles varied from 4 mm to 12 mm, the maximum width was 1.2 mm, the minimum width was 0.4 mm, and the average value was 0.913 mm.

The average percentage of damage for this area in 2018 was 54.63%, we noted the wide fluctuations in damage level: from 5% to 100%. Analysis of the damage category showed that the second and third categories prevailed (the average value is 2.4). In 2019, the average damage percentage was 54.56%; the values ranged from 0 to 100%. Mostly the second and third categories prevailed; the first was rare.

Table 2. Comparative analysis of the state of the environment in the studied areas for 2018 and 2019.

| Site number   | Damage in % | Wilting type | Category of environmental condition |
|--------------|-------------|--------------|-------------------------------------|
| Site number | 2018 | 2019 | 2018 | 2019 | |
| 1.1 (2.5 km) | 62.533 | 60.500 | 2.67 | 2.57 | Satisfactory |
| 2.1 (5 km) | 59.400 | 58.333 | 2.63 | 2.60 | Satisfactory |
| 2.2 (5 km) | 49.933 | 48.333 | 2.40 | 2.47 | Satisfactory |
| 2.3 (5 km) | 54.567 | 53.500 | 2.50 | 2.57 | Satisfactory |
| 3.1 (7.5 km) | 71.867 | 71.667 | 3.17 | 3.13 | |
| 3.2 (7.5 km) | 63.333 | 60.167 | 2.77 | 2.67 | Satisfactory |
| 4.1 (10 km) | 32.400 | 29.500 | 1.90 | 2.00 | Good |
| 4.2 (10 km) | 61.400 | 61.000 | 2.70 | 2.73 | Satisfactory |
| 5.1 (12.5 km) | 48.500 | 48.500 | 2.40 | 2.47 | Satisfactory |
| 5.2 (12.5 km) | 33.633 | 33.667 | 1.93 | 1.93 | Good |
| 6.1 (base) | 22.733 | 22.833 | 1.57 | 1.60 | Good |
| 6.2 (base) | 21.933 | 20.833 | 1.63 | 1.60 | Good |
| 7.1 (base) | 15.833 | 15.333 | 1.43 | 1.50 | Good |
| 7.2 (base) | 15.833 | 15.667 | 1.37 | 1.40 | Good |
| 7.3 (base) | 9.677 | 10.167 | 1.23 | 1.20 | Good |
| 7.4 (base) | 11.667 | 11.500 | 1.37 | 1.20 | Good |
| Average value | 39.702 | 38.843 | 2.104 | 2.102 | Satisfactory |

In 2018, the calculation of the wilting type showed that the prevailing type is 1-3; the average value was 2.51. The radius of the needles ranged from 0.25 to 0.5 (the average is 0.43). The hemispherical side of the needles varied from 3.14 to 20.72 (the average is 10.91); the minimum indicator for the total surface of the needles was 5.14 mm²; the maximum was 33.92 mm² (the average value was 17.87 mm²). In 2019, the 1-3 type also prevailed (the average was 2.50). The average radius of the needles was 0.457, the hemispherical surface of the needles ranged from 5.36 to 18.94 (the average value was 12.44). The smallest value of the total surface of the needles was 8.52 mm²; the largest was 33.74 mm² (the average was 20.36 mm²).

The analysis for 2018 and 2019 at site No. 2 showed that all three samples belong to the “satisfactory” category.

The third site was located 7.5 km from Kola MMP. In 2018, the length ranged from 7 mm to 17.3 mm (the average was 11.82 mm); the average width of the needles was 0.94 mm (the maximum width of the needles was 1.1 mm, the minimum was 0.7 mm). An analysis of samples in 2019 showed that the average length of the needles was 11.96 mm (varied from 7 mm to 15.2 mm), and the average width was 0.94 mm (maximum width 1.2 mm and minimum 0.5 mm).
The damage analysis, as in the previous test, showed wide variability: from 0 to 100% (the average percentage of damage in 2018 was 67.67% and in 2019 - 65.92%). The damage category was in the range from 1-3 (the average for site No. 3 in 2018 was 2.56, in 2019 - 2.55).

