State of woody vegetation in an urbanized environment (the example of Krasnoyarsk)

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Abstract. Woody plants are one of the effective ways of stabilising the ecological environment of large industrial cities. In order to maximize the effect of green spaces a large and diverse research effort is needed to study the urban green spaces, assess their ecological plasticity and adaptive potential. The results of such research will be the basis for recommendations on the selection of an assortment of species for landscaping of urban areas. The aim of the study was to investigate the condition of woody plants growing in the urban environment of Krasnoyarsk. Within the framework of the study a comprehensive assessment of existing urban green spaces was carried out for the first time for Krasnoyarsk. The species composition and age structure of plantings are established by the results of inventory of public plantings. The vital state of dominant species has been evaluated and their ecological and physiological characteristics, including the study of water retaining capacity of leaves, has been carried out. That allowed to estimate the impact of anthropogenic environment on the condition of urban woody plants.

1. Introduction

Atmospheric air pollution is the largest environmental risk to public health in the world, and this issue is particularly acute for urbanized areas. On the territory of the Russian Federation the list of cities with "very high" and "high" level of air pollution according to the data for 2019 includes 40 cities with a population of 10.6 million people. Traditionally, this list includes Krasnoyarsk, a major industrial centre of Siberia. According to the data for 2019, the level of atmospheric pollution in Krasnoyarsk was characterized as "high" – API₅ <13 (in 2018 API₅ >14 – "very high"). The main contributors to the pollution level were suspended substances, nitrogen dioxide, ammonia, formaldehyde, benz(a)pyrene [2]. The leading sources of air pollution in Krasnoyarsk are machine-building, non-ferrous metallurgy enterprises (JSC "RUSAL Krasnoyarsk", JSC "Krasnoyarsk aluminum plant"), chemistry, power engineering (Krasnoyarsk HPP), construction industry, boiler houses and motor transport [1, 2].

The environmental situation in Krasnoyarsk is aggravated by a number of specific natural and climatic factors, architectural and planning solutions. Krasnoyarsk territory has a complex relief, the city is located in a deep hollow, sheltered from winds by the Sayan mountains ranges, which contributes to poor ventilation of urban space and, consequently, low dispersion capacity of the atmosphere. The water vapour cloud of the Yenisei River, which is not frozen, also does not help to disperse pollutants. In addition, active development of urban space – development of new areas, increase in the height of buildings, etc., has led to the disruption of natural air circulation along the Yenisei River valley and the accumulation of toxic substances in the atmosphere of the city. During
periods of adverse meteorological conditions (AMC) - a special combination of meteorological factors (wind weakening, doldrums, fogs, etc.), contributing to the accumulation of pollutants in the surface layer of the atmospheric air, the city is covered with a "cap" of acrid smog, and the problem of environmental safety of the population becomes visible to the naked eye [1]. For the first time, Krasnoyarsk introduced the AMC regime in February 2012, and it has been repeated with enviable consistency since then. For example, during 2020 there were 10 times of such regime (with a total duration of about 30 days) and in the first month of 2021 there were 4 times (with a total duration of about 8 days). A similar situation is developing in many industrial cities of the Russian Federation; therefore, more and more attention is now being paid to studying and finding ways to resolve environmental problems. Along with the reduction of emissions from the main industries through the installation of more advanced dust-collecting equipment, regulation of emissions of enterprises during the periods of AMC, redistribution of traffic flows, organization of monitoring of atmospheric air condition, an important place belongs to measures for landscaping and beautification of urbanized territories.