In the selected samples of 2018 and 2019, the fourth wilting type prevails, with an average value of 2018 of 2.96 and 2019 of 2.9. In 2018, the maximum value of the radius was 0.55, the minimum was 0.35 (the average was 0.47), and in 2019 the largest value of the radius of the needles was 0.60, the smallest was 0.25 (the average radius of the needles is equal to 2018) The hemispherical side of the needles of 2019 ranged from 8.79 to 25.9. The average value was 17.7. In 2019, the range of the hemispherical side of the needles was from 6.28 to 28.26; the average was 17.78. The calculation of the total surface of the needles showed that the average value of 2018 is 28.97 mm², and the values ranged from 14.39 mm² to 42.4 mm². For 2019, the average value of the total surface of the needles was 29.1 mm² with a range from 10.28 mm² to 46.26 mm².

The analysis of morphometric indicators on the third site for 2018 and 2019 allows us to evaluate its state as “satisfactory.”

The analysis of the results at site No. 4 (at 10 km from Kola MMP: Severonikel) in 2018 showed that the average length of the needles was 9.79 mm, the maximum value was 15 mm, and the minimum was 5 mm. The width ranges of the needles ranged from 0.7 to 1.2 mm; the average value was 0.94 mm. In 2019, the largest length indicator was 16 mm; the smallest was 5 mm (the average value was 9.6 mm). The width of the needles varied from 0.6 to 1.3 mm, and the average value was 0.95 mm.

The calculation of the percentage of damage in 2018 and 2019 showed that the minimum value varied from 0 to 100% (the average value for 2018 was 46.9%, for 2019 - 45.25%). The analysis of damage shows the prevalence of the 1-3 categories; the average values were 2.1 in 2018 and 2.06 in 2019.

The average value of the wilting type 2018 was 2.3, and in 2017 - 2.36. The needles radius in 2018 ranged from 0.35 to 0.6 (the average was 0.47). In 2019, the maximum value of the radius of the needle was 0.65, the minimum 0.3 (the average was 0.48). The hemispherical side of the needles in 2018 ranged from 4.71 mm² to 28.15 mm², which was an average of 14.71 mm². In 2019, the largest value of the hemispherical side of the needles was 30.61 mm²; the smallest was 5.49 mm² (the average value was 14.78 mm²). The total surface in 2018 was 7.71 mm² - 46.08 mm² (the average was 24.08 mm²); in 2019, the data ranged from 8.99 mm² to 50.1 mm².

The analysis of the main indicators for 2018 and 2019 at site No. 4 allows us to classify sample 4.1 as “good,” and sample 4.2 as “satisfactory” (see table 2).

Samples from site No. 5 (30 samples from each tree) were taken at 12.5 km from the chimney of the site of the Severonikel plant. Measurements taken in 2018 indicate that the maximum length value was 17.3 mm, the minimum was 5.5 mm (the average was 12.47 mm). The width of the needles varied in the range of 0.5-1.2 mm; the average value was 0.92 mm. In the 2019 samples, the range of the needles was from 5.5 mm to 18 mm, with an average of 12.43. The width in 2019 ranged from 0.6 mm to 1.3 mm (the average was 0.96 mm).

Minimum damage percentage in samples 2018 and 2019. amounted to 0%, the maximum - 100%, the average percentage of damage in 2018 - 41.06%, in 2019 - 41.08%. The damage category varied in the range of 1-3 (the average values were 2.01 for 2018 and 2.0 for 2019).

The analysis of the wilting in 2018 and 2019 allowed us to attribute it to the fourth type. For 2018, the minimum value was 1.0; the average value was 2.16. For 2019, the average value was 2.2. The radius of the needles in 2018 ranged from 0.25 to 0.6 (the average was 0.46). In 2019, the range of needles radius was from 0.3 to 0.65 (the average value was 0.48). The calculation of the hemispherical side of the needles showed that in 2018, the maximum value was 32.02 mm², the minimum was 5.18 mm², and the average was 18.49 mm²; in 2019, the largest value was 33.91 mm², the smallest was 5.18 mm², the average is 19.21 mm². The total surface area of needles in 2018 ranged from 8.48 mm² to 52.428 mm² (the average was 30.27 mm²), in 2019 the range was 8.48 - 55.51 mm².
The analysis of main indicators for the test site No.5 for 2018 and 2019 allows us to attribute sample 5.1 to the category “satisfactory,” and sample 5.2 of the category “good” (see table 2).

The sixth site was a control one: needles were selected in the area of Lake Chaika (East-Bypass Road, the 8th km.). As at previous sites, two samples of 30 needles were taken in 2018 and 2019.

In 2018, the length of the needles was 7-15.5 mm (the average was 12.02 mm). The maximum width was 1.2 mm; the minimum was 0.4 mm (the average was 0.91 mm). In 2019, the length of the Siberian spruce needles was from 7 mm to 16 mm; the average was 11.98 mm. The largest value was 1.3 mm; the smallest was 0.5 mm (the average was 0.97 mm).

The average damage in 2018 was 22.33%, in 2019 - 21.83% (there were some fluctuations from 0% to 100%). The minimum damage category varied in both years from 1 to 2 (the average value was 1.61 in 2018 and 1.55 in 2019).

In 2018 and 2019, the first wilting type predominates (with an average value of 1.6 for 2018 and 2019). In 2018, the radius ranged from 0.25 to 0.6 (the average was 0.45), in 2019 the largest radius was 0.65, the smallest was 0.25 (the average radius was 0.47). The maximum hemispherical side of the needles for 2018 was 28.82 mm²; the minimum indicator was 5.49 mm²; therefore, the average indicator was 17.64 mm²; for 2019, the range of variation was from 5.49 mm² to 30.61 mm², and the average was 18.63 mm². The calculation of the total surface of the needles showed that in 2018 the average value was 28.88 mm²; fluctuations were found in the range from 8.99 mm² to 47.18 mm²; in 2019, the average value was 30.5 mm², with a range from 8.99 mm² to 50.11 mm².

Based on this, samples from 6.1 and 6.2 were taken in 2018 and 2019 can be classified as “good” (table 2).

For the reliability of the study, one more control site was selected - site No. 7 - in the area of Lake Lapot (Kola District, 20 km along the Kola-Serebryansky HPP highway). This site of 10×10 m, 4 had the Picea obovata trees of the same age, we took 30 needles from each spruce (a total of 120 needles for 2018 and 2019).

The analysis of the morphometry of needles in 2018 showed that the length of the needles varied from 9.8 mm to 19 mm, and the average value was 14.86 mm. The maximum width of the needles was 1.7 mm, and the minimum was 0.5 mm, which on average was 1.12 mm. For 2019, the largest length was 18.8 mm and the width of 1.6 mm; the smallest values for length was 9.6 mm and width - 0.6 mm. The average length was 14.63 mm and a width of 1.1 mm.

The range of damage to needles in 2018 and 2019 varied from 0 to 100, and the first damage category prevailed (the average value for 2018 was 1.33; for 2019 it was 1.35). The most common wilting type in 2018 and 2019 was 1.00 (with an average of 1.35 for 2018 and 1.32 for 2019).

The radius of the needles in 2018 ranged from 0.25 to 0.85 and averaged 0.56. In 2019, the largest radius was 0.8, and the smallest 0.3 (the average of 0.55). The maximum hemispherical side of the needles in 2018 was 45.96 mm², and the minimum was 8.47 mm², which averaged 26.82 mm²; in 2019, the values ranged from 9.92 mm² to 44.27 mm² (the average of 25.97 mm²).

The average total needle surface for 2018 was 43.91 mm² with maximum values of 75.24 mm² and minimum of 13.87 mm². In 2019, the range of the total surface of the needles varied from 15.11 mm² to 72.47 mm², the average value was 42.53 mm².

Based on this analysis, all the samples at the seventh site, taken in 2018 and 2019, were classified as “good” (see table 2).

Analyzing external deviations in the development of needles, we also note that according to the results of the study, there is a decrease in damage to the needles with distance from the source of impact. Since no Picea obovata plants were found near the plant, samples were taken at a considerable distance from the target, which in general corresponds to the peak of maximum concentration.

We also found a correlation between the maximum concentration of emissions and damage to the Siberian spruce needles, which decreases with distance from the source of exposure ($r = -0.75$).
4. Conclusions

It is shown that conifers can act as bioindicators of the state of the environment. The most popular bioindicators are the Siberian pine and the Siberian spruce, which have a significant sensitivity to pollution.

The following deviations were found in the morphometric parameters of the needles of *Picea obovata* growing in the area of activity of the Kola Mining and Metallurgical Plant: a decrease in the length and width of the needles, a reduction in the surface of the needles, damage and wilting of the needles. In areas with a more intense impact, a regular increase in the average percentage of damaged plants is observed compared to baseline sites.

A comparative analysis of the state of the environment for the suppression of the Siberian spruce needles for 2018 and 2019 indicates a slight change in the morphometric parameters of spruce needles, and the studied sites can be classified as “satisfactory” and “good”.

The results of the study can be used in the design of landscaping of urban areas, considering the types of indicators [10 - 12].

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