Urban green spaces are an important habitat-forming and habitat-improving factor that ensures the stability of urban development. Vegetation is actively involved in the formation of a favorable environment for life and health: it improves the microclimate, reduces the level of physical pollution of the atmosphere (noise, vibration, etc.), improves the visual properties of urban landscapes, creates optimal conditions for recreation in the open air, a beneficial effect on the human psyche, promotes relaxation, etc. [3-5]. Urban vegetation plays an important role in improving air quality. Tree plants have a large surface area (leaves, branches, bark, etc.), so the main mechanism of reducing air pollution is precipitation (filtration) of pollutants in their crowns [6, 7]. It has been shown that plantings along traffic arteries can reduce pollutant concentrations by 40% for NO2 and 60% for PM10 [8]. However, urban vegetation can also increase local air pollution levels by blocking wind circulation [9]. According to a study by Abhijith et al. the use of tall trees in street canyon conditions leads to deterioration of air quality, while hedges help to reduce exposure to various gaseous pollutants [10]. In contrast, according to Taleghani et al., hedgerows lead to increased concentrations of pollutants at the pedestrian level, while trees contribute to better dispersion of pollutants and lower NO2 concentrations [11]. Such opposite results are apparently caused by the different composition and combination of pollutants, as well as by the microclimate features (wind speed, humidity level, etc.) of the territories studied. Thus, it becomes apparent that the positive effect of green spaces in terms of improving air quality is determined by the structure and configuration of plantings, which must be developed taking into account the characteristics of a particular territory (natural and climatic, environmental, etc.) [7].

Technogenic environment is aggressive in relation to all components of wildlife, not excluding vegetation. High concentrations of pollutants inherent in the urban environment can negate all the positive effects of green spaces, reducing their vitality, accelerating aging, contributing to the invasion of pests and diseases, and eventually leading to their death. The impact of technogenesis on the physiological and biochemical parameters of plants has been studied for many years [12-15]. Technogenic environment leads to physiological, structural and morphological changes that can serve as effective indicators of the general impact of air pollution on living organisms. Recently, the use of higher plants for bioindication purposes has become increasingly widespread due to the high availability of biological material, ease of species identification, sampling and processing, as well as the ubiquity of some genera, which allows covering of large areas. At the same time, the searches for pollutant-sensitive species to be used for bioindication, on the one hand, and tolerant species that can be used and recommended for the creation of sustainable green spaces, on the other hand, are of great importance [15].

It is obvious that landscaping of urbanized areas should be based on a scientific approach to the selection of species composition, based on the assessment of the sanitary-ecological condition of the existing woody vegetation and taking into account the level of anthropogenic pressure on them. The data of such studies will allow to select options for optimal combinations of plant species that are not
only resistant to the existing environmental conditions, but also have the life potential for its stabilization and improvement.

Currently, there is a strong interest in the study of urban vegetation. Domestic and foreign scientists are continuing studies aimed at discovering the adaptation mechanisms and the degree of ecological plasticity of plants in an urban environment [3, 16-18], ways to enhance the environment-forming functions of plantations [19-23], mechanisms for sustainable management of urban vegetation [24, 25], etc.

For Krasnoyarsk this kind of research is very relevant both because of the severe ecological situation in the city and because of the lack of objective information on the current state of the available green spaces.

The aim of this work is to study the state of woody plants growing in the urban environment of Krasnoyarsk.

2. Methods and Materials

The objects of the study were woody plants in different ecological categories of public plantations in Krasnoyarsk.

The green space inventory was carried out on a total area of about 60 hectares, and included the most frequented squares and parks, as well as the main transport arteries of the city. The inventory of greeneries was carried out by the method of continuous enumeration on the studying object, dividing it by species and age. The age structure of the plantations was determined according to the ontogenetic-population approach [26].

For the ecological and physiological characteristics of the state of woody plants in plantations of different ecological zones, the "through" species (having representation in all types of urban plantations) - Betula pendula Roth., Malus baccata Borkh., Tilia cordata Mill. and Padus maackii Kom. were selected. The study plots were laid out in different administrative districts of Krasnoyarsk city, and included plantings of gardens or parks, as well as roadside plantings. The Arboretum of the Forest Institute of the Siberian Branch of the Russian Academy of Sciences, located in the Oktyabrsky District of Krasnoyarsk, remote from industrial enterprises and major traffic arteries, was chosen as the area of conditional control. In each sample area 10 single-aged individuals of the studied species were selected from which experimental samples were collected for laboratory studies. The ecological and physiological assessment of the studied species included: visual assessment of the vital state of the woody plants and the study of the water retaining capacity (WRC) of the leaves.

The degree of disturbance of the assimilation apparatus and tree crowns was the basis for visual assessment of plant health. A ten-point scale was used to assess the percentage of live branches in tree crowns (P1), the degree of crown foliage (P2), the percentage of live (without necrosis) leaves (P3), and the average percentage of live leaf area (P4). The total assessment of the state of each plant species (Cv) was calculated using the formula (1) [27]:

\[ C_v = P_1 + P_2 + P_3 + P_4 \]  

Based on Cv, the state of trees of each species was assessed according to a category scale: 39-40 points – good condition; 35-38 – satisfactory; less than 35 points – weakened plants.

To determine WRC of leaves, a weight method, based on determining the rate of water loss by isolated leaves over a certain period of time, was used [28]. To interpret the results of the study, leaf water loss during the first 60 min of observation was taken. The study of WRC was conducted twice during the growing season (July, August).

3. Results and Discussion

On the basis of the inventory carried out it has been established that Krasnoyarsk green spaces are diverse. According to taxonomic analysis in the surveyed plantations there are 53 species of woody vegetation, which belong to 39 genera and 18 families. It is worth noting that the highest number of species is found in public gardens (50 species) and parks (47 species). The least species diversity is observed in street landscaping with 28 species. The leading position in taxonomic composition of urban plantations is held by representatives of the family Rosaceae, which is represented in
Krasnoyarsk greenery by 14 genera and 18 species. The families **Pinaceae** and **Caprifoliaceae** include 3 genera each, **Oleaceae**, **Elaeagnaceae**, **Grossulariaceae**, **Salicaceae** – 2 genera each. There are 11 monotypic families, including **Betulaceae**, **Ulmaceae**, **Aceraceae**, **Fabaceae**, **Tiliaceae**, etc. In general, the systematic structure of Krasnoyarsk flora has a low saturation of families and genera.

Evaluation of quantitative participation of species showed that 4 species are the dominant in all types of the surveyed plantations among deciduous species. These are representatives of the families: **Rosaceae** – *Malus baccata* Borkh., **Aceraceae** – *Acer negundo* L., **Salicaceae** – *Populus balsamifera* L. and **Ulmaceae** – *Ulmus pumila* L. The proportion of participation of these species in Krasnoyarsk public plantations was 49.8%, indicating sufficient diversity of assortment composition, and as a consequence low ornamental and aesthetic properties of plantations. Species with an average proportion of participation (from 1 to 5%) include: *Syringa josikaea* Jacg. fil. – 4.89 %, *Betula pendula* Roth. – 3.43 %, *Caragana arborescens* Lam. – 2.89 %, *Sorbus sibirica* Hedl. – 2.50 %, *Tilia cordata* Mill. – 2.28 %, *Padus avium* Mill. and *Padus maackii* Kom. – 1.97 and 1.91 %, respectively, *Populus alba* L. – 1.56 % and *Pyris ussuriensis* Maxim. – 1.34 %, *Prunus ussuriensis* Maxim., *Grataegus sanguinea* Pall., *Acer ginnala* Maxim., *Elaeagnus argentea* Pursh., *Fraxinus excelsior* L., etc. have low participation (less than 1 %) in urban plantations of Krasnoyarsk.

Coniferous species are quite actively used in Krasnoyarsk landscaping. Among them *Picea obovata* Ledeb. – 6.82 %, *Larix sibirica* Ledeb. – 5.38 % and *Pinus sylvestris* L. – 5.12 %.

The most important characteristic of tree species is their age status, which allows us to assess the development of the population at the present stage, as well as to predict its future prospects [26]. The age structure of the surveyed green spaces in Krasnoyarsk is shown in figure 1.

![Figure 1. Age structure of public plantations in Krasnoyarsk.](image-url)
predominance of virginile individuals in the age spectrum indicates, on the one hand, the relatively recent introduction of a particular species into the green space, which requires tracking the nature of their growth and development, to assess the feasibility and effectiveness of their use in landscaping. Examples of such species are _Prunus ussuriensis Maxim., Thuja occidentalis L., Berberis amurensis Rupr._ etc. On the other hand, it is not promising to use this species in planting greenery, as due to its biological and ecological characteristics, this species is not able to move into the next age category. For example, plantings of _Pinus sibirica Du Tour., Quercus robur L._ et al.

Specimens of the "old generative trees" category are poorly represented in Krasnoyarsk plantations, occurring mainly in the age spectrum of _Pinus sylvestris, Populus balsamifera, Ulmus pumila, Larix sibirica._ etc., growing predominantly in park plantations. The reason is that in urban conditions the trees die before reaching this age stage and, due to loss of ornamental and aesthetic qualities, they are simply removed. No individuals of the senile stage of ontogenesis were identified within the study.

Assessment of the age structure of the dominant species in Krasnoyarsk landscaping showed that there are practically no young specimens (individuals of categories v and g1) in plantations of _Populus balsamifera_ and _Ulmus pumila_ (comprising no more than 7% of the population). In this regard, we can assume that the quantitative participation of these species in the greenery plantations of Krasnoyarsk will gradually decrease. In spite of the fact that at present almost no new _Acer negundo_ specimens are planted in Krasnoyarsk, its high capacity for seed regeneration and intensive re-growth ensures a stable succession of generations. This means that in the nearest future this species will continue to dominate in urban green spaces. This fact is of great concern since _Acer negundo_ is an invasive species capable of suppressing, displacing and preventing the renewal of species of the natural flora of the region. In this connection, some measures are taken in Moscow and other cities of the European part of the Russian Federation to remove this species from the territories of the green fund [29]. Obviously, the positive experience of these cities in the fight against uncontrolled spreading of _Acer negundo_ should be used in Krasnoyarsk green spaces as well.

The analysis of the age structure of green spaces in Krasnoyarsk has revealed a change in the species composition of urban plantations. On the one hand, the share of dominant species is gradually decreasing, as evidenced by the predominance in the age spectrum of _Populus balsamifera_ and _Ulmus pumila_ of medium-aged generative trees and the low representation of virginile individuals. On the other hand, many non-native species are now being introduced into landscaping plantations, represented mainly by virginile and young generative trees, the feasibility and viability of which remain to be seen.

Woody plants are differently tolerated by the extreme conditions of the urban environment, so the ecological and physiological assessment of the state of green spaces is particularly important. At the same time, to improve the reliability of ecological assessments of the state of green spaces, it is necessary to increase the number of methods and ways of research and studied parameters [27]. To identify the current state of green spaces in Krasnoyarsk and assess their prospects for the future, we used visual and physiological methods of ecological assessment.

The vital state of woody plants reflects their response to the complex impact of factors of the urbanized environment [27, 28].

As studies have shown (figure 2), a decrease in vitality indicators was marked for studied species under conditions of anthropogenic environment.

If the vital state of _Betula pendula, Tilia cordata, Padus maackii_ in the control area conditions is characterized as "satisfactory," then it corresponds to the category "weakened" in the conditions of trial areas. This is mainly due to an increase in the degree of damage to the assimilating apparatus of plants (rust, blotchiness, damage by entom pests, etc.), and, as a consequence, a decrease in the living area of leaf plates. In addition, mechanical damages of trunks and branches are observed in all categories of plantations in the studied species, there are signs of necrotic-cancerous diseases, which are a consequence of the presence of withering and dry branches in the crowns of plants. The lowest total grade of state and, consequently, the more weakened one of the studied species is noted in roadside plantings. There is an increase in occurrence and area of leaf damage by various necroses,
reduction of crown foliage in roadside plantings, while the percentage of dry branches in the crowns does not increase, which seems to be connected with the timely care of this category of plantings.

Among the studied species a relatively high total grade of the vital state is marked in *Betula pendula*. The state of this species is estimated as "satisfactory" ($C_v = 38\) under control and park plantations while it decreases to "weakened" ($C_v = 34\) in roadside plantations mainly due to decrease of crown foliage and increase of damage of the assimilating apparatus.

*Malus baccata* has low viability and the status of this species is assessed as "impaired" ($C_v \leq 30\) in all categories of studied plantations. This species was found to be infested by entomaceous pests that have a negative impact on the viability of the species.

Thus, the assessment of the vital state of species has shown that the technogenic environment of the city leads to a deterioration in the general state of vegetation. All of the studied species show a decrease in crown development and assimilation apparatus, which affects the ornamental and aesthetic properties of the plantations. Among the measures aimed at improving the vital state of plants, we can recommend the sanitary care of plantations, consisting in the timely removal of withering and dry trunks and branches, as well as measures for the timely detection and control of plant pests and diseases.

A diagnostic indicator of important physiological processes occurring in the plant organism is WRC of leaves. Atmospheric air pollution by acidic gases causes disturbances in the integrity of biological membranes in plant cells, resulting in a decrease in their ability to retain water. Thus, the adaptive capacity and ecological plasticity of species can be judged by the WRC indicator, the higher the WRC of plant leaves, the more resistant they are to adverse environmental conditions [28].
As a result of this research, it was found that the change in WRC of the leaves of the studied species is due to the species specificity, the growing conditions and the vegetation period (figure 3).

![Figure 3](image_url)

**Figure 3.** Leaves water retention capacity of the studied species in Krasnoyarsk: (a) *Betula pendula*, (b) *Malus baccata*, (c) *Tilia cordata*, (d) *Padus maackii*.

A study of WRC of some species showed that the leaves of *Betula pendula* had the highest WRC under control area conditions at the beginning of the growing season. Water loss by its leaves compared to *Malus baccata*, *Padus maackii* and *Tilia cordata* was lower by 14.2%, 26.9% and 46.0%, respectively. By the end of the growing season, the plants showed a general decrease in leaves WRC relative to July data. Under control conditions, the decrease in *Betula pendula* was by 55.6%, in *Malus baccata* – by 37.5% and in *Tilia cordata* - by 8.7%. Overall, however, the rate of water loss in these species did not exceed 10% under control conditions. In August, in contrast, *Padus maackii* showed a 35% increase in WRC of leaves under control conditions and a 15.8% increase in park plantations compared with July data. Apparently it is caused by features of *Padus maackii* seasonal development, connected with short period of vegetation of this introducer in Krasnoyarsk conditions. The period of autumn coloration of *Padus maackii* leaves falls at the end of August and early September [30], we can assume that by the time of the study this species were already actively preparing for winter, which is associated with the removal of excess water from tissues and leaves and that could not but affect the dynamics of WRC.

Investigating leaves WRC dynamics of the studied species in area categories, we have established that in July a reliable increase in leaves WRC in park and roadside plantations compared to the conventional control zone was observed for individuals of *Padus maackii* (by 28.8% and 22.5%, respectively), *Betula pendula* (by 14.2% and 33.3%, respectively) and *Tilia cordata* (by 48.9% and
47.8%, respectively). No significant differences in this trait were found for *Malus baccata*. Increase in leaves WRC in conditions of technogenic pollution was noted by other researchers [28].

By the end of the vegetation period, *Betula pendula*, *Tilia cordata* and *Malus baccata* showed a general decrease in WRC relative to data from July in all categories of studied areas. Apparently, this is related both to natural aging of cell membranes which by the end of vegetation period can no longer effectively control water retention processes, and to disturbance of their protective properties due to prolonged exposure of plants to pollutants and accumulation of significant amounts of toxic substances in them. However, the tendency to increase WRC in *Betula pendula* in city conditions relative to the control area remains. Thus, individuals of this species growing in roadside plantations are distinguished by the highest WRC, water losses in these conditions were lower by 38.8% comparing with the control data. For individuals of *Tilia cordata*, the ability to control water yield processes effectively by the end of the vegetative period is maintained only in park plantations, while in roadside plantations water losses increased by 45% relative to the control area. Maximum water losses for *Malus baccata* were registered in August in park conditions, exceeding control data by 56.6%, and by 49.5% – in roadside plantings. Decrease of WRC by 50% in relation to the control zone in August was also noted in *Padus maackii* growing in roadside plantations.

Thus, the study found that *Betula pendula*, *Tilia cordata* and *Padus maackii* are able to control water-release processes effectively by increasing the WRC of leaves under the influence of the anthropogenic environment. However, towards the end of the growing season this ability weakens in *Tilia cordata* and *Padus maackii* in park stands and is lost in roadside plantings. This probably indicates that, despite the adaptive potential of these species, high level of anthropogenic pollution causes disturbances in plant life processes, and with time their effects become increasingly evident. Stability in the dynamics of leaves WRC both by the level of contamination of sample areas and by the period of vegetation is noted for individuals of *Betula pendula*, which seems to be a sign of high plasticity of this species to the conditions of the urban environment. Leaves WRC for *Malus baccata* in July showed practically no differences by area categories, and the ability of this species to adapt to the degree of technogenic load was not established. However, by the end of the growing season, a sharp increase in water yield under technogenic conditions is observed, in connection with which we can conclude that this species is unstable to the conditions of urbanization.

### 4. Conclusion

In the course of the research it was established that there are 53 species of woody vegetation in the public plantations of Krasnoyarsk, which belong to 39 genera and 18 families. The assortment composition of landscaping plantings in Krasnoyarsk is monotonous as 50% of its composition is formed by only 4 species, these are: *Malus baccata*, *Acer negundo*, *Populus balsamifera*, *Ulmus pumila*, which is a consequence of low decorative and aesthetic properties of plantations.

Analysis of the age structure of Krasnoyarsk plantations showed that 42.7% of specimens by age belong to the category of "medium-aged generative trees", hence, the existing plantations at this stage of ontogenesis perform their maximum functions. Assessment of age spectra of dominant species revealed an outlined trend of changing species composition. Populations of *Populus balsamifera* and *Ulmus pumila* will gradually decline, as their renewal by young individuals does not take place. It is possible to expand the range of species for landscaping plantations with species whose age spectra include young generative trees along with virginile individuals - *Fraxinus excelsior*, *Syringa josikaea*, *Padus maackii*, *Physocarpus opulifolius*, *Cotoneaster melanocarpus* and *Cotoneaster lucida*, etc. The *Acer negundo* population needs to be regulated, otherwise the species may threaten the survival of other species' populations.

The ecological and physiological assessment of the "transversal species" revealed a deterioration in the general condition of the vegetation under the influence of the anthropogenic environment. According to visual assessment, *Betula pendula*, *Malus baccata*, *Tilia cordata* and *Padus maackii* show disturbance of crown development and plant assimilation apparatus. Mechanical damages of trunks and branches are observed in all categories of plantations in the studied species, there are signs
of necrotic-cancerous diseases, reduction of shoots foliage and increase in the degree of leaf blade damage (rust, spot disease, entomovirus damage, etc.) are noted. Of the studied species, a relatively high total vital state grade is observed for Betula pendula, while a low vital state grade is characteristic of Malus baccata.

The study of leaves WRC revealed that in response to anthropogenic pollution Betula pendula, Tilia cordata, Padus maackii are able to reduce the process of dehydration, but, depending on the degree of anthropogenic impact and the growing season, this ability is lost in some species. Stability in leaves WRC dynamics and high indexes of vital state have been found in Betula pendula, on the basis of which we recognize this species as the most plastic in adaptation to conditions of anthropogenic environment of Krasnoyarsk.

The results of this research can be used in the organization of monitoring of plant communities of contaminated areas, as well as in the design of landscaping objects of industrial cities.

